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# DEA IN PERFORMANCE MEASUREMENT OF TWO-STAGE PROCESSES: COMPARATIVE OVERVIEW OF THE LITERATURE[3]

*Standard non-parametric Data Envelopment Analysis (DEA) introduced by Charnes, Cooper, Rhodes (1978) does not provide adequate detail to identify the specific sources of inefficiency embedded in the activities on the level of production sub-processes of an enterprise, without considering the internal structure of the business. One of the DEA applications is to evaluate the efficiency of two-stage processes, where all outputs of the first stage are intermediate measures, which are considered as inputs of the second stage. In recent years, there has been an exponential growth in the number of publications related to theory and applications of efficiency measurement for two-stage systems. These models assess both the overall efficiency score of the whole process and each of the individual sub-processes. Results from the analysis give an approach to the significant more detailed information that would otherwise remain hidden in the ,,black box" of efficiency analysis. Opening the black box of efficiency analysis offers managers to monitor and measure the efficiency of their production sub-processes. The management is able to early detection of the inefficiencies in the production process.*
*The aim of the paper is twofold. The first task is to survey and classify the Two-stage DEA models and present the applications of these models across the literature. The second aim is to offer important support to future researchers, providing a ,,new" knowledge base regarding network DEA methods and encourage researchers to collect data suitable for this type of network analysis.*
*The objective of the work is to review the network DEA literature, because the number of studies which seek to measure the efficiency and productivity of decision-making units with internal structures has increased in the last years dramatically. This paper aims to support future researchers on this topic.*
*Keywords: Data Envelopment Analysis; Efficiency; Intermediate product; Internal structures; Two-stage process; Two-stage NDEA*
*JEL: C61; Q12; Q19*

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## 1. Introduction

Data Envelopment Analysis (DEA) is a non-parametric technique for evaluating the efficiency of organisations in terms of inputs and outputs. DEA is a mathematical programming technique originally developed by operations research workers studying business firms and not-for-profit organisations to identify best-practice efficiency frontiers and to measure shortfalls from the frontiers. The basic goal of DEA models is to evaluate on a comparative basis the efficiency of homogeneous decision-making units (DMUs), which use inputs for their activities and transform them into desirable or undesirable outputs. The beginnings of the ideas leading to the current form of this non-parametric method can be found in the study of Farell (1957), which was significantly followed by the work of Charnes et al. (1978) and Banker et al. (1984). Authors formulated exactly radial DEA models under the assumption of constant returns to scale (CCR model), or taking into account the variability of returns to scale (BCC model). The pioneers in the formulation and application of non-radial DEA models are the studies of Charnes et al. (1985) and Tone (2001). These models pertain to single level situations, in which the production process consists of single stages for each member of a given set of Decision Making Units (DMUs).

The production process can have multiple stages, and therefore measuring the efficiency of every single stage separately would be necessary and useful to diagnose and improve the overall efficiency of the production activities. The first idea that the production systems consist of a finite set of sub-technologies (also referred as sub-activities, sub-processes, sub-systems) was mentioned in the work by Shephard, Färe (1975). In recent years, an application and theory of Network Data Envelopment Analysis (NDEA) has received more attention in the DEA literature. Many authors provide literature reviews on the empirical surveys in the field of NDEA efficiency analysis, the most relevant NDEA techniques, approaches, methodological development, application fields and development trends. Cook, Seiford (2009) provided a literature review of the various DEA models and presented the multilevel models with the concept of sub-technologies inside the process of efficiency analysis. Halkos et al. (2014) presented different Two-stage DEA approaches and defined four categories with their mathematical formulations and applications, namely independent, connected, relational and game-theoretic Two-stage DEA models.

Emrouznejad, Yang (2018) made a survey and analysis of the first 40 years of DEA literature (1978-2016). Authors investigated the top 5 most popular research keywords in 2015 and 2016 investigated in journal DEA – related articles with the second place for research keywords: Network DEA, Two-stage DEA and efficiency Decomposition. Zhou et al. (2021) suggested future research DEA application directions in using the NDEA models, which take into account the inner operational mechanism of the sub-systems in each DMU under evaluation. Xu et al. (2020) mentioned the Network DEA method as a new concept of extended DEA in the field of the DEA method, which can show more detailed efficiency in the production process. Daraio et al. (2020) made a systematical review of empirical surveys that have been written in the field of efficiency and productivity analysis using frontier estimation methodologies and identified the term networks as one of the most attractive terms extracted from the departing bibliography list by their systematic review of the empirical surveys. Lampe and Hilgers (2015) focused on the DEA and Stochastic Frontier Analysis

(SFA) papers and identified three main research topics from Network DEA models, namely Relational Network Model (Kao, 2009 and Kao, Hwang, 2008), Multi-Activity Network DEA (Yu, Lin, 2008) and Slacks Based Network DEA (Avkiran, 2009, Tone, Tsutsui, 2009). Zhou, Xu (2020) summarised the research studies of the Fuzzy Data Envelopment Analysis (FDEA) research and developed the FDEA model to integrate the fuzzy sets with different DEAs, such as the network DEA and two-stage DEA.

Färe, Whittaker (1995) and Färe, Grossskopf (1996) first proposed an input-oriented Two-stage NDEA model to study the relative efficiency of dairy production processes. In another study, Färe, Grossskopf (2000) presented a NDEA model for assessing Swedish Institute for Health Economics. This concept became the basis for the further studies and research in this area. However, many more complex cases have been studied during the literature where the business system is separated into more processes, either with series or parallel structure, or some mix of these. These structures are called in the literature network structures, and the DEA techniques developed to measure efficiency in such systems is referred as network DEA (Kao, 2014). Network DEA has been widely used for efficiency in various industrial and commercial sectors. The application field of Two-stage DEA models is miscellaneous. Luo (2003), Chen, Zhu (2004), Avkiran (2009), (2015), Kao, Liu (2014), Wang et al. (2014), Wanke, Barros (2014) Kwon, Lee (2015), Zha et al. (2016), Wanke et al. (2017), An et al. (2018), Ding et al. (2019), Halsaf et al. (2020), Henriques et al. (2020) proposed applications of Two-stage DEA to banking sector. Yang (2006), Chen et al. (2009) created a Two-stage DEA model allowing for applications to the life and health insurance companies. Zhu (2011), Gramani (2012), Lu et al. (2012), Lozano et al. (2013), Tavassoli et al. (2014) proposed applications of Two-stage DEA to airline performance. Färe, Whittaker (1995) Majiwa et al. (2018) developed a NDEA approach allowing for applications to agriculture. Chiu, Lin (2018), Yin et al. (2020) presented a performance evaluation with NDEA model in tourist hotels. Eco-efficiency analysis with Two-stage NDEA approach became a hot research topic in the studies Chu et al. (2015), Chen et al. (2018), Mirmozaffari (2018). Yang et al. (2008), Tsolas (2011), Lozano et al. (2013), Wang et al. (2014), Wu et al. (2016), Chen et al. (2018) provided an approach for analysing the reuse of undesirable intermediate outputs in a Two-stage production process with an application in different sectors. Liang et al. (2011), Kao, Lin (2012), Lee, Worthington (2016), Golshani et al. (2019) applicate NDEA to measure the quality of the university research services.

The overall efficiency of Two-stage DEA models can be evaluated with the decomposition approach presented by Kao, Hwang (2008), Chen et al. (2009), Wang, Chin (2010), Zhu (2011), Gramani (2012), Chu et al. (2015), Despotis (2016a), Chen et al. (2016), and game-theoretical approach proposed by Chen et al. (2006), Liang et al. (2008), Izadikhah et al. (2018).

We emphasise that the goal of our paper is to present a systematic survey of the literature on using the NDEA in Two-stage processes, because the number of studies on this topic is quite large, as depicted by Emrouznejad, Yang (2018) and Zhu (2020). The listing of NDEA related publications and articles is the most complete source of references for this topic and its applications in measuring the efficiency of Two-stage processes, productivity or performance with internal structures.

The article is organised as follows. Following the introduction, the series and parallel structure and types of Two-stage processes are described in Section 2. Section 3 proposed an NDEA literature review, which applied Two-stage static approaches to measure the performance of DMUs. Section 4 outlines conclusions and discusses the possibilities for further research in this area.

## 2. Basic Structures and Types in Network Systems

A common feature among the several models is that the efficiency evaluation of the DMU depends on the efficiency values of its sub-processes, thereby increasing the discrimination power of DEA methodology with respect to the black-box approach (Castelli et al., 2010). We classify the contributions of DEA literature assessing DMUs, whose internal structure is known.

Network models use different structures. In the development of NDEA were used different models with two or multiple stages (static models) or extend it to time-dependent processes (dynamic models). NDEA approach is constructed under Constant Returns to Scale (CRS) or Variable Returns to Scale (VRS) and can be input-, output- or non-oriented. In this section, we describe the structures and types of models, including intermediate flows between the sub-processes in the production process.

### *2.1. Two basic structures in NDEA*

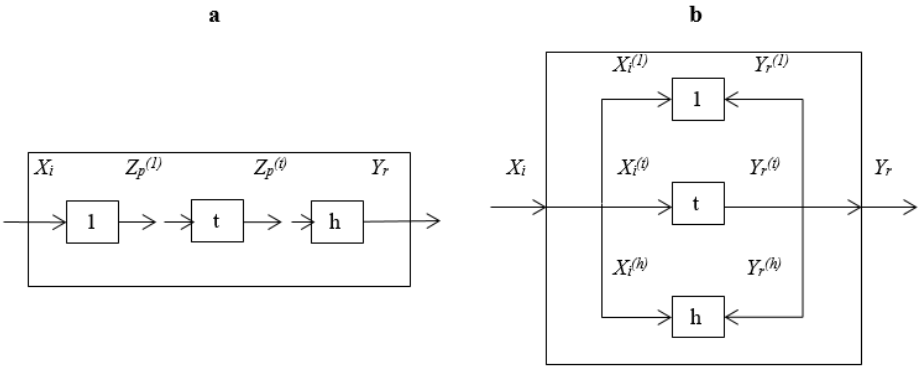
Barlow, Proschan (1975) assert that parallel and serial structures are two basic structures of a system, but a more complex network system can be represented by a parallel system with serial sub-processes or a serial system with parallel sub-processes. For each of these structures, system (in)-efficiency can be broken down into (in)-efficiency of individual processes (Kao, 2009). The serial network model contains DMU with two or with multiple sub-processes, linked by an intermediate product. The authors divide the serial structure into a simple and extended one depending on the possibility of exogenous inputs into sub-processes and on the possibility to produce final outputs in each sub-process (Kao, 2014). In this section, we study the difference between series and parallel structure. In NDEA study, authors often use the combination of both of them, e.g. study Javan, Malkhalifeh (2016), Ma et al. (2017).

The Series system of $h$ sub-processes with the structure of *DMU j* is shown in Figure 1a. $X_{ij}$ and $Y_{rj}$ represent the inputs and outputs of the network system. Stage 1 consumes all the inputs $X_{ij,\ i=1,\ldots,j,}$ supplied from outside to produce the intermediate products $Z_{pj}^{(t)}$ $p=1,\ldots,q$ from process $t$, $t=1,\ldots,h-1$. The intermediate product from process $t$ is output from sub-process $t$ and also an input for sub-process $t+1$. This series structure can be used in static or dynamic models, including time period. The number of intermediate products can be different for each sub-process. Series system of sub-processes in static understanding is described in studies Luo (2003), Kao, Hwang (2008), Liang et al. (2011), Amirteimoori et al. (2016), Despotis et al. (2016a), Izadikhah et al. (2018), Tsolas (2020).

Another basic structure in network systems is parallel (see application for parallel production system in study Kao, Lin, 2012). Figure 1b shows the structure of the general parallel systems, where the sub-processes are operating independently (Halkos, et al., 2014). Kao, Hwang (2010) emphasise that parallel structures are a special case of serial structures without intermediate measures. Each stage consumes the inputs $X_{ij}^{(t)}$, i=1,...,m to produce the outputs $Y_{rj}^{(t)}$, r=1,...,s for *DMU j*. The sum of inputs for all the sub-processes is equal to the input of the whole network system of *DMU*, as: $\sum_{t=1}^{h} X_{ij}^{(t)} = X_{ij}$. The same also applies to outputs, $\sum_{t=1}^{h} Y_{rj}^{(t)} = Y_{rj}$. The series system considers of *h* sub-processes and a parallel structure is composed of *h* sub-processes.

Figure 1

a Series systems, b Parallel systems




*Source: Edited by Kao, 2009.*

### *2.2. Types of NDEA models*

The main types of NDEA models are discussed in the research papers from Färe, Whittaker (1995), Färe, Grosskopf (1996, 1997, 2000), Färe et al. (2007) and presented and applied in the studies mentioned in Table 1. Figure 2 shows the Two-stage processes in static and dynamic understanding and with shared input to sub-processes. The presented study focuses on the static Two-stage NDEA model, but for a full understanding, all types of NDEA models are presented.

Static network model

Cook et al. (2010a) detected that the most commonly used static model is the Two-Stage Network DEA Model (NDEA model). Kao (2014) divides Two-stage static DEA models into

basic and general. The difference between the general model and the basic model consist in the possibility of exogenous inputs $X_i^{(2)}$ to the second sub-process and the possibility of producing the final outputs $Y_r^{(1)}$ in the first stage (Figure 2a). Halkos et al. (2014) refer to the static NDEA model as a model, where the sub-technologies are connected by the intermediate product, and where exogenous inputs can enter to the process in each sub-activity. Also, final output can be produced in each sub-process.

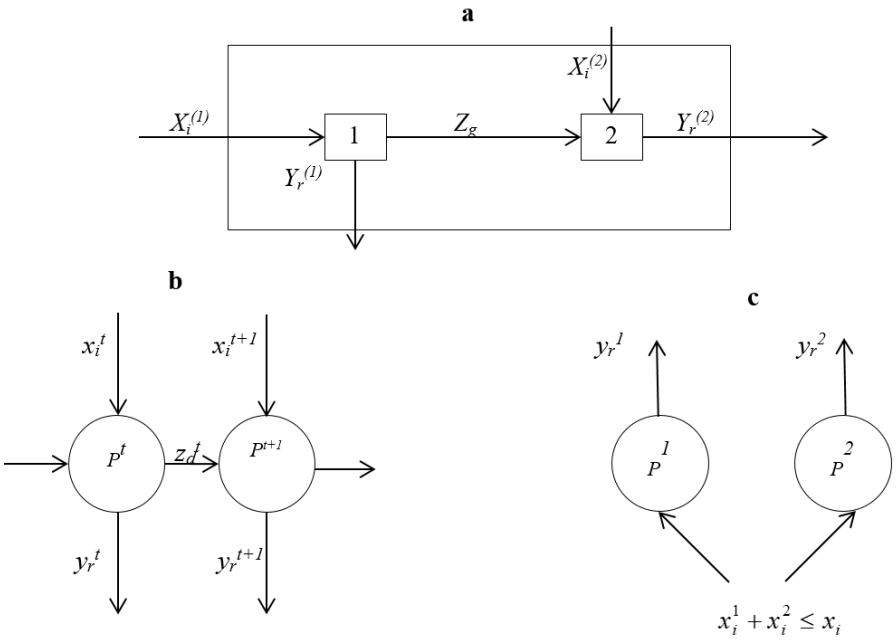
Dynamic network model

A dynamic model has introduced the dynamic aspect of the production process. Intermediate product acts as an output in the first time period and enters to the production process the next period of time. Färe, Grosskopf (2000) considered the same production process in two successive periods with period-specific inputs and outputs. In addition, some of the outputs in the first period are used as inputs in the second. By representing the production processes as nodes or subunits, these time-intermediate products are the intermediate flows of a (dynamic) network (Castelli et al., 2010). Figure 2b shows a model constructed in two-time periods *t* and *t + 1*. Two sub-processes are $P^t$ and $P^{t+1}$. Sub-technology produces as final output and as intermediate at time t, and represents exogenous inputs to the process. Sub-process $P^t$ produces $y_r^t\left(r=1,...,s^t\right)$ as final output and $z_d^t\left(d=1,..,D^t\right)$ as an intermediate product at time *t*. Inputs $x_i^t\left(i=1,...,m^t\right)$ and $x_i^{t+1}\left(i=1,...,m^{t+1}\right)$ are exogenous inputs to the process.

Technology adoption model

Figure 2c illustrates a simple version of the distribution of resources among two sub-processes, where the flow of one production process does not follow the results of the second process (parallel structure). Research studies (see also Chen et al., 2010) also called this model a Shared resources model. Inputs $x_i$ are divided between two sub-processes $P^1$ and $P^2$. Input $x_i^1$ is the input for sub-process $P^1$ and $x_i^2$ is the input for sub-process $P^2$. The sum of individual inputs must not exceed the total inputs, ie. $x_i \geq x_i^1 + x_i^2$. These two sub-processes produce final outputs $y_r^1$ and $y_r^2$.

Figure 2
a Static Two-stage model, b Dynamic model, c Technology adoption model




*Source: Edited by Färe, Grosskopf (2000).*

## 3. Literature Overview of the Literature and Classification of Two-Stage Static DEA Approaches

An important area of development in the non-parametric DEA methodology in the last years has been devoted to applications wherein DMUs represent Two-stage or multi-stage processes (sub-processes). The current paper presents an overview of journal articles dealing with DMUs with Two-stage static sub-processes (Table 1). Empirical studies primarily deal with the creation of an innovative NDEA model and apply it to illustrative numerical examples. Cook et al. (2010a) reviewed the various existing DEA models for measuring efficiency in the mentioned Two-stage network structures or processes. Authors classify these DEA models into four categories: standard DEA approach (e.g. studies Seiford, Zhu, 1999; Sexton, Lewis, 2003); efficiency decomposition approach (e.g. studies Chen, et al., 2009, (2016; Wang, Chin, 2010; Zhu, 2011; Chu, et al., 2015; Despotis, et al., 2016a); network-DEA approach (e.g. studies Färe, Whittaker, 1995; Chen, Zhu, 2004); and game-theoretic approach (e.g. studies Chen, et al., 2006; Liang, et al., 2008; Izadikhah, et al., 2018).

Fukyama, Mirdehghan (2012) presented that the assumption of proportional changes in inputs and outputs were not correct in some cases and it was advisable to use a non-radial measure of efficiency. Tone, Tsutsui (2009) proposed a network slacks-based DEA model

(called NSBM), that could deal with intermediate products formally. NSBM can be input-, output- or non-oriented (see also Tone, Tsutsui, 2010). Using this model of the divisional efficiencies along with the overall efficiency of DMUs can be evaluated. Their study has been the basic framework of NSBM and was extended in many other research papers, like Avkiran, McCrystal (2012), Lozano et al. (2013), Tavassoli et al. (2014), Chiu, Lin (2018), Golshani et al. (2019). Two-stage processes usually have undesirable intermediate outputs, which are normally considered to be unrecoverable final outputs. In the literature overview, we have found papers Yang et al. (2008), Tsolas (2011), Chen et al. (2015), Wang et al. (2014), Wu et al. (2016) and Chen et al. (2018) that discusses the undesirable intermediate outputs in Two-stage structure.

Fuzzy DEA approach for parallel series was proposed in the study by Kao, Lin (2012) and for series structure in the study by Yang, Liu (2012). NDEA models, which allow for any orientation or scale assumption, were described in the study by Sexton, Lewis (2003). Input-oriented Two-stage DEA model was used in the study by Lu et al. (2012), Tsolas (2020) and the un-oriented Two-stage model in the study by Lewis et al. (2013).

In the Two-stage process, authors developed additive models. Research papers by Chen et al. (2009), Cook et al. (2010b) introduce an additive decomposition approach to the Two-stage network studied by Kao, Hwang (2008) and use DMU-specific weights to reflect the „sizes" of the stages within a DMU. This additive approach can be applied under CRS and VRS assumptions. Additive models for Two-stage processes with flexible intermediate measures and shared inputs, which measure the efficiency of not only the overall process, but also the individual sub-processes are extended in studies Lu et al. (2012), Wang et al. (2014), Amirteimoori et al. (2016), Ding et al. (2019), Guo et al. (2020).

The relational approach to measuring the efficiency of Two-stage processes assumes a mathematical relationship between overall efficiency and individual efficiency of sub-processes. The study by Kao (2009) builds a relational NDEA model, taking into account the interrelationship of the processes within the system, to measure the efficiency of the system and those processes at the same time. By introducing dummy processes, the original network system can be transformed into a series system, where each stage in the series is from a parallel structure. This study extended the paper by Kao, Hwang (2008), where the relational NDEA model for the series structure was introduced. Many other authors Liu, Wang (2009), Kao, Hwang (2010), Lozano (2011), Sun et al. (2013) and An et al. (2018) provided more alternative ways for measuring the performance of the Two-stage process using relational NDEA model.

Some research papers by Chen, Zhu (2004) show that using the concept of cooperative game theory, or centralised control, for a Two-stage process can be viewed as the one, where the stages jointly determine a set of optimal weights on the intermediate factors to maximise their efficiency scores. The centralised approach generated efficiency decomposition for the two individual stages. The centralised model was developed in the study by Liang et al. (2008) and extended with shared inputs and outputs (see Li et al. (2016), Ding et al. (2019)), and applied to banks Wanke, Barros (2014), airlines Zhu (2011) and university research services Lee, Worthington (2016).

This paper is a literature overview of static Two-stage NDEA models and proposes a classification and bibliographic collection of the static Two-stage publications shown in Table 1. The analysis comprised of the 76 NDEA research articles published from 1995 to 2021 (a large number of citations on the Web of Science). The second column shows the non-parametric approaches to measuring the network efficiency and classifies the articles by the used NDEA methods. The third column shows the application fields of NDEA methodology including the Banking sector, Insurance companies, High-tech industries, Airlines, Universities and others. The fourth column contains Two-stages (two sub-processes), that make up the whole production process of DMU. N/A means, that the research study was theoretical or the application was an only illustrative example. The last column shows the type of research paper: Theoretical (T), Theoretical and Practical (T/P) and Practical (P). If the paper was only Theoretical (T), it is indicated in parentheses, what was innovative and developing NDEA methodology in the presented paper.

Table 1

Comparative overview of static Two-stage NDEA approach

| Author (s) | Applied techniques | Application field | Two Sub-processes | Type |
|---|---|---|---|---|
| Amirteimoori et al. (2016) | Additive models for Two-stage NDEA | Numerical example | N/A | T (proposed additive NDEA model in series processes with shared resources) |
| An et al. (2016) | Internal resource waste in Two-stage NDEA model | Numerical example | N/A | T (developed Two-stage model considering a degree of centralisation) |
| An et al. (2018) | Relational DEA model for a Two-stage system | Commercial banks | Production/profitability | T/P |
| Avkiran, McCrystal (2012) | NSBM: Sensitivity Analysis of NDEA | Illustrative example: Retail Bank Branch | Division of tellers/Division of bankers | T (first systematic investigation of the sensitivity of NDEA) |
| Chen et al. (2006) | Supply Chain DEA Game model | Numerical example (Enterprises) | Supplier/ Manufacturer | T (developed two efficiency functions for supplier and manufacturer and proposed a bargaining model) |
| Chen et al. (2009) | Additive Two-Stage NDEA (additive efficiency decomposition approach) | Non-life insurance companies | Premium acquisition/ Profit generation | T/P |
| Chen et al. (2010) | DEA frontier for Two-stage processes | Numerical example (Non-life insurance companies) | Premium acquisition/ Profit generation | T (developed approach for determining the frontier projections for Two-stage processes) |
| Chen et al. (2012) | Two-stage NDEA model to evaluate sustainable product design performances „sustainable design efficiency” | Automotive industry | Product design/ Environmental impact | T/P |

| Author (s) | Applied techniques | Application field | Two Sub-processes | Type |
|---|---|---|---|---|
| Chen et al. (2016) | Two- stage DEA model with slacks-based measures | Numerical example | N/A | T (proposed SBM-based approach to extend the work of Tone, Tsutsui (2009) and derive the efficiency decomposition and frontier projection) |
| Chen et al. (2018) | Two-stage NDEA model with undesirable intermediate measure | Environmental evaluation (regional industrial water system) | Economic development/ Environmental protection | T/P |
| Chen et al. (2020) | Shared Inputs Two-Stage Network DEA developed by Castelli et al. (2010) | High-tech industries | Technological development/Technological conversion | T/P |
| Chen, Zhu (2004) | Centralized Two-stage DEA efficiency model | Impact of IT on Enterprises | IT investment/ Firm performance | T/P |
| Chiu, Lin (2018) | Two-stage NSBM model developed by Tone, Tsutsui (2009) | Tourist hotels | Service Production stage/Service Operation stage | P |
| Chu et al. (2015) | Two-stage NDEA approach with equitable efficiency decomposition | Eco-efficiency analysis (provincial-level regions) | Production system/ Pollution control system | T/P |
| Despotis et al. (2016a) | Two-stage series NDEA: composition vs decomposition approach | Illustrative application | N/A | T (developed a novel approach to assess the individual and the overall efficiencies in Two-stage NDEA) |
| Despotis et al. (2016b) | Two-stage NDEA model (Weak-link approach) | Numerical example | N/A | T (developed the weak-link approach in simple and general two-stage processes) |
| Ding et al. (2019) | Additive Two-Stage model with fixed cost allocation | Banking sector | Productivity /Profitability | T/P |
| Färe, Whittaker (1995) | Static and dynamic NDEA approach | Dairy farms | Crops production/Livestock production | T/P |
| Galagedera et al. (2016) | Two-stage NDEA model modelling leakage | Mutual funds families | Operational Management Process/Portfolio Management Process | T/P |
| Golshani et al. (2019) | Two-stage NDEA with intermediate measures | Illustrative application (Chinese universities) | N/A | T (proposed super efficiency of network NSBM model) |
| Gramani (2012) | Two-stage NDEA model (Efficiency Decomposition Approach) | Airlines | Operational performance/ Financial Performance | P |
| Guo et al. (2020) | Two-stage additive network DEA | Illustrated examples | N/A | T (frontier projection and divisional efficiency) |

| Author (s) | Applied techniques | Application field | Two Sub-processes | Type |
|---|---|---|---|---|
| Guo, Zhu (2017) | Two-stage non-cooperative NDEA model | - | - | T (developed non-cooperative model with a shared resource and general non-cooperative model) |
| Hafsal et al. (2020) | Two-stage DEA (developed by Kao, Hwang (2008)) General Two-stage DEA (developed by Kao (2017)) | Banks | Divisional/System efficiency | P |
| Henriques et al. (2020) | Two-stage DEA | Banks | Literature review | T (Controversies and future directions in Two-stage NDEA approach) |
| Izadikhah et al. (2018) | Two-stage series model with freely distributed initial inputs and shared intermediate outputs | Numerical example for banks | Profitability/Marketability | T (proposed Two-stage model built on the concept of Stackelberg leader-follower game model) |
| Javan, Malkhalifeh (2016) | Two-stage NDEA with interval data | Numerical example | N/A | T (proposed DEA models for measuring the efficiency of series and parallel systems with interval data) |
| Jiang et al. (2021) | The uncertain two-stage network DEA models | Numerical example | N/A | T (expands the application of DEA models by establishing the uncertain two-stage NDEA) |
| Kao (2009) | Relational network DEA model | Non-life insurance companies | Premium acquisition/ Profit generation | T/P |
| Kao, Hwang (2008) | Two-stage NDEA relational model considering series relationship of two sub-processes | Non-life insurance companies | Premium acquisition/ Profit generation | T/P |
| Kao, Hwang (2010) | Relational NDEA model | Impact of IT on Enterprises (Banking industry) | IT investment/ Firm performance | T/P |
| Kao, Lin (2012) | Fuzzy NDEA approach for parallel production systems | Departments on University | Teaching/ Research | T/P |
| Kottas et al. (2020) | Variable intermediate measures Slacks-Based Measure (VSBM) Two-Stage network DEA approach (developed by Chen et al. (2016) | Turbofan aero-engines | Specific Fuel Consumption/Take-off specific thrust | P |
| Kwon, Lee (2015) | DEA-neural Two-stage network approach | Banking sector | Production process/ Profit Earning Process | T/P |

| Author (s) | Applied techniques | Application field | Two Sub-processes | Type |
|---|---|---|---|---|
| Lee, Worthington (2016) | Centralised NDEA model base on Liang et al. (2008) | University research services | Research/ Grant Applications | P |
| Lewis et al. (2013) | Un-oriented Two-stage NDEA model using the classical radial objective | Major League Baseball | Front office/ On-field | T/P |
| Lewis, Sexton (2004) | NDEA model for two and multiple stages | Major League Baseball | Front office/ On-field | T/P |
| Li et al. (2016) | Two-stage NDEA model with shared inputs and outputs among the stages | Numerical example | N/A | T ( extended the centralised model to measure the efficiency with shared inputs and outputs) |
| Li et al. (2018) | Non-cooperative Two-stage NDEA approach | Illustrative application | N/A | T (identify the leader stage of a two-stage DEA) |
| Li et al. (2021) | Two-stage fixed-sum DEA approach | Countries performance in the winter Olympic Games | Non-specific | T/P |
| Liang et al. (2008) | Two-stage NDEA centralised model using the game theory concept | Numerical example (three data sets) | N/A | T (developed Non-cooperative and Centralised model for Two-stage processes) |
| Liang et al. (2011) | Two-stage series NDEA model with feedback variables | Universities | Teaching/ Research | T/P |
| Lim, Zhu (2016) | Two-stage NDEA model (frontier projection and duality) | Numerical example | N/A | T (developed formulas to calculate the frontier projections and divisional efficiency) |
| Liu et al. (2015) | Two-stage NDEA model with undesirable inputs, intermediates and outputs | Numerical illustrations (Banking sector) | N/A | T (developed Two-stage model with undesirable input-intermediate-outputs) |
| Liu, Lu (2012) | Two-stage NDEA model (ranking function based on network method) | Numerical illustrations (Research & Development) | Technology development/ Technology Diffusion | T/P |
| Liu, Wang (2009) | Relational two-stage NDEA approach developed by Kao, Hwang (2008) | Manufacturing firms | Production acquisition / Profit earning | P |
| Löthgren, Tambour (1999) | Two-stage NDEA model | Pharmacies | Production / Consumption | T/P |
| Lozano (2011) | Relational NDEA model (Technical and Cost Efficiency NDEA model) | Numerical illustrations (Manufacturing firms) | Production acquisition / Profit earning | T (proposed simple technical and cost efficiency NDEA models, each sub-process can have its |

| Author (s) | Applied techniques | Application field | Two Sub-processes | Type |
|---|---|---|---|---|
| | | | | own Returns to Scale assumption) |
| Lozano et al. (2013) | Two-stage NDEA approach with undesirable outputs | Airlines | Production Process/ Sales Process | T/P |
| Lozano, Khezri (2021) | Proposed smallest improvement NDEA approach | Illustrated example | N/A | T (Proposed improvement NDEA approach for cooperative, non-cooperative scenarios) |
| Lu et al. (2012) | Additive Two-stage NDEA model developed by Chen et al. (2009), Cook et al. (2010b) | Airlines | Production / Marketing | P |
| Luo (2003) | Two-stage series NDEA model | Banking sector | Profitability/ Marketability | P |
| Ma et al. (2017) | Hybrid Two-stage DEA with additional inputs | Illustrative application | N/A | T (Two-stage model with parallel-series hybrid system with additional inputs) |
| Majiwa et al. (2018) | Two-stage NDEA model | Rice processing industry | Drying/Milling | P |
| Mirmozaffari (2019) | Two-stage NDEA model | Eco-efficiency analysis (Cement companies) | Production stage/pollution Control Stage | P |
| Nemati et al. (2020) | Two-stage DEA model (developed by Ma (2015)) | Refinery industries | Production/Sale | T/P |
| Seiford, Zhu (1999) | Two-stage NDEA model | Banking sector | Profitability/ Marketability | P |
| Sexton, Lewis (2003) | Two-stage NDEA model, which allows for any orientation or scale assumption | Major League Baseball | Front office/ On-field | T/P |
| Sun et al. (2013) | Relational Two-stage NDEA model with VRS | Numerical illustrations (Banking sector) | Productivity /Profitability | T (developed Two-stage NDEA model with Variable Returns to Scale by abandon this assumption) |
| Tavana et al. (2016) | Two-stage DEA model in supply chains | Numerical example | N/A | T (proposed Generalized Two-stage model measuring performance in three-level supply chains with VRS and CRS) |
| Tavassoli et al. (2014) | NSBM with shared inputs to measure technical efficiency and service effectiveness | Airlines | Production Process/ Service Process | T/P |
| Tsolas (2011) | Two-stage NDEA model including undesirable outputs | Banking sector | Profitability/ Market Value Generation | P |

| Author (s) | Applied techniques | Application field | Two Sub-processes | Type |
|---|---|---|---|---|
| Tsolas (2020) | Two-stage series DEA method | Mutual fund performance evaluation | Operational management/ Performance management | P (input-oriented BCC model developed by Banker et al. 1984) |
| Wang , Chin (2010) | Two-stage NDEA model, which compared decomposition models and the weighted harmonic one | Numerical illustrations | N/A | T (proposed alternative DEA model for Two-stage process, focused on Weighted harmonic mean model and Generalised Two-stage DEA model) |
| Wang et al. (2014) | Additive Two-stage NDEA model under VRS with undesirable output | Banking sector | Deposit producing/ Profit Earning | P |
| Wang et al. (2016) | Two-stage innovation efficiency model: a non-radial DEA approach | Energy enterprises | Research and development/Marketing | T/P |
| Wang et al. (2020) | Two-stage network DEA approach | High-tech industries | R&D stage/ The commercialisation stage | T/P |
| Wanke, Barros (2014) | Centralised Two-stage NDEA efficiency model | Banking sector | Cost efficiency/ Productive efficiency | P |
| Wu et al. (2016) | Shared flow Two-stage DEA model with undesirable outputs | Industrial production | Production/Waste disposal | T/P |
| Yang (2006) | Two-stage NDEA model | Insurance Industry | Production/ Investment | P |
| Yang et al. (2008) | Two-stage NDEA model including undesirable outputs | Agricultural Sector | Production/ Abatement | T/P |
| Yang et al. (2011) | Supply chain Two-stage CRS DEA model | Banking sector | Production/ Performance | T/P |
| Yin et al. (2020) | Two-stage network approach base on bi-objective model | Hotel performance | Hotel operations/Hotel marketing | T/P |
| Yu et al. (2016) | Fixed cost allocation based on Two-stage NDEA | Numerical example | N/A | T (proposed a novel Two-stage DEA based model for allocating fixed cost to DMUs) |
| Zhu (2011) | Centralised Two-stage NDEA efficiency model (efficiency decomposition for two individual stages) | Airlines | Operational Performance/ Financial Performance | T/P |
| Zhu et al. (2019) | Two-stage NDEA with fixed cost allocation | Numerical example | N/A | T (developed the model, that add and allocate fixed cost as an additional input in each stage) |

*Source: Own resourcing.*

## 4. Conclusions and Future Research Directions

Since the seminal paper of Färe, Whittaker (1995) in Network DEA, there has been a dramatically growth in the number of NDEA articles in the last years. The presented study provides a literature overview of the Two-stage NDEA models, structures and types for measuring the efficiency in DMUs, taking into account their internal structures. A comparative overview of the research papers, the most used methodological approaches, the application field and the sub-processes of Two-stage production process are shown in Table 1. It has been shown that the NDEA model has more discriminate power than the standard DEA model. While the standard DEA model deems most of the DMUs efficient, the NDEA model is able to evaluate the performance with respect to its internal structure (sub-processes).

The authors see the limitation of measuring the efficiency with the NDEA method in the data set, which is needed for this type of non-parametric analysis. We would like to point out to collect the data from DMUs with internal structures.

This study should be an incentive to collect this type of data and extend, and improve the NDEA methodology. In our future research, we will focus on applying the NDEA methodology to agricultural enterprises with sub-processes (complex structures are made from crop and livestock production). We will show how to measure the efficiency and productivity of agricultural enterprises with a complex internal structure on the level of sub-technologies (NDEA methodology), as well as on the level of the whole production system (standard DEA methodology).

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