A Review on the 40 Years of Existence of Data Envelopment Analysis Models: Historic Development and Current Trends

Ankita Panwar · Maryam Olfati · Millie Pant · Vaclav Snasel

Received: 25 January 2022 / Accepted: 10 May 2022 / Published online: 10 June 2022
© The Author(s) under exclusive licence to International Center for Numerical Methods in Engineering (CIMNE) 2022

Abstract

DEA, incepted in 80s, has emerged as a popular decision-making technique, for determining the efficiency of similar units. Due to its simplicity and applicability, DEA has gained the attention of scientists and researchers working in diverse areas, which has contributed towards a rich literature both in terms of theoretical development as well as different applications. This paper tries to bring together the near 40 years of existence of DEA in a concise format by discussing the popular DEA models, their advantages and shortcomings, and different applications of DEA. It also provides a brief bibliometric analysis to highlight the development of DEA over the years in terms of publication trends, highly cited papers, journal citation, etc.

1 Introduction

1.1 Data Envelopment Analysis (DEA)

The success of an organization or unit, whether government or private, depends on its efficiency. Measurement of efficiency of units of similar type, not only help in identifying the shortcomings of the unit, but also it helps in the development of the unit by eradicating or minimizing those shortcomings, thereby developing the country as a whole.

The first and the foremost principle of efficiency is to attain the best outcome through the minimum utilization of resources. Efficiency measurement and efficiency enhancement is a crucial and essential part of every organization for its future development [1]. However, measuring the efficiency, though extremely important, is not an easy task. For simple cases, when units have a single output and single input, efficiency could be measured as the ratio of the two. But, things become challenging when efficiency is to be calculated depending on multiple-input and output. This has attracted the scientists and researchers working in the area of decision-making and operations research since many years.

Fifty years ago, in 1957, Farrel introduced the assessment of productivity efficiency in his classical paper [2]. Around twenty years later, in 1978, Charnes et al. [3] introduced a methodology named Data Envelopment Analysis (DEA) to calculate the relative efficiency of units based on multiple outputs and multiple inputs. He defined efficiency as the ratio of the weighted sum of the outputs to the weighted sum of inputs, and gave the mathematical representation described in detail are below. Some notable advantages of DEA are [4]:

- It may maintain multiple outputs and multiple input variables, which may have different units.
- It is able of engaging with qualitative as well as quantitative data.
- It acts an effective decision-making tool in directing the attention of management to the area that can be improved.

* Millie Pant
  pant.milli@as.iitr.ac.in
  Ankita Panwar
  anpanwar@as.iitr.ac.in
  Maryam Olfati
  maryam.olfati@vsb.cz
  Vaclav Snasel
  vaclav.snasel@vsb.cz

1 Department of Applied Mathematics and Scientific Computing, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India
2 Electrical Engineering and Computer Science, Department of Computer Science, Technical University of Ostrava, Ostrava, Czech Republic
3 Mehta Family School for Data Science and Artificial Intelligence, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India
Literature reveals that from 1978 to 1995, there has been a constant growth in the publications of DEA, but 1995 onwards there has been an exponential rise in the publications of DEA, both in terms of theoretical development and in terms of diverse applications such as banking [5], transportation [6], health sector [7], tourism [9], finance [10], sports [11], and many more. This trend is clearly reflected in Fig. 1.

1.2 Basic DEA Model

We now come to the basic DEA model, which laid the foundation for several modified DEA variants. The idea was conceptualized by Charnes et al., in their highly cited paper published in 1978 [3]. DEA is a two-step process wherein the initial step the problem is formulated in the fractional form, which is simplified to the linear form in the second step [12].

Efficiency, by definition, is the ratio of the output upon the input as given in Eq. (1).

\[
\text{Efficiency} = \frac{\text{Outputs}}{\text{Inputs}}
\]  

However, things become tricky in case of multiple input and multiple output, which is usually the case with real-life scenarios.

This is where, the notion of DEA comes to the rescue, according to which efficiency can be calculated as the weighted sum of output to the weighted sum of input, mathematically represented as Eq. (2).

\[
\text{Efficiency} = \frac{\text{Weighted sum of the Output}}{\text{Weighted sum of the Inputs}}
\]

To explain (2) in a better manner, let us assume that there are \( y_t \) and \( x_s \) output and input criteria respectively, where the output \( y_t \) is to be maximized, and input \( x_s \) is to be minimized. Here, we have considered M DMUs. Now, if we have to maximize the efficiency of the \( z \)th DMU, then its mathematical representation can be the following equations:

\[
\begin{align*}
\text{Maximize:} & \quad E_z = \sum_{t=1}^{T} c_{tz} y_{tz} \\
\text{Subject to:} & \quad \sum_{t=1}^{T} c_{tz} y_{tz} - \sum_{s=1}^{S} d_{sz} x_{sz} \leq 0 \\
& \quad \sum_{s=1}^{S} d_{sz} x_{sz} = 1 \\
& \quad c_{tz}, d_{sz} \geq 0, t = 1, 2, \ldots, T, \quad s = 1, 2, \ldots, S
\end{align*}
\]  

Fig. 1 DEA publications since 1980

If the efficiency score of a DMU is one, then it is known to be a relative efficient DMU otherwise it is said as a relative inefficient DMU [13]. Once the problem has been formulated considering the input and the output criteria, it is simplified into a linear programming (LP) model as followed.

\[
\begin{align*}
\text{Maximize:} & \quad E_z = \sum_{t=1}^{T} c_{tz} y_{tz} \\
\text{Subject to:} & \quad \sum_{t=1}^{T} c_{tz} y_{tz} - \sum_{s=1}^{S} d_{sz} x_{sz} \leq 0 \\
& \quad \sum_{s=1}^{S} d_{sz} x_{sz} = 1 \\
& \quad c_{tz}, d_{sz} \geq 0, t = 1, 2, \ldots, T, \quad s = 1, 2, \ldots, S
\end{align*}
\]  

where, \( E_z \) is the efficiency of the \( z \)th DMU, \( y_{tz} \) shows the \( t \)th output of the \( z \)th DMU, \( c_{tz} \) denotes the weight of the \( t \)th output, \( x_{sz} \) is the \( s \)th input of the \( z \)th DMU, and \( d_{sz} \) shows the weight of the \( s \)th input.

1.3 Significance of the Present Study

Many authors surveyed DEA literature in the past era on different aspects. Cooper et al. [14] in their review, discussed the theory of DEA models. Adler et al. [15] provided a review of different ranking methods of DEA. Kuah et al. [16] focused on the methodological development of DEA. Liu et al. [17] reviewed the citation-based survey from 1978-2010. An application of DEA-based literature was reviewed by Liu et al. [17]. Seiford [18] and Emrouznejad et al. [19] provided a bibliometric survey of taking into account 30 years of its development. Mardani et al. [20] and Xu et al. [21] provided a review on the energy efficiency evaluation based on DEA. The study aims to find a set of papers that cover the development in the DEA area in the last 40 years. The study adopts to review various DEA models, major
application areas of DEA, details of the software, and bibliometric analysis. The present study is based on the following research questions (RQ):

- **RQ1**: What are the different variants of DEA that have emerged during the 40 years of its existence?
- **RQ2**: What are the advantages and disadvantages of different DEA models?
- **RQ3**: What are the different application areas where DEA has been applied?
- **RQ4**: What are major trends of DEA in terms of publications?

The paper is categorized into nine sections, including Sect. 1, a deep explanation of introduction of DEA. Section 2, examines the collecting of the information. Section 3 reviews selected DEA models, and Sect. 4 discusses the advantages and disadvantages of DEA models. Section 5 reviews the applications of the DEA and its variants. Section 6 discusses the software and conferences related to the DEA. A bibliometric analysis is propounded in Sect. 7, and conclusion and future measures are described in Sect. 8, and Sect. 9.

### 2 Collecting the Information

The purpose of this study is to abreast the reader with the historical and recent developments of DEA for which a large number of papers were surveyed through the standard ISI Web of Science (WOS) database.

According to the citation database, WOS is the world’s leading disciplinary coverage of high-impact journals in sciences, social sciences, as well as international progress. The selection of the publications is based on SCIE and SSCI index. Conference proceedings citation index-Science (CPCI-S), Art and humanities citation index (A&HCI), Conference proceeding citation index -social science & humanities (CPCI-SSH). More details are mentioned in Table 1. We have tried to bring together the different models of DEA, discussed in detail in Sect. 3.

The search for research articles to be comprised of this paper is based on Journal Citation Report (JCR), and their impact factor (shown in Fig 12).

**Choice of Keywords:** We started the search by considering the following keywords:

‘Data Envelopment Analysis’, ‘Additive DEA approach’, ‘Slacks-Based DEA technique’, ‘Russel Measure DEA approach’, ‘Cross efficiency approach’, ‘Super efficiency DEA technique’, ‘Network DEA Models’, ‘Hierarchical DEA Models’, ‘Supply Chain DEA procedures’, ‘Stochastic DEA models’, ‘Fuzzy DEA model’, ‘Banking and DEA’, ‘Sports and DEA’, ‘Agriculture & farm and DEA’, ‘Transportation and DEA’, ‘Education and DEA’, ‘Communication and DEA’, ‘Fishery and DEA’, ‘Tourism and DEA’, ‘Health care and DEA’, ‘Automobile and DEA’, ‘Forestry and DEA’, ‘Water and DEA’, ‘Real estate and DEA’, ‘E-business and DEA’.

The number of articles that appeared using the above keywords are listed in Table 1 for the time window 1981 – 2021. Searching the database on the basis of applications of DEA, the data obtained is illustrated in Fig. 2. In the subsequent sections we will discuss modified DEA models, their applications and so on Fig. 3.

### 3 DEA Models

Nothing in the world is flawless, not even DEA, and though it gave an initial concept of efficiency measurement for units having multiple input and output, researchers realized that despite being an advantageous technique, there are certain drawbacks, listed below, associated with DEA.

- It is a non-parametric approach, so statistical hypothesis testing is difficult.
- Lack of discriminating power between the DMUs.
- It cannot predict the performance of other DMUs.

Since the initial conceptualization of DEA, several models have been proposed to improve its performance. DEA models can also be segregated as per different terminologies one of which can be Radial and non-radial [4]. While radial models directly assume proportion change of output/input variable, and generally, resting slacks are indirectly accounted for inefficiency, the non-radial models deal with slacks of all output/input variable separately and combine them into an efficiency measure. In the present study we have segregated the models on the basis of their development as follows:

1. Classical DEA methods
2. Extended DEA methods
3. Multistage and multi-level DEA models
4. Stochastic and Fuzzy DEA techniques.
5. Hybrid DEA models
6. AI/ML assisted DEA models

3.1 Classical Models of DEA

The three models, viz. CCR, BCC and SE are placed under the classical model’s category. These models helped in designing DEA in the initial stage and also laid the foundation for other variants of DEA. In the following sub sections, we will describe the models one by one.

3.1.1 CCR (CRS) Model

CCR is the first DEA approach, and investigated by Charnes et al. in 1978 [3]; it is named as CCR model after the first letter of their names. The mathematical structure is the CCR model is shown in Eq. 4. Since the DMUs are \( M \), the approach is run \( M \) times to recognize the relative efficiency value of all DMUs. Each DMU choose a collection of output weights \( (c_i) \) and input weights \( (d_i) \) which maximize the efficiency value. This model presumes constant returns to scale (CRS) supposition. The efficiency is also denominated as the overall technical efficiency (OTE) score.

3.1.2 BCC Model

It was observed that the CCR approach is focused on the proper DMU when it can consider all DMUs on an optimal scale. Some application areas like incomplete completion and restrictions on finance etc., may give rise to DMUs to operate away from the optimal scale. The extension technique of CCR technique was given via Banker, Charnes and Cooper in 1984 [13] and is also known as the VRS method. The efficient frontier of VRS is constituted by the convex hull of the DMUs which are available [16]. The efficiency

Fig. 2 Science index of the DEA

![Fig. 2 Science index of the DEA](image)

Fig. 3 Steps of the workflow for reviewing the literature of DEA

![Fig. 3 Steps of the workflow for reviewing the literature of DEA](image)
measures obtained from the BCC technique, denominated pure technical efficiency (PTE) value. Mathematical form of the model is given below:

\[
\max E_z = \sum_{s=1}^{r} c_s y_s + w_q,
\]

\[
\text{s.t.}
\sum_{t=1}^{s} d_{st} x_t = 1
\]

\[
\sum_{j=1}^{r} c_j y_j - \sum_{j=1}^{r} d_{jst} x_j + w_q \leq 0, \quad y = 1, 2, \ldots, Y
\]

\[
c_{st}, d_{st} \geq 0, \quad s = 1, 2, \ldots, S, \quad t = 1, 2, \ldots, T
\]

\[w_q\] is unrestricted in sign

Main variation between the CCR and BCC techniques is convexity constraint. In the BCC technique, the sum of the \(\sum w_q = 1\). If the value is \(\sum w_q \leq 1\), instead of the \(\sum w_q = 1\) then the technique is Non-Increasing Returns to scale (NIRS) form. If the value is \(\sum w_q \geq 1\), instead the \(\sum w_q = 1\) thus, the approach is called Non-Decreasing Returns to scale (NDRS). CCR efficiency score is always less and equal to the BCC efficiency score.

Here, it is seen that the form of the BCC is different from the CCR model. This model has an extra convexity constraint, \(\sum w_q = 1\). The difference between both models is explained by Fig. 4.

Here, it can be observed the straight-line “opqr”, which shows the CRS surface and the line “lsqwz” which shows the VRS. Under the CCR model, DMU \(q\) is efficient, and the remaining are inefficient DMUs. Under the VRS model, the efficient DMUs are \(s, q, w,\) and \(z\). These efficient units are called BCC-efficient. The line segments \(s\) and \(q\) is IRS, and point \(q\) shows the CRS while the other point on right side of the \(q\) is experiencing decreasing returns to scale (DRS).

### 3.1.3 Scale Efficiency (SE) Model

The ratio of the CCR score into the BCC score shows the value of the scale efficiency [22]. It measures the influence on scale value on the efficiency of a DMU.

\[
\text{Scale efficiency} = \frac{E_{CCR}}{E_{BCC}}
\]

(6)

where, \(E_{CCR} = \text{CCR score of the DMU, and } E_{BCC} = \text{BCC score of the DMU}\)

### 3.2 Extended Versions of DEA Model

The traditional DEA approaches determine the relative efficiency of the DMUs, but they are not able to attain ranking for the efficient units. Lack of discriminating power is the major drawback of the model. If the number of input and output variables are greater than the number of decision units, it may reduce the discriminating tendency of the technique.

To deal with this drawback, researchers extended the basic model and proposed modifications in DEA to enhance its discriminatory power. Some extended models of the DEA are discussed in this section.

#### 3.2.1 Additive DEA Model

The additive DEA model is non-radial and it proceeds the inefficient DMU to the efficient frontier by reducing the input and increasing output simultaneously. Also, This technique is called the Pareto Koopmans model and was presented by Charnes, Cooper, Golany, Seiford and Stutz in 1985 [23]. BCC and CCR models can be explained in the form of the additive model. The mathematical form is shown in Eq. (7).

\[
E_0 = \max \sum_{i} s_i^+ + \sum_{i} s_i^-
\]

\[
\text{s.t.}
\sum_{u} \delta_u x_{iu} - x_{iu} + s_i^- = 0
\]

\[
\sum_{u} \delta_u y_i - y_i - s_i^+ = 0
\]

\[
\sum_{u} \delta_u = 1
\]

\[
s_i^-, s_i^+ \geq 0
\]

\(s_i^-\) and \(s_i^+\) are show slacks, when \(s_i^-\) is input excesses and \(s_i^+\) is output shortfalls.

If the values of all slacks are zero, then DMU is called additive efficient at its optimum solution.

#### 3.2.2 Slacks-Based Model (SBM)

SBM technique is used to surmount the drawback of the additive approach. This technique is a variation of the
additive model and was recommended by Tone [24]. Efficiency measurement of the SBM model is shown in Eq. (8).

$$\min E = \frac{1 - \frac{1}{a} \sum x_i / x_o}{1 + \frac{1}{b} \sum y_i / y_o}$$

s.t.

$$\sum \delta a x_{ia} - x_{ea} + s^- = 0$$
$$\sum \delta y_i - y_{0i} - s^+ = 0$$
$$\sum \delta a = 1$$
$$\delta a, s^- , s^+ \geq 0$$

This fractional form can be transformed into the linear form, as shown in [25]. When all slacks are equal to 0, then the optimum solution of the SBM model is 1. SBM model is an example of the non-radial model.

### 3.2.3 Russel Measure Model (RM)

One of the other important DEA models is RM, introduced by Fare and Lovell [25] in 1978. Computationally, RM model is very complicated because it was formulated as a non-linear programming model (NLP) [26].

They revisited the RM model in 1999, called the Enhanced Russell Graph Measure model (EGRM). EGRM is an improved model of the RM model [26], and is calculated as the ratio among the average efficiency of the inputs to the average efficiency of outputs. EGRM is best model because it is capable of overcoming the computational complexity in the RM model. Pastor et al. published the development of RM. Without depending on EGRM, the second-order cone programming (SOCP) model is used directly to solve RM. The exact RM score can provide through the SOCP model.

### 3.2.4 Free Disposal Hull Model (FDH)

FDH [27] is an easy-to-use model and could be generated from the VRS or CRS model, with the extra restriction $\delta u \in \{0, 1\}$. In 1999, Thrall [28] challenge this idea, from the economic theory perspective which can be rebutted strongly by Cherchye et al. [29] and FDH remains a noteworthy technique for measuring efficiency. Figure 5 shows the “hull” of the boundary of sets and its connection concept of the FDH model [16].

### 3.2.5 Cross Efficiency DEA Model

This model was introduced by Sexton, Silkman, and Hogan in 1986 [30]. It evaluates the weights of outputs and inputs of each DMU with the help of the DEA. In the next step, weights of each DMU, using $m$ sets of weights, and getting $m$ efficiency value of each DMU. Finally, the cross-efficiency value of a DMU is the intermediate score of its efficiency score. According to cross efficiency value to give the rank of DMU. More discussion of the cross-efficiency model is mentioned in [31]. Some improved models along with applications are discussed in the references [32, 33].

### 3.2.6 Super Efficiency Model (SE-DEA)

The SE-DEA model was introduced by Andersen and Petersen [34]. This model performs very well, however, the DMU is omitted from the peer set under the evaluation. The super-efficiency model has been extensively used in various application areas, as an example, measuring the efficiency regions [35], ranking of the efficient DMUs [34], and detecting the extreme efficient DMUs [36]. The mathematical form of the super efficiency model defined under DEA-CCR is expressed as [37]:

$$\max E \sum_{t=1}^{T} c_{iz} y_{iz}$$

s.t.

$$\sum_{s=1}^{S} d_{xz} x_{iz} = 1$$
$$\sum_{t=1, z \neq a}^{T} c_{iz} y_{it} - \sum_{s=1}^{S} d_{z} x_{si} \leq 0, \forall i$$
$$c_{iz}, d_{zi} \geq 0; s = 1, 2, \ldots, S, t = 1, 2, \ldots, T$$

$y_{iz}$ and $x_{si}$ are the $t$th output and $s$th input respectively of the $i$th DMU, where $i = 1, 2, \ldots, I$, and $s = 1, 2, \ldots, S, t = 1, 2, \ldots, T$.

Linear programming technique is used to solve each decision-making units above mathematical formulation [38]. The difference between the classical DEA (DEA-CCR) and the super-efficiency technique is exclusion of unit $z$ as the constraint set in Eq. 10. When included unit $z$ in Eq. 10, the maximum score of efficiency score is 1. Outputs are maximized when no longer in the second constraint $(i)$ under the evaluation unit.
3.3 Multistage and Multilevel Models

Till now, the discussion was on the single-level DEA models. The concept of single level models extended further to multistage and multilevel DEA models. These models could be distinguished into three cliques: Network DEA approaches, Hierarchical DEA approaches and Supply Chain DEA models. These are explained briefly below:

3.3.1 Network DEA Models

Network model implements DEA for estimating the relative efficiency of the DMUs, taking its internal structure, which is not considered by the classical DEA models. Grosskopf and Fare [39] and Flare and Whittaker [40] proposed similar network models. Those models define the peer group for the DMU, as is the common practice in DEA that set of all convex linear compositions of DMUs. Some researchers also called the “black box” of DEA because in this model DMU is a black box. Fare et al. introduced the three general network DEA model as (i) static network model (ii) dynamic network model and (iii) technology adoption network model.

Lewis and Sexton [41] used the DEA technique in their paper to show the advantage of the network DEA model over the classical DEA technique. They took the Major League Baseball example. Network DEA Model could figure out inefficiencies that the efficient DEA Model displaces. Some examples of the network DEA model are: slack based DEA model [42], measuring the customer satisfaction and productivity of pharmacies [43]. The number of studies is increasing on the network DEA; thus, this is the future direction.

3.3.2 Hierarchical DEA Models

Few conditions of multistage efficiency assessment might include hierarchy structure. The concept of the model was established to determine the DMUs that fall naturally into a hierarchy. In this technique, measurement through pairwise comparisons by organizing the homogenous clusters of factors. Determining priority scales depend on the judgment of the experts. One of the applications of the hierarchical model is to find the power plant efficiency with several operating units [44].

The researchers determined the relative efficiency of each power unit and power plant, and hierarchical structure was observed as a multistage procedure. Green and Cook [45] modified the model, such that modified hierarchical efficiency assessment could be viewed at all levels concurrently.

3.3.3 Supply Chain DEA Model

One of the great competitive strategies is the supply chain, which modern enterprises can use because this strategy can influence the production of a variety of products at low expenses, high quality, and short lead times. Newly, DEA has been developed to specify the performance of supply chain operations and the recently proposed ‘supply chain model,’ is applied in the multistage DEA model. Optimization criteria in supply chains models have mentioned cost, inventory levels, profit, fill rates, stock out probability, product demand variance and system capacity. Present DEA-based supply chain models describe and calculate the efficiency of the supply chain. Authors showed that the DEA-based supply chain technique measures the efficiency of its member [46]. Another example is Wong and Wong [47] who studied efficiency of supply chain with the help of the DEA model.

3.4 Stochastic and Fuzzy DEA Model

One of the weaknesses of traditional DEA models is the fixed nature of input and output variables ignoring the stochastic fluctuations in output-input data, such as data entry and computational mistakes [36]. There are two DEA models viz. Stochastic DEA models and Fuzzy DEA models that can deal with the uncertainties associated with the data. These models are described below: If the final solutions are not accepted, then it gathers new data and proceeds next iterations of multi-criteria models. There are two DEA methods, viz. Stochastic DEA approaches and Fuzzy DEA methods that can deal with the uncertainties associated with the data. These models are described below:

3.4.1 Stochastic DEA Model

Stochastic DEA model uses non-parametric convex hull reference techniques depend upon axioms via a statistical infrastructure in basis of axioms from statistics assumption that allow for an estimation reference technology [48]. Some researchers have included stochastic output and input variables into the DEA methodology.

Stochastic models allow the only inefficiency, but also statistical noise. They identify most quantile rule on assumptions of the composed error terms. These models allow for the probability of two-sided random disturbance, such as determine and specification error in output and input data.

These techniques attain the existence of data error in data and give probabilistic-based outcomes. Some applications are as follows: technical efficiency evaluated through the stochastic DEA, and other is Chance-Constrained Programming (CCP) approach [49]. Khodabakhshi and Asgharian [50] used the stochastic DEA model on input relaxation to measures of efficiency. CCP approaches used by Cooper et al. [49] used stochastic DEA to handle congestion issues.
3.4.2 Fuzzy DEA Models

To deal with the impreciseness of data in real life scenarios, concepts of fuzzy mathematical programming is integrated with DEA to provide a more realistic solution. For example, in [51] the authors incorporated fuzzy mathematical programming into the DEA model, and showed the performance of the DMU as a fuzzy efficiency.

Actually, DEA efficiency scores vary in \((0, 1]\) and DEA methodologies assess the performance of different DMUs. Qin and Liu [52] used fuzzy inputs and outputs in the DEA methodology. Azadeh et al. [53] used integrated approaches like; computer simulation, fuzzy C-means, and fuzzy DEA to optimize operator allocation.

Fuzzy DEA models introduced by Peijun [54] extended the CCR technique to more general forms where crisp, fuzzy and hybrid data could be applied comfortably. Due to uncertainty existing in human contemplation and judgement, fuzzy DEA techniques could play a significant role in conceptual assessment problems comprehensively existing in the real-life.

3.5 Hybrid DEA Models

In this paper, we are referring to hybrid DEA models as the ones in which DEA is integrated with other techniques like soft-computing, machine learning, dimensionality reduction methods and other MCDM techniques.

3.5.1 DEA + Soft-Computing Techniques

Soft-Computing (SC), a vital area of study in computer science since the early 90s, originally referred to the umbrella term for Fuzzy Logic, Genetic Algorithms and Artificial Neural networks. However, with the passage of time, other nature inspired algorithms like Particle Swarm Optimization (PSO), Differential Evolution (DE) etc. are also considered to be a part of SC methods. For the more details of the SC techniques, the interested readers may refer to [55–57].

Here we are not discussing fuzzy logic embedded DEA because a portion of it has been discussed in component B of Section 3.4. In this article, the following papers have been reviewed covering the years between 2016 to 2021. Mogha and Yadav [58] proposed a simple DE (SDE) to solve the DEA-based models. Pelesaraei et al. [59] hybridized DEA with Multi-objective Genetic Algorithm (MOGA) to approximate the energy efficiency and GHG emissions of wheat production. Misiunas et al. [60] recommended DEANN, a hybrid of DEA and ANN called DEANN and applied it to predict the functional status of the patients. This technique expressed that DEA will assess efficiencies on an expanded set of DMUs by preparing data for the ANN (training set), a supernumerary ANN interpolated DMU for each of the principal DMU, and it uses it to figure the efficiency frontier by comprising all DMUs.

Jauhar et al. [61] combined DEA with Differential Evolution (DE) and multi-objective differential evolution (MODE) and showed that the integration enhances the discriminatory powers of DEA.

Pendharkar [62] introduced a hybrid GA and DEA framework to solve the constant cost allocation (FCA) problem. This framework allowed to compound various FCA sub-objectives for efficient and inefficient DMUs and solved the FCA problem, and the entire entropy of resource designation is maximized for efficient DMUs. Jauhar et al. [8] applied DE integrated DEA for calculating the performance of a remarkable educational supply chain.

Shabanpour et al. [63] proposed a hybrid of dynamic DEA and ANN, to forecast the future efficiency of the DMUs. Modhej et al. [64] integrated inverse DEA with neural network for preserving the relative efficiency value. Vlontzos and Pardalos [65] consider a combination of DEA with ANN to measure and prognosticate green house gas emissions of EU countries. Mozaffari et al. [66] presented a hybrid GA and ratio-DEA (R-DEA) technique to determine the efficiency of the sustainable supply chain.

Tsolas et al. [67] used a two-phase hybrid DEA and ANN technique (DEA-ANN), which is used as a preprocessor, to use the large size branch data of Greek commercial banks. Pendharkar [68] expressed that an ANN trained by sustainable power on the “efficient” training data subset is powerful than the predictive performance of an ANN trained on the “inefficient” training data subset. Bose et al. [69] have smoothened the efficiency frontier of DEA via training an artificial neural network from input/output prediction multiple of DMUs. Out of the various soft computing techniques, ANN is the one that is integrated the most with DEA.

3.5.2 DEA + Machine Learning Techniques

Potential of ML techniques have been leveraged by several researchers in diverse areas and the domain of DEA is no exception. In this section, we go through selected papers where the researchers have implemented the concepts of ML to enhance the performance of DEA.

Dariush et al. [70] proposed a new framework to reduce calculation time of efficiency when the number of DMU’s are more. Zhu et al. [71] recommended the algorithm to precipitate the computational procedure in the big data environment. The authors proposed DEA as a tool for data-oriented analysis to execute evaluation and benchmark testing. Although the calculation of algorithms has been introduced under the basis of traditional DEA to produce large scale of data (decisions making, units, input, and outputs), the precious knowledge is displayed by the network structure that should be hidden in big data and extracted by DEA [71].
The selected papers are from the years 2020 and 2021 only. More information of the Machine learning techniques can be found in [72, 73].

Tayal et al. [74] measured the efficiency analysis for the stochastic dynamic facility layout problems by metaheuristics, DEA, and machine learning techniques. They proposed three-stage techniques, where DEA was amplified with supervised and unsupervised ML technique to obtain the unique ranks and predicting the efficiency values of the layouts. Qu et al. [75] investigated the redevelopment of the urban centre blocks, and introduced a DEA, deep learning model. They introduced the DEA, and utilized a deep learning model to predict output-oriented indicators of non-intensive blocks.

Mirmozaffari et al. [76] integrated DEA with clustering algorithms to improve the accuracy of results. Aydin and Yurdakul [77] analyzed the performance of the 142 countries against the COVID-19 through a new three-staged framework by combining DEAP approach with four ML algorithms viz. k-means, hierarchic clustering, decision tree, and random forest algorithms. Rebai et al. [78] predicted the performance of the secondary schools in Tunisia by the machine learning techniques. They used a two-level analysis part.

In the first stage, the directional distance function (DDF), estimated through the DEA, was used to deal with the desirable outputs while in the second stage, decision tree, and random forest algorithms were used to identify and visualize the variables of high-school performance. Salehi et al. [79] analyzed and improved the level of adaptive capacity of a the petrochemical plant. They used the DEA method for computing and analyzing the resilience engineering indicators, redundancy, and teamwork. They implemented multilayer perceptron (MLP) to estimate the level of adaptive capacity on the basis of the data.

Nandy and Singh [80] examined farm efficiency by machine learning and DEA techniques to predict the impact of the environmental factor on the farms’ performance. Jomthanachai et al. [81] introduced a cross-efficiency DEA model to find a set of risk factors obtained from failure mode and effect analysis (FMEA) and used ML techniques to predict the degree of remaining risk depending on simulated data corresponding to the risk treatment scenario. Thaker et al. [82] integrated random forest regression with DEA under a two-phase model and measured the corporate governance and bank efficiency.

Zhu et al. [83] combined the machine learning and DEA technique and used BPNN-DEA, GANN-DEA, ISVM-DEA, SVM-DEA techniques. They measured and predicted the efficiency of manufacturing companies of China. Jomthanachai et al. [84] used the DEA models with ML techniques to examine risk management. They used cross-efficiency DEA with ANN and predicted the level of risk. Zhong et al. [85] used an integrated DEA with machine learning technique, Super SBM-DEA-BPNN.

The aim of the authors is to improve the fusion efficiency. Taherinezhad and Alinezhad [86] used integrating DEAML techniques to predict the efficiency score of nations in the COVID-19 data. They used GANN, BPNN, SVM, and ISVM techniques and predicted the regression target (efficiency values). Nandy and Singh [80] determined the farm efficiency by the hybrid machine learning and data envelopment analysis. They used a two-stage DEA model with random forest and logistic regression techniques.

### 3.5.3 DEA + MCDM Techniques

Despite availability of various Multi criteria decision-making techniques [87], the application of DEA as a discrete alternative MCDM method is also an accepted way to attain reasonable decisions. The foundation of the MCDM techniques was laid in the 1950s and 1960s [88].

For more brief on MCDM techniques, the interested reader may refer to [89, 90]. This section brings forward a succinct review of the recent work on the integration of the DEA with MCDM techniques. The selected papers are taken from the years 2020 and 2021 only.

Kaewfak et al. [91] fuzzy-AHP (FAHP) and DEA model to identify and measure quantitative risk. Bajec et al. [92] developed a distance-based AHP-DEA super efficiency technique to attain the demands of premeditated groups by applying the slack variables.

The purpose of the distance-based AHP model was to attain a hierarchy structure and weights for the criteria.

The aim of the DEA approach was the efficiency evaluation of the 21 fictional providers of the electric bike-sharing system. Reza Hoseini et al. [93] used a Z-AHP and Z-DEA, and a Z-AHP-DEA model in their study. The Z-AHP model aimed to identify the conventional sustainability criteria and calculate importance weights. Z- DEA and Z-AHP-DEA models were introduced to measure project efficiency and concluded that Z-AHP-DEA model gave the more effective solution.

Banihashemi and Khalilzadeh [94] used the network DEA model to choose the best mode to mitigate the environmental impacts. Rank measurement of the different execution modes of each activity waas done through the TOPSIS. Wang et al. [95] presented a hybrid approach, DEA window analysis, and FTOPSIS and determined the abilities of 42 countries in terms of renewable energy capacity. Karasakal et al. [96] proposed two novels PROMETHEE based ranking approach to determine the weights and threshold values obtained by the DEA method.

Hoseini et al. [97] measured the performance of the research and development (R&D) organizations by hybridizing DEA and ANP. Lee et al. [98] utilized various DEA
models and VIKOR to determine the 12 manufacturing industries in Taiwan. They compared different models of the DEA (CCR, super efficiency, cross efficiency, Doyal-Green efficiency) with MCDM approach VIKOR technique. Karami et al. [99] proposed a three-step integrated procedure, DEA-PCA-VIKOR to evaluate garment industry. PCA reduced the criteria, and the additive DEA model measured the efficiency of the suppliers or efficient suppliers.

Finally, VIKOR was activated to determine the ranking of the efficient suppliers. Mei and Chen [100] used the rough-fuzzy best-worst method and rough-fuzzy DEA to determine and select sustainable hydrogen production technologies. Here, the rough-fuzzy BWM was procedure is introduced for measuring the relative weights of the sustainability criteria, and rough-fuzzy DEA was introduced to prioritize the alternative HPTs. Tanasulis et al. [87] introduced a comprehensive technique of higher education teaching evaluation connecting AHP and DEA (fuzzy AHP is included).

AHP permits the regard of the different values of each teaching performance criteria, although DEA can create a comparison to the teaching perceived by the tutor and the student to understand the range of development for each tutor. Lee et al. [101] developed the integrated two-phase MCDM technique to recognize the relative weights of criteria and examine energy technologies’ relative efficiency against high oil prices. In the first phase, the fuzzy–AHP allocates the relative weights to criteria. In the second phase, the DEA technique determined the relative efficiency of energy technologies versus high oil prices from an economic standpoint.

### 3.5.4 Miscellaneous

In this section we have incorporated that the techniques that could not fit under the previous sections but play an important role in improving the performances of DEA. Here we have considered only the papers 2018 onwards. Zelemyuk [102] explored price-based aggregation to solve the large dimension. Lee and Cai [103] recommended the Least Absolute Shrinkage and Selection Operator (LASSO) variable selection technique, in data science to extract significant factors. They combined the LASSO and sign-constrained convex non-parametric the least squares (SCNLS), which could be represented as DEA estimators.

The proposed LASSO-SCNLS methods and their variants gave beneficial guidelines for DEA with small datasets. Chen et al. [104] used the latest version of LASSO, known as elastic net (EN), adapted it to DEA, and proposed the EN-DEA and used it for reducing the large dimensions into sparser. Limleamthong and Gosalbez [105] used the mixed-integer programming (MIP) technique for dimensionality reduction of the input and output variables. Main purpose of the authors has to elevate the prejudiced ability of classical DEA technique. Davoudabadi et al. [106] and Deng et al. [107] also used PCA technique to decrease the dimensions of the data.

Smirlis et al. [108], Azizi [109] solved the missing value problem in the crisp dataset by an interval DEA approach. Kuosmanen [110] used an alternative method, constructing the best-practice frontier technique to take missing values. Tao et al. [111] approach contributes to relaxing convexity assumption on production possibility set (PPS) in benchmarking using DEA and provides a powerful managerial instrument to improve the performance. Ren et al. [112] used DEA to identify the congestion in projects of universities.

### 4 Advantages and Disadvantages of the Models

Up till now we have seen that there exists a fair number of DEA models. Each model has advantages as well as disadvantages. These are summarized in Tables 2 and 3 [16, 113–116], so that the user can identify the most appropriate model to be used for a particular problem.

### 5 Applications of the DEA and Its Variants

This section is segregated into two parts. In the first part we provide the implementation of different DEA models on different application problems, while in the second section we provide an overview of the different real life problems that have been solved through DEA or its variants.

DEA models described above have been implemented for solving a wide range of real life problems described in Tables 4 and Table 5. While Table 4 lists the application of traditional DEA models, Table 5 provides the application of hybrid DEA models. It was observed that out of the papers reviewed for this study, Hierarchical DEA models and Stochastic DEA models have been used more for real life problem-solving in comparison to other methods. Hybrid DEA models, particularly DEA hybridized with soft-computing methods and DEA hybridized with each-other, appear to be more popular in comparison to the traditional DEA models. These Tables are prepared on the basis of the most cited papers.

### 5.1 Applications of DEA

In this subsection, the review has been done from the point of view of the application and which models have been applied for solving the applications.
5.1.1 Banking

One of the earliest applications of DEA is found to be in the banking sector in the year 1984. David Sherman and Franklin Gold [162] determined the efficiency of 14 branch offices of a bank. They used the CCR model and compared operating efficiency between the branches. In 1987, Celik Parken [163] examined the performance of the thirty-five branches of the Canadian bank and measured the efficiency.

Rangan et al. [164] recommended the production frontier technique to determine the technical efficiency of the 215 US banks. Pastor et al. [165] introduced the DEA with Malmquist index techniques to study bank efficiency and productivity growth rate. Thompson et al. [166] integrated the sense of the confidence region with the DEA model (DEA/AR). They measured the 100 largest banks of the US. Soteriou and Zenios [167] used benchmarking technique of DEA to approximation the efficiency and credible charge of bank products at the branch level. Dekker and Post [168] used the Free Disposal Hull (FDH) model to find the efficiency of Dutch banks. Sueyoshi [169] used an extended DEA model, DEA-Discriminant Analysis (DEA-DA) to evaluate the performance of the Japanese bank.

Chen [170] examined the technical efficiency of 39 banks of Taiwan. He used chance-constrained data envelopment analysis (CC-DEA) and stochastic frontier analysis (SFA). Emrouznejad and Anouze [171] calculated the efficiency of the banking branches in the Gulf Cooperation Council countries. They proposed a DEA framework with a classification & regression model. Azad et al. [172] examined the efficiency of Islamic, the conventional banks in Malaysia. They used the customary efficiency sense, a black box with three-stage NDEA model. Thaker et al. [82] investigated the efficiency of Indian banks. They used a machine learning technique and random forest regression with DEA under a two-phase model and measured the efficiency of Indian bank.

5.1.2 Sports

Sueyoshi et al. [173] examined the efficiency of baseball players. They used a slack-adjusted (SA-DEA) model to determine their ranking scores. Lozano et al. [174] determined the efficiency of the nations at the recent five summer Olympic Games. Garcia-Sanchez [175] applied a three-phase DEA technique to specify the efficiency of the Spanish football teams. Gutierrez and Ruiz [176] introduced the DEA and cross-efficiency appraisement to measure the individual game performance of Spanish Premier League handball players. Dhordjevic et al. [177] evaluated the technical efficiency of the national football team for the 2010 FIFA World Cup.

They used the multi-stage DEA model. Villa and Lozano [178] determined the efficiency of the basketball performance on the basis of assessment of the players and the performance of the teams. The authors used the dynamic network DEA model. Adhikari et al. [179] used a modified DEA technique, namely supper efficiency DEA, to select the cricket players.

5.1.3 Agriculture & Farm

The first paper observed to be in the field of agriculture is by Fare et al. [180]. Who determined the technical efficiency (TE) of agriculture in Philippine. Cloutier and Rowley [181] measured the productive efficiency of the Quebec dairy farms at Quebec. Zaibet and P.S. Dharmapala used stochastic production frontier (SPF) and DEA methods to determine the percentage of the farmers. Majiwa et al. [182] have explained the network DEA technique to determine the PH efficiency of milling using the data of the rice procuring industry. Stefanos et al. [183] applied fuzzy DEA technique in the agriculture sector to determine the efficiency of the organic farms. Sefeedpari et al. [184] examined the efficiency assessment of dairy farming in Iran by implementing window data envelopment analysis (W-DEA) model with energy use as inputs and milk production as output for 25 provinces in Iran. Candemir [185] determined the efficiency of the cotton enterprises Kahramanmaraş in Turkey. He obtained technical efficiency, pure technical efficiency (TE), scale efficiency (SE), allocative efficiency (AE), and economic efficiency (EE). Cecchini et al. [186] used the two-stage DEA model to measure the efficiency and super efficiency of the 76 meat-producing sheep farms. Their second objective was to examine the effect of animal welfare and management indicators on TE values.

5.1.4 Transportation

Michael Schefczyk [187] introduced the DEA methodology to examine the efficiency of 15 airlines. Their study analyzed the factor of the high profitability and performance of the airline. Oum and Yu [188] used a two-step procedure in their study. First, they examined the gross efficiency index from the panel data of 19 railways through DEA, and then they implied Tobit regression to identify the public subsidies. Cowie and Riddington [189] measured the efficiency of European railways. Nicole AdlerBoaz Golany [190] determined the deregulated railway networks used by combining DEA and principal component analysis (PCA). They studied the West European air transportation industry. Laya Olfat and Mahsa Pishdar [191] proposed fuzzy dynamic NDEA model based on the double production frontier for evaluating the sustainability of the Iranian airports. Sarmento et al. [192] in their paper measured the efficiency of the seven
highway projects in Portugal by exploiting DEA and the Malmquist index techniques. Song et al. [193] introduced a three-stage DEA technique and measured the operational efficiency of the air transport industry in China. Chen et al. [194] utilized inverse DEA technique for analyzing the road safety issues in China.

5.1.5 Education

Charnes et al. [195] used the DEA model for measuring the efficiency of public schools’ education. One of the other studies in the school areas was Bessent and Bessent [196]. Sarrico and Dyson [197] introduced the DEA model to evaluate the performance of UK universities. Casu and Thanassoulis [198] measured the cost-efficiency in central administrative services in UK Universities. Kongar et al. [199] used a two-step DEA approach to determine the relative efficiency of the applicants to for graduate programs in engineering. Miranda et al. [200] introduced DEA and stochastic frontier analysis (SFA) models to examine the technical performance of the higher education institutions in the field of business administration courses. Thanassoulis et al. [87] evaluated higher education in Greece. They combined analytic hierarchy process along with DEA. Si and Qiao [201] determined the performance of the financial expenditure in science and maths education in China. Iulian [202] used the CRS DEA and Malmquist indicators models and measured the performance of the Romanian higher public education institutions. Foladi et al. [203] introduced the inverse dynamic DEA (IDDEA) approach for evaluating the faculties of the different departments of Urmia University. Chen and Chang [204] measured the efficiency of the National Chung Cheng University departments in Taiwan.

5.1.6 Communication

The DEA utilization, in communication, has attained great attention in the current years. The studies are mostly in the areas of computer network, telecom industry, Information and communication technology (ICT) etc.

Giokas and Pentzaropoulos [205] evaluated the operational efficiency of large-scale computer networks. Uri [206] calculated the technical and allocative efficiency of the local substitution carriers. Fernandez-Menendez et al. [207] showed in their paper the level of information and communication technology (ICT) within the organization. They measured the technical efficiency of the Spanish firms through the DEA. Goto [208] studied the fiscal effort of the world telecommunications industry via DEA–Discriminant Analysis (DEA-DA). Liao and Lien [209] measured the technology gaps related to the efficiency of Asia Pacific Economic Cooperation (APEC) integrated telecommunications operators using the DEA meta frontier technique. Lu et al. [210] investigated the influence of the information and communication technology (ICT) progress on construction labour productivity (CLP).

5.1.7 Fishery

Vestergaard et al. [211] measured the capacity and capacity utilization (CU) in the fishery through the DEA. Maravelias and Tsitsika [212] applied a simple DEA technique and found Mediterranean fisheries’ fleet capacity and economic efficiency. Rowe et al. [213] recommended a combination of life cycle assessment (LCA) and DEA technique life cycle assessment (LCA) and DEA to link socioeconomic and environmental evaluations of fisheries. Kim et al. [214] measured the productive efficiency of the sandfish coastal gillnet fishery through the stochastic frontier analysis (SFA). Espino et al. [215] examined the fishing valence and structure excess of fishing valence over the endurable level of the fleet. Wang et al. [216] evaluated the performance of fisheries enterprises using the Malmquist model.

5.1.8 Tourism

Onut and Soner [217] evaluated the energy efficiency of 32 five-star hotels in the Antalya regions. Sun and Lu [218] evaluated the Taiwan hotel industry by the weight slack-based technique. Chou et al. [219] measured human resource management in the tourism industry or agency through the Malmquist productivity index analysis technique. Taheri and Ansari et al. [220] determined the technical performance of the cultural-historical museums in Tehran, through DEA. Chiu and Wu [221] analyzed the efficiency of 49 international tourist hotels (ITHs). Shieh [222] investigated the connection between the green and cost efficiency in the international tourist hotels in Taiwan. Huang et al. [223] improved the two-stage DEA model and to investigate the effect on the productive efficiency, occupancy, and catering service of Taiwan’s hotels. Cuccia et al. [224] explored the influences of cultural heritage in fostering tourism through their paper. Their study checked the influences of UNESCO world heritage list inscription on tourism destination efficiency in Italy. In their empirical study, Yang et al. [225] took eight ethnic regions of China and evaluated the tourism investment and poverty alleviation.

5.1.9 Health care

The first paper in the area of healthcare was observed to be of Nunamaker [226], where the author provided an application of DEA to calculate the efficiency of the routine nursing service at the Wisconsin hospital. Jimenez and Smith [227] judged the performance of primary health care through
Johnston and Gerard [228] measured the relative efficiency of the breast screening units of UK. Kontodimopoulos and Niakas [229] measured the efficiency of the hemodialysis units in Greece. Rouse and Swales [230] identified the efficient expenditure level of public health care service through DEA. Ballestero and Maldonado [231] employed DEA to measure the rank of the hospital activities. Nayar and Ozcan [232] determined the technical efficiency of the hospital and measured the quality performance. Jat and Sebastian [233] determined the technical efficiency of the district hospitals in Madhya Pradesh, India. Arteaga et al. [234] evaluated the efficiency of kidney transplantation using DEA. Cinaroglu [235] examined the effect of hospital size on converts in the efficiencies of public hospitals. More recently, Hamzah [236] measured the efficiency of the healthcare system for COVID-19 restraint through the network DEA model.

5.1.10 Automobile

Brey et al. [237] applied a non-parametric technique to conduct the development of technologies in the automobile sector. Parameshwaran et al. [238] measured the performance of the automobile repair shops through integrating fuzzy AHP and DEA techniques. Hwang et al. [239] investigated the communication between the dynamic of price discounts at the dealership level and production efficiency in the auto market in Spanish. Wang et al. [240] analysed the performance of the world’s top 20 automakers by Malmquist productivity index [MPI], a DEA model. In the automobile area, the reviewed papers show that the CCR model, integrating fuzzy AHP and DEA, Malmquist productivity index [MPI], VRS multiplier DEA, techniques used.

5.1.11 Forestry

Vitala and Hanninen [241] measured the efficiency of the regional Forestry organization through the DEA. Bogetoft et al. [242] evaluated the different offices of the Danish Forestry extension service and Safak et al. [243] specified the efficiency of the forest sub-district in the Denizli Forestry Regional Directorate by fuzzy-DEA model. Limaei [244] examined the efficiency of the Iranian forest industry. Li et al. [245] determined performance of the China’s forestry resources and sustainable development of forestry. Lu et al. [246] studied the non-dynamic Slack-based DEA model and evaluated the energy efficiency of forestry areas.

5.1.12 Water

Lambert et al. [247] investigate the relative efficiencies of the publicly and privately owned water utilities. Thanassoulis [248] estimated the cost-saving for water companies in England. Daz et al. [249] studied of the irrigation districts in Andalusia, Southern Spain. Lilienfeld and Asmild [250] examined the influence of irrigation system type. Alsharif et al. [251] determined the efficiency of the water supply system for West Bank and Gaza. Frija et al. [252] investigate the technical efficiency of unheated greenhouse farms and measured the water efficiency used for irrigation. Rosas et al. [253] estimated the operational productivity of the Mexican water utilities and identified the context variables that influence their efficiency. Soltani et al. [254] developed a new water quality index (WQI) of the 47 Algerian dams.

5.1.13 Real estate

Lins et al. [255] measured the value range for real estate units. Wang examined the performance of the government real estate investment. Xue et al. [256] applied DEA base MPI technique to assess the performance of the construction industry in China. Chancellor and Lu [257] analyzed the regional productivity of Chinese construction industry. Liu et al. [258] determined the performance of the contractors in China and Hong-Kong. Li et al. [259] studied the real estate market of China and determined the supply side efficiency of 29 provinces. Liu et al. [260] utilized the two-stage MPI in their paper and calculated the productivity efficiency of the real estate industry in China. Liu et al. [261] studied the same problem, but they used the meta-frontier SBM technique. Malmquist productivity index (MPI), Slack-based DEA, double perspective-DEA (DP-DEA), Färe-Primont DEA, techniques were used in the real estate application.

5.1.14 E-business

Cinca et al. [262] determined the efficiency in dot-com firms. The objective of the firms is to obtain revenues from their activities and make an impact on the internet. Menendez et al. [207] examined the technical efficiency of Spanish firms by the information and communication technology (ICT). An et al. [263] measured the performance of the Chinese high-tech industries through the dynamic network DEA technique. Table 6 shows the various models used in the different application area (Table 6).

6 Software

We were able to identify 18 software that can be utilized for application of DEA. Description of the software is provided in Table 7 [264, 265].
Bibliometric analysis is an excellent way of identifying the trends in a research area. Therefore, the remaining sections of this article are devoted to it. The bibliometric analysis is based on the database “web of science” for the years 1981 through 2021. The statistics is based on: year of publications, application area, journal quartile and its publication, area of research, and country-wise distribution and researcher statistics (Figs. 6, 7, 8, 9).

7.1 Year-Wise Statistics

Since 1981 to 2021, the total number of papers listed in web of science database is 10,691. The first paper, published in 1981 [178], has more than 733 citations. In 1984 two papers were published on the basic concept of the efficiency measurement of the DMUs. 1994 onward, the number of papers on DEA started increasing. This trend is shown in Table 8 and a pictorial representation is given in Fig. 9 (Table 8). Table 9 shows the published number of articles in the year 1981 to 2021 and graphically representation shows in the Fig. 10.

7.2 Statistical Analysis Based on the Quartile

Tables 10, and 11 show the list of journals, along with their quartile, where DEA articles have been published (Fig. 10).

7.3 Researchers Statistics

In this section, information about the most cited authors is listed in Table 12. We have listed only the papers for which the citation is above ten thousand.

7.4 Recent Trends

In this section, we review the current trends of research in DEA, which includes articles from the years 2020 and 2021. The search results are taken from the WoS database (Table 13).

8 Conclusion

The main objective of this paper is to revel the 40 years of existence of DEA and to generate an interest among the new researchers towards DEA by bringing forward its variants, its applications and above all its potential. This article presents an overview of DEA (1981–2021). From the collected data and statistical analysis, the following conclusions may be drawn:

- Since 1981, the graph of DEA is constantly rising with number of papers being more than 4000 between the period 2018 – 2021 in comparison to only 9 publications during the period 1981–1987. W.W. Cooper is to be the most cited author with around 40000 (forty thousand) citations till date.
- Due to the applicability of DEA to diverse domains, one can find articles related to DEA in several journals. It was observed that there are around 169 journals that have published papers related to DEA, out of which 81 belongs to the first quartile or are Q1 journals, at the time of writing this report.
- DEA has been hybridized with other methods so as to improve its efficiency and to increase its discriminatory power, a major shortcoming of DEA. Mostly DEA is used in conjugation with other MCDM method like AHP, TOPSIS etc. but it has also been combined with ANN.
### Table 2 Advantages and disadvantages of the DEA models

| Models                          | Advantages                                                                 | Drawbacks                                                                 |
|--------------------------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------|
| Russel model                   | Differentiate the performance of efficient DMUs.                          | Model does not increase their discrimination power in the sense that      |
|                                | Russel measure needs to be solved using a non-linear programming problem (NLP).| If a DMU is efficient in a standard data model with the radial measure,   |
|                                |                                                                           | It also goes with the Russell measures.                                    |
| Free disposal hull model (FDH) | FDH model relaxes the convexity assumption.                                | FDH makes weak assumptions regarding production technology.               |
| Additive model                 | It is capable of handling non-linear and non-monotonic relationships among the reaction and the predictor variables. And also able to deal with categorical predictors. | It does not purvey an exact measure of efficiency.                        |
| Cross efficiency model         | Unbiased for self-evaluation.                                              | Neglects the real value                                                   |
| Stochastic DEA models          | A significant decisional technique to calculate different DMUs in a stochastic environment provides a more approximate measure under randomness. | Stochastic models in continuous time are complicated                      |
|                                |                                                                           | The model will not produce one determined outcome.                        |
| Super efficiency model         | It is finding outliers.                                                   | It expresses the occasional impractical results.                          |
|                                | It provides an efficiency score greater than 1.                           |                                                                           |
| Hierarchical DEA models        | AHP can organize into considerations to the relative priorities of problems | Complex and stretched methodology.                                       |
|                                | AHP express a simple and significant model for the important circumstances. | AHP does not always maintain the solution to the linear equation.         |
|                                | AHP provides a simply executable decision-making approach which assists the decision-maker in analysing their precise selection. | These calculation needs for enormous small problem.                       |
|                                | Either objective or subjective observations, or either quantitative or qualitative knowledge, plays a significant role during the decision proceeding. | AHP employed only for fuzzy triangular numbers (TFNs).                    |
|                                | In this procedure, the noteworthy key points of this focus or the problem would be expressed to ease standards in priority scales. | AHP depends on both probability and possibility measures.                 |
|                                | It can organize the homogeneous clusters problems                          | Rank several realities that can be notified out carefully during the application. |
|                                |                                                                           | It clarifies the changes of the order of the synthesis alternatives when a new synthesis alternative is demonstrated to the factor. The proof of the rank reversal is still notified out in the literature. |
| Slack based model              | It can be solved using LP technology or techniques.                       |                                                                           |
|                                |                                                                           | It has a lack of discriminatory power with respect to efficiency rankings. |
| Network DEA models             | NDEA model can detect inefficiencies that the traditional DEA model misses | The multiplier and envelopment DEA models are not dual models.            |
|                                |                                                                           | The envelopment network DEA model does not necessarily provide information on divisional efficiency. |
|                                |                                                                           | Divisional efficiency obtained from the multiplier network DEA model can be infeasible on the envelopment side. |
| Fuzzy DEA models               |                                                                           | Occasional infeasible results.                                            |
|                                |                                                                           | Ignore the effect of exogenous variables in operations                    |
|                                |                                                                           | Ignore the statistical errors                                              |
|                                |                                                                           | Do not know how to improve efficiency                                    |
|                                |                                                                           | Difficult performs the statistical task with results                      |
Table 2 (continued)

| Models                  | Advantages                                                                 | Drawbacks                                                                 |
|-------------------------|----------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Supply chain model      | The small span of control                                                 | Bad controllability                                                       |
|                         | Remaining flexible and creative                                           | Incompatibility                                                           |
|                         | High customizations and exclusiveness of products                         | Uncertainty about prices and deliveries of supplies                      |
|                         | Variable cost                                                             | Un predictability of supplies                                             |
|                         | Flexible to various changes and external attentiveness                    | High transaction cost                                                     |
|                         |                                                                           | Low internal efficiency                                                   |

Table 3 Advantages and disadvantages of the hybrid DEA models

| Models                                               | Advantages                                                                                                                                                                                                 | Disadvantage                                                                 |
|------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| DEA models with artificial neural network           | ANN is an efficient technique to display multiple inputs and multiple outputs                                                                                                                        | DEA has a prompt reaction to data noise                                     |
|                                                     | Neural DEA efficiency has a less response to the number of efficient DMUs                                                                                                                                | The subject of the non-smooth, piecewise linear efficiency frontier display |
|                                                     |                                                                                                                                             | Weakness in the approximation of relative efficiency.                       |
| DEA models with big data                            | Big data analysis computes innovative solutions.                                                                                                                                                    | Traditional storage could create a lot of costs to store big data.          |
|                                                     | It motivates in progressing science and research.                                                                                                                                                    | Lots of big data is indeterminate                                           |
|                                                     | It has a high influence on financial trading, sports, polling, security etc.                                                                                                                             | Big data analysis contravenes principles of privacy.                        |
|                                                     | One platform preserves extended information                                                                                                                                                    | It could be introduced for the manipulation of customer records.            |
| MCDM-DEA models                                     | Avoid the chance of rank reversal.                                                                                                                                                                        | Only input-oriented                                                        |
|                                                     | Overcome the violation of element domination when an AHP problem is linked with DEA                                                                                                                   |                                                                             |

Table 5 Application of the hybrid DEA techniques

| Techniques                      | Applications                                                                 |
|---------------------------------|------------------------------------------------------------------------------|
| Soft-computing techniques       | Hospital, Agriculture, Health care, Automobile industry, Education, Environment, Bank |
| Machine learning technique      | Agriculture, Real estate, Health sector, Education, Electric power plants    |
| Multi-criteria decision-making  | Education, Transportation, Environment, Industry                           |
| Miscellaneous                   | Hotel, Environment                                                           |

| Techniques                      | Applications                                                                 |
|---------------------------------|------------------------------------------------------------------------------|
| Soft-computing techniques       | DE [8, 58, 61], MOGA [59], GA [62, 66], ANN [60, 63, 65, 67, 69, 158]        |
| Machine learning technique      | Decision tree [72], Unsupervised and Supervised machine learning [74], Deep learning, Clustering algorithms [76], (Naive Bayes, Random Forest, and SVM) [78], Stress-strain model [79], Random forest [80], Big data [70] |
| Multi-criteria decision-making  | AHP [87, 91, 92, 101], TOPSIS [94, 95], PROMETHEE [96], ANP [97], VIKOR [98, 99], BWM [100] |
| Miscellaneous                   | Least Absolute Shrinkage and Selection Operator (LASSO) [103, 104], mixed-integer programming [105], PCA [104, 106, 107, 159–161] |
From the application point of view, the two areas where DEA has been applied most frequently are education and banking. One of the reasons for this could be the availability of data that may be shared. In the last two years, business economics and operations research and some new emerging areas where DEA is being applied are remote sensing and polymer science.

In the last two years, the highest number of publications in the area of business economics (388), operational research (279), engineering (266), and science technology (229). These areas have seen the application of DEA earlier as well but it was interesting to see newer areas like geology, chemistry, physics, polymer science and remote sensing where application of DEA has started.

Out of the various DEA models proposed so far, Network DEA, hierarchical DEA, and stochastic DEA models are apparently, the most frequently used models in different application areas. All these models are the extension of classical DEA models. However, DEA has also been hybridized with other decision making techniques like AHP, TOPSIS etc.
Integration of DEA with Machine Learning models is one of the emerging areas of DEA which may have a lot of potential in the coming years due to the increase in volume of data, availability of good computing facilities and increase in the complexities of real world problems.

### Future Directions

- DEA is a versatile technique having immense scope from the development as well as from the application point of view. In the present review article, we saw areas like polymer science and remote sensing where DEA is applied likewise there can be new avenues where potential of DEA can be explored.
Integration of DEA with ML algorithms is another interesting area which seems to have a lot of potential. Both are decision making techniques but are conceptually different. DEA is mainly employed for determining the efficiency of the DMUs but after integrating it with ML techniques, one can also forecast the future efficiency of DMUs. Also for handling big data, ML and DEA can be combined for more efficient decision making.

Fuzzy DEA is an important concept which tries to incorporate the uncertainties of the real world scenarios. In this article we have devoted a small section to Fuzzy DEA, which probably is not justified considering the significance of the method. A separate detailed study can be prepared for Fuzzy DEA in the form of a review article.

Some of the important areas not included in this study are ranking methods and time series methods of DEA. A detailed analysis of these techniques will form an interesting piece of article. Further, a study on identifying and handling of undesirable input and output variables will also provide useful information to the researchers working in this area.

| Table 8 | Year of publications |
|---------|----------------------|
| Publication years | Paper published |
| [1981 – 1987] | 9 |
| [1988 – 1992] | 47 |
| [1993 – 1997] | 207 |
| [1998 – 2002] | 377 |
| [2003 – 2007] | 750 |
| [2008 – 2012] | 1671 |
| [2013 – 2017] | 3131 |
| [2018 – 2021] | 4499 |

| Table 9 | Types of articles published |
|---------|-----------------------------|
| Articles | Number of articles |
| Articles | 10252 |
| Early access | 261 |
| Proceeding papers | 218 |
| Review articles | 190 |
| Editorial materials | 58 |
| Meeting abstracts | 31 |
| Corrections | 15 |
| Book reviews | 14 |
| Letters | 6 |
| Reprints | 2 |

Fig. 9 Year-wise publication of DEA papers

Fig. 10 Quantitative analysis of the articles on the basis of article type
| Q1                                                                 | Q2                                                                 |
|-------------------------------------------------------------------|-------------------------------------------------------------------|
| European Journal of Operational Research                          | International Conference on Data Envelopment Analysis             |
| Social-Economic Planning Sciences                                  | Journal of Computational Science                                   |
| Journal of Cleaner Production                                      | Journal of Econometrics                                            |
| Transportation                                                    | Journal of Productivity Analysis                                   |
| Transport Policy                                                  | Industrial Management & Data Systems                               |
| Computer & Industrial Engineering                                  | Journal of Applied Mathematics and Computing                       |
| Journal of Agricultural Economics                                   | Management Science                                                |
| Computer & Operations Research                                     | Networks and Spatial Economics                                     |
| Applied Mathematical Modelling                                     | Information Systems and Operational Research (INFOR)              |
| Fuzzy Sets and Systems                                            | Ecological Indicators                                             |
| The International Journal of Advanced Manufacturing Technology    | Health Economics                                                  |
| Omega                                                             | Socio-Economic Planning Sciences                                   |
| Applied Energy                                                    | Applied Science                                                  |
| Ecological Economic                                               | Computers & Industrial Engineering                                |
| International Journal of Environmental Research and Public Health  | Natural Hazards                                                   |
| Journal of Cleaner Production                                      | Fuzzy Optimization and Decision-Making                            |
| International Journal of Production Economics                      | Sustainability                                                   |
| Energy Conversion and Management                                   | Sustainable Production and Consumption                             |
| Expert Systems with Applications                                   | Clean Technologies and Environmental Policy                       |
| Renewable Energy                                                  | International Journal of hydrogen Energy                          |
| Energy Policy                                                     | International Journal of Advanced Manufacturing Technology       |
| International Journal of Production Research                       | Empirical Software Engineering                                    |
| Renewable and Sustainable Energy Reviews                          | Tourism Economics                                                 |
| Resources, Conservation and Recycling Journal of Water Resources Planning and Management Current Biology | Economics Letters                                                |
| Journal of Computational and Applied Mathematics                  | Food Security                                                     |
| Fuzzy Sets and Systems                                            | Italian Journal of Animal Science                                 |
| Mathematics                                                       | International Transactions in Operational Research                |
| International Journal of Biological Macromolecules                | Social Indicators Research                                         |
| Energy                                                            | Scientometrics                                                    |
| Journal of Environmental Management                               | Telecommunications Policy                                          |
| Transportation Research Part A-Policy and Practice                | Journal of Marine Systems                                         |
| Journal of Operations Management                                   | Journal of Cultural Heritage                                      |
| Technovation                                                      | Global Health Action                                              |
| Annals of Operations Research                                      | Fisheries Research                                                |
| International Journal Production Economics                         | Health Care Management Science                                    |
| Journal of Computational and Applied Mathematics                  | Food Security                                                     |
| Fuzzy Sets and Systems                                            | Italian Journal of Animal Science                                 |
| Mathematics                                                       | International Transactions in Operational Research                |
| International Journal of Biological Macromolecules                | Social Indicators Research                                         |
| Energy                                                            | Telecommunications Policy                                          |
| Journal of Environmental Management                               | Journal of Marine Systems                                         |
| Transportation Research Part A-Policy and Practice                | Journal of Cultural Heritage                                      |
| Journal of Operations Management                                   | Global Health Action                                              |
| Technovation                                                      | Tourism Economics                                                 |
| Renewable and Sustainable Energy Reviews                          | Safety Science                                                    |
| Applied Soft Computing                                            | Fisheries Research                                                |
| Annals of Operations Research                                      | Health Care Management Science                                    |
| International Journal Production Economics                         | Economics Letters                                                 |
Appendix A: Important definitions in terms of DEA [266]:

- **Decision-making unit (DMU):** A DMU is an entity useful to transport input variables into output variables. For instance: educational institutions, hospitals, banks, and any other decision-making firms.

- **Efficiency:** A calculated of a unit’s maintaining to make outputs from its set of inputs. Since obtained efficiency is relative due to the efficiency of DMU is determined to all other DMUs.

- **Inefficiency:** When the entity lies below and above its frontier line or production.

- **Reference set/peer group:** A set of efficient units from which the inefficiency of an inefficient unit is determined.

- **Reference unit/peer unit:** Any unit part of the peer group.

- **Technical efficiency (TE):** When the efficiency is determined from the CCR/CRS model, is defined TE.

- **Pure technical efficiency (PTE):** The efficiency examined from the BCC/VRS technique is defined as PTE.

- **Scale efficiency (SE):** SE model depends on the TE and PTE score and is calculated by the ratio of the TE to PTE.
| Table 11 | Journal names and ranking |
|---------|--------------------------|
|         | Q3                       | Q4                       |
| Journal of Operational Research Society | Macromolecular Theory and Simulations |
| International Journal of Systems Science | Journal of the Indian Society of Remote Sensing |
| Operations Research Asia-Pacific | Journal of Operational Research |
| Engineering Computations | International Journal of Islamic and Middle Eastern Finance and Management |
| Mathematical Problems in Engineering | Economic Computation and Economic Cybernetics Studies and Research |
| Journal of Chemistry | European Journal of Industrial Engineering |
| Silicon |                          |                          |
| International Journal of Geo Information |                          |                          |
| Central European Journal of Operations Research |                          |                          |
| Forest Science |                          |                          |
| International Journal of Information Technology & Decision-Making |                          |                          |
| Utilities Policy |                          |                          |
| Journal of Sport Management |                          |                          |
| Journal of Irrigation and Drainage Engineering |                          |                          |
| Post Communist Economies |                          |                          |
| Flow Measurement and Instrumentation |                          |                          |
| Online Information Review |                          |                          |

**Fig. 11** IF of different journals based on quartiles
Appendix B: List of acronyms

| Acronyms   | Description                                      |
|------------|--------------------------------------------------|
| PROMETHEE  | Preference Ranking Organization Method for Enrichment Evaluation |
| TOPSIS     | Technique for Order of Preference by Similarity to Ideal Solution |
| VIKOR      | ViseKriterijumska Optimizacija I Kompromisno Resenje |
| LASSO      | Least Absolute Shrinkage and Selection Operator |
| CCDEA      | Chance-Constrained Data Envelopment Analysis |
| DEA-DA     | Data Envelopment Analysis -Discriminant Analysis |
| IDDEA      | Inverse Dynamic Data Envelopment Analysis |
| ICT        | Information and Communication Technology |
| NDEA       | Network Data Envelopment Analysis |
| DEA        | Data Envelopment Analysis |
| DMU        | Decision-Making Unit |
| TE         | Technical Efficiency |
| PTE        | Pure Technical Efficiency |
| SE         | Scale Efficiency |
| CRS        | Constant Returns to Scale |
| VRS        | Variable Returns to Scale |
| NIRS       | Non-Increasing Returns to Scale |
| NDRS       | Non-Decreasing returns to Scale |
| DRS        | Decreasing Returns to Scale |
| SBM        | Slacks-Based Model |
| FDH        | Free Disposal Hull Model |
| RM         | Russel Measure |
| SE Model   | Super Efficiency Model |
| MCDM       | Multi Criteria Decision-Making |
| N-LPP      | Non-Linear Programming Problem |
| ANN        | Artificial Neural Network |
| DE         | Differential Evolution |
| GA         | Genetic Algorithm |
| MOGA       | Multi Objective Genetic Algorithm |
| ML         | Machine Learning |
| DDF        | Directional Distance Function |
| MLP        | Multilayer Perceptron |

Table 12  Highest cited publications

| Authors       | Year active | Number of papers | Citation |
|---------------|-------------|------------------|----------|
| Cooper, W.W.  | 1981–2014   | 78               | 38518    |
| Charnes, A    | 1981–1987   | 25               | 32447    |
| Banker, Rajiv D. | 1981–2017  | 38               | 20637    |
| Fare, Rolf     | 1989–2021   | 48               | 16638    |
| Grosskof, Shawna | 1989–2020  | 47               | 15035    |
| Zhu J          | 1996–2021   | 160              | 11734    |
| Liang L        | 2004–2021   | 181              | 10936    |
| Seiford, Larry M. | 1990–2013 | 38               | 10780    |

Table 13  Area of research of the DEA

| Area of research        | Number of publications (2020) | Number of publications (2021) |
|-------------------------|-------------------------------|-------------------------------|
| Business economics      | 388                           | 351                           |
| Operational research    | 279                           | 277                           |
| Engineering             | 266                           | 255                           |
| Science technology other topics | 229                 | 227                           |
| Computer science        | 158                           | 137                           |
| Mathematics             | 61                            | 73                            |
| Geology                 | 21                            | 11                            |
| Chemistry               | 11                            | 12                            |
| Physics                 | 8                             | 11                            |
| Remote sensing          | 1                             | 2                             |
| Polymer science         | 2                             | 0                             |

| Acronyms   | Description                                      |
|------------|--------------------------------------------------|
| SAW        | Simple Additive Weighting                        |
| AHP        | Analytic Hierarchy Process                       |
| ANP        | Analytic Network Process                         |
| PCA        | Principal Component Analysis                     |
| EE         | Economic Efficiency                              |
| BWM        | Best Worst Method                                |
| MIP        | Mixed-Integer Programming                        |
| SA Model   | Slack-Adjusted Model                             |
| C & R Model| Classification & Regression Model                |
| W-DEA      | Window Data Envelopment Analysis                 |
| LCA        | Life Cycle Assessment                            |
| SCIE       | Science Citation Index Expanded                   |
| SSCI       | Social Sciences citation Index                   |
Acknowledgements  This work was supported by the Metaheuristics framework for combinatorial optimization problems (META-MOCOPS) under Grant DST/INT/Czech/P-12/2019.

Declarations

Conflict of interest  On behalf of all authors, the corresponding authors states that there is no conflict of interest.

References

1. Kao C (2014) Network data envelopment analysis: a review. Eur J Oper Res 239(1):1–16
2. Farrell M (1957) The measurement of productive efficiency. J Royal Statist Soc 120(3):253–290
3. Charnes A, Cooper WW, Rhodes E (1978) Measuring the efficiency of decision making units. Eur J Oper Res 2(6):429–444
4. Xie HSCQ, Zhu Y, Li Y (2021) Variations on the theme of slacks-based measure of efficiency: convex hull-based algorithms. Comput Ind Eng 159:8–14
5. Goyal RSJ, Singh M, Aggarwal A (2019) Efficiency and technology gaps in Indian banking sector: application of meta-frontier directional distance function dea approach. The Journal of Finance and Data. Science 5:156–172
6. Mahmoudi R, Emrouznejad A, Shetab-Boushehri S-N, Hejazi SR (2020) The origins, development and future directions of data envelopment analysis approach in transportation systems. Socioecon Plann Sci 69:100672
7. Yeşilyurt ME, Şahin E, Elbi MD, Kızılkaya A, Koyuncuoğlu MU, Akbaş-Yeşilyurt F (2021) A novel method for computing single output for dea with application in hospital efficiency. Socioecon Plann Sci 76:100995
8. Jauhar SK, Pant M, Nagar AK (2017) Sustainable educational supply chain performance measurement through dea and differential evolution: a case on indian hei. J Computat Sci 19:138–152
9. Paço CL, Pérez JMC The use of dea (data envelopment analysis) methodology to evaluate the impact of ict on productivity in the hotel sector, International Interdisciplinary Review of Tourism 10. Moon H, Min D (2020) A dea approach for evaluating the relationship between energy efficiency and financial performance for energy-intensive firms in korea. J Clean Prod 255:120283
11. Cooper WW, Ruiz JL, Sirvent I (2009) Selecting non-zero weights to evaluate effectiveness of basketball players with dea. Eur J Oper Res 195(2):563–574
12. Panwar A, Tin M, Pant M (2021) Assessment of the basic education system of myanmar through the data envelopment analysis. In: Proceedings of International Conference on Scientific and Natural Computing, Springer, pp 221–232
13. Cook WD, Seiford LM (2009) Data envelopment analysis (dea)-thirty years on. Eur J Oper Res 192(1):1–17
14. Cooper W, Seiford L, Tone K, Zhu J (2007) Some models and measures for evaluating performances with dea: past accomplishments and future prospects. J Prod Anal 28(3):151–163
15. Adler LFN, Sinuany-Stern Z (2002) Review of ranking methods in the data envelopment analysis context. Eur J Oper Res 140(2):249–265
16. Kuah CT, Wong KY, Behrouzi F (2010) A review on data envelopment analysis (dea). In: 2010 fourth Asia international conference on mathematical/analytical modelling and computer simulation, IEEE, pp 168–173
17. Liu JS, Lu LY, Lu W-M, Lin BJ (2013) Data envelopment analysis 1978–2010: a citation-based literature survey. Omega 41(1):3–15
18. Seiford LM (1997) A bibliography for data envelopment analysis (1978–1996). Ann Oper Res 73:393–438
19. Emrouznejad A, Parker BR, Tavares G (2008) Evaluation of research in efficiency and productivity: a survey and analysis of the first 30 years of scholarly literature in dea. Socioecon Plann Sci 42(3):151–157
20. Mardani A, Zavadskas EK, Streimikiene D, Jusoh A, Khoshroudi M (2017) A comprehensive review of data envelopment analysis (dea) approach in energy efficiency. Renew Sustain Energy Rev 70:1298–1322
21. Xu T, You J, Li H, Shao L (2020) Energy efficiency evaluation based on data envelopment analysis: a literature review. Energies 13(14):3548
22. Shahwan TM, Hassan YM. Efficiency analysis of uae banks using data envelopment analysis. J Econom Adm Sci
23. Charnes A, Cooper WW, Golany B, Seiford L, Stutz J (1985) Foundations of data envelopment analysis for pareto-koopmans

Fig. 12  Number of publications of area of research
efficient empirical production functions. J Econometr 30(1–2):91–107
24. Tone K (2011) Slacks-based measure of efficiency. In: Handbook on data envelopment analysis. Springer, pp 195–209
25. Färe R, Lovell CK (1978) Measuring the technical efficiency of production. J Econom Theory 19(1):150–162
26. Simar L, Wilson P (1999) An enhanced DEA Russell graph efficiency measure. Eur J Oper Res 115:596–607
27. Zhu J (2006) Measuring labor efficiency in post offices (2006)
28. Thrall RM (1999) What is the economic meaning of fdh? J Prod Anal 11(3):243–250
29. Cheung YL, Kuosmanen T, Post T (2000) What is the economic meaning of fdh? A reply to thrall, J Product Anal 263–267
30. Sexton TR, Silkman RH, Hogan AJ (1986) Data envelopment analysis: critique and extensions. New Direct Program Evaluat 1986(32):73–105
31. Doyle J, Green R (1994) Efficiency and cross-efficiency in dea: derivations, meanings and uses. J Operat Res Soc 45(5):567–578
32. Green RH, Doyle Jr, Cook WD (1996) Preference voting and project ranking using dea and cross-evaluation. Eur J Oper Res 90(3):461–472
33. Anderson TR (2002) A cross-evaluation model 249–255
34. Per Andersen NCP (1993) A procedure for ranking efficient units in data envelopment analysis. Manage Sci 39(10):1261–1264
35. Wilson PW (1993) Deterministic with nonparametric outputs multiple. J Bus Econ Stat 11(3):319–323
36. Thrall RM (1996) Duality, classification and slacks in dea. Ann Oper Res 66(2):109–138
37. Lee H-S, Chu C-W, Zhu J (2011) Super-efficiency dea in the production frontier. J Econometr 172(1):141–150
38. Liu W-B, Wongcha A, Peng K-C (2012) Adopting super-efficiency dea approach for multi-criteria fixed cost allocation. Soft Comput 22(2):7315–7324
39. Shabanpour H, Yousefi S, Farzipoor Saen R (2017) Forecasting efficiency of green suppliers by dynamic data envelopment analysis and artificial neural networks. Int J Intell Fuzzy Syst 32(6):4047–4058
40. Vlontzos G, Pardalos P (2017) Assess and prognostic green house gas emissions from agricultural production of eu countries, by implementing, dea window analysis and artificial neural networks. Renew Sustain Energy Rev 76:155–162
41. Moazzam R, Ostrowski and Fernandez Wanke P (2020) A hybrid genetic algorithm-ratio dea approach for assessing sustainable efficiency in two-chelon supply chains. Sustainability 12(19):8075
42. Tsolakis IE, Charis V, Gherman T (2020) Supporting better practice benchmarking: a dea-ann approach to bank branch performance assessment. Expert Syst Appl 160:113599
43. Pендхаркар RC (2018) A hybrid genetic algorithm and dea approach for multi-criteria fixed cost allocation. Soft Comput 22(22):7315–7324
44. Lewis HF, Sexton TR (2004) Network dea: efficiency analysis of organizations with complex internal structure. Comput Operat Res 31(9):1385–1410
45. Tone K, Tsutsui M (2009) Network dea: a slacks-based measure approach. Eur J Oper Res 197(1):243–252
46. Lohgren M, Tambour M (1999) Productivity and customer satisfaction in Swedish pharmacies: a DEA network model. Eur J Oper Res 115(3):449–458
47. Cook WD, Chai D, Doyle J, Green R (1998) Hierarchies and groups in dea. J Prod Anal 10(2):177–198
48. Cook WD, Green RH (2005) Evaluating power plant efficiency: a hierarchical model. Comput Operat Res 32(4):813–823
49. Zhu J (2014) Quantitative models for performance evaluation and benchmarking: data envelopment analysis with spreadsheets, Vol. 213, Springer
50. Wong WP, Wong KY. Supply chain performance measurement system using dea modeling. Indus Manag Data Syst 46(2):201–213
51. Olesen OB, Petersen NC (2016) Stochastic data envelopment analysis-a review. Eur J Oper Res 251(1):2–21
52. Cooper WW, Deng H, Huang Z, Li SX (2004) Chance constrained programming approaches to congestion in stochastic data envelopment analysis. Eur J Oper Res 155(2):487–501
53. Khodabakhshi M, Asgharian M (2009) An input relaxation measure of efficiency in stochastic data envelopment analysis. Appl Math Model 33(4):2010–2023
54. León T, Liern V, Ruiz J, Sirvent I (2003) A fuzzy mathematical programming approach to the assessment of efficiency with dea models. Fuzzy Sets Syst 139(2):407–419
55. Qin R, Liu Y-K (2010) A new data envelopment analysis model with fuzzy random inputs and outputs. J Appl Math Comput 33(1):327–356
56. Azadeh A, Anvari M, Ziaei B, Sadeghi K (2010) An integrated fuzzy dea-fuzzy c-means-simulation for optimization of operator allocation in cellular manufacturing systems. Int J Adv Manuf Technol 46(1–4):361–375
57. Peiun G, Hideo T (2001) Fuzzy dea: a perceptual evaluation method. Fuzzy Sets Syst 119(1):149–160
58. Yan Y, Wang L, Wang T, Wang X, Hu Y, Duan Q (2018) Application of soft computing techniques to multiphase flow measurement: a review. Flow Meas Instrum 60:30–43
59. Chandra Sekaran M, Muruldhar M, Krishna CM, Dixit U (2010) Application of soft computing techniques in machining performance prediction and optimization: a literature review. Int J Adv Manuf Technol 46(5):445–464
60. Saridakis KM, Dentsoras AJ (2008) Soft computing in engineering design-a review. Adv Eng Inform 22(2):202–221
61. Mogha SK, Yadav SP et al (2016) Application of differential evolution for data envelopment analysis. Int J Data Sci 1(3):247–258
62. Nabavi-Pelesaraei A, Hosseinzadeh-Bandbafha H, Qasemi-Kordkheili P, Kouchaki-Penchah H, Riahir-Dorcheh F (2016) Applying optimization techniques to improve of energy efficiency and ghg (greenhouse gas) emissions of wheat production. Energy 103:672–678
63. Misiunas N, Oztekin A, Chen Y, Chandra K (2016) Dea: a healthcare analytic methodology of data envelopment analysis and artificial neural networks for the prediction of organ recipient functional status. Omega 58:46–54
64. Jauhar SK, Pant M (2017) Integrating dea with de and mode for sustainable supplier selection. J Comput Sci 21:299–306
65. Pendharkar PC (2018) A hybrid genetic algorithm and dea approach for multi-criteria task allocation. Soft Comput 22(22):7315–7324
66. Shabanpour H, Yousefi S, Farzipoor Saen R (2017) Forecasting efficiency of green suppliers by dynamic data envelopment analysis and artificial neural networks. J Clean Product 142
67. Modhej SMSNHFD (2017) Integrating inverse data envelopment analysis and neural network to preserve relative efficiency values. Int J Intell Fuzzy Syst 32(6):4047–4058
68. Vlontzos G, Pardalos P (2017) Assess and prognostic green house gas emissions from agricultural production of eu countries, by implementing, dea window analysis and artificial neural networks. Renew Sustain Energy Rev 76:155–162
69. Mozaffari MR, Ostovan S, Fernandes Wanke P (2020) A hybrid genetic algorithm-ratio dea approach for assessing sustainable efficiency in two-chelon supply chains. Sustainability 12(19):8075
70. Tsolakis IE, Charles V, Gherman T (2020) Supporting better practice benchmarking: a dea-ann approach to bank branch performance assessment. Expert Syst Appl 160:113599
71. Pendrahek RC (2003) Technical efficiency-based selection of learning cases to improve forecasting accuracy of neural networks under nonmonotonicity assumption. Decis Support Syst 37(136):117–136 (2003)
72. Bose A, Patel G (2015) "neuraldea"-a framework using neural network to re-evaluate dea benchmarks. OPSSearch 52(1):18–41
73. Khezrimotlagh D, Zhu J, Cook WD, Toloo M (2019) Data envelopment analysis and big data. Eur J Oper Res 274(3):1047–1054
74. Zhu J (2020) Dea under big data: Data enabled analytics and stochastic data envelopment analysis. Ann Oper Res 1–23 (2020) Springer
72. Mishra S, Mishra D, Santra GH (2016) Applications of machine learning techniques in agricultural crop production: a review paper. Indian J Sci Technol 9(38):1–14
73. Tsai C.-F., Hsu Y.-F., Lin C.-Y., Lin W.-Y (2009) Intrusion detection by machine learning: a review. Exp Syst Appl 36(10):11994–12000
74. Tayal A, Kose U, Solanki A, Nayyar A, Saucedo JAM (2020) Efficiency analysis for stochastic dynamic facility layout problem using meta-heuristic, data envelopment analysis and machine learning. Comput Intell 36(1):172–202
75. Qu JLB, Ma J. Investigating the intensive redevelopment of urban central blocks using data envelopment analysis and deep learning: a case study of Nanjing, China. IEEE Access
76. Mirmozaffari M, Yazdani M, Bovskabadi A, Ahady Dolatsara H, Kabirifar K, Amiri Golilzar N (2020) A novel machine learning approach combined with optimization models for eco-efficiency evaluation. Appl Sci 10(15):5210
77. Aydin N, Yurdakul G (2020) Assessing countries’ performances against covid-19 via wsidea and machine learning algorithms. Appl Soft Comput 97:106792
78. Rebai FBYS, Essid H graphically based machine learning approach to predict secondary schools performance in Tunisia. Socioecon Plann Sci 70
79. Salehi V, Veitch B, Musharraf M (2020) Measuring and improving adaptive capacity in resilient systems by means of an integrated dea-machine learning approach. Appl Ergon 82:102975
80. Nandy A, Singh PK (2020) Farm efficiency estimation using a hybrid approach of machine-learning and data envelopment analysis: evidence from rural eastern india. J Clean Prod 267:122106
81. Jomthananachi S, Wong W-P, Lim C-P An application of data envelopment analysis and machine learning approach to risk management. IEEE Access
82. Thaker K, Charles V, Pant A, Gherman T (2021) A dea and random forest regression approach to studying bank efficiency and corporate governance. J Operat Res Soc 1–28
83. Nan Zhu A. E, Zhu Chuanjin (2021) The dimensionality of counterproductivity: are all counterproductive behaviors created equal? J Manag Sci Eng 6(4):435–448
84. Jomthananachi S, Wong W-P, Lim C-P (2021) An application of data envelopment analysis and machine learning approach to risk management. IEEE Access 9:85978–85994
85. Zhong K, Wang Y, Pei J, Tang S, Han Z (2021) Super efficiency sbm-dea and neural network for performance evaluation. Inform Process Manag 58(6):102728
86. Tahernejadzeh A, Alinezhad A (2022) Nations performance evaluation during sars-cov-2 outbreak handling via data envelopment analysis and machine learning methods. Int J Syst Sci 1–18
87. Thanassoulis E, Dev PK, Petridis K, Goniadis I, Georgiou AC (2017) Evaluating higher education teaching performance using combined analytic hierarchy process and data envelopment analysis. J Operat Res Soc 68(4):431–445
88. Mardani A, Jusoh A, Nor K, Khalifah Z, Zakwan N, Valipour A (2015) Multiple criteria decision-making techniques and their applications-a review of the literature from 2000 to 2014. Econ Res-Ekonomska istraživanja 28(1):516–571
89. Stojić M, Zavadskas EK, Pamučar D, Stević Ž, Mardani A (2019) Application of mcdm methods in sustainability engineering: a literature review 2008–2018. Symmetry 11(3):350
90. Kaya I, Çolak M, Terzi F (2018) Use of mcdm techniques for energy policy and decision-making problems: a review. Int J Energy Res 42(7):2344–2372
91. Kaewfik K, Huynh V-N, Ammarapala V, Ratisoontorn N (2020) A risk analysis based on a two-stage model of fuzzy ahp-dea for multimodal freight transportation systems. IEEE Access 8:153756–153773
92. Bajec P, Tuljak-Suban D, Zalokar E (2021) A distance-based ahp-dea super-efficiency approach for selecting an electric bike sharing system provider: one step closer to sustainability and a win-win effect for all target groups. Sustainability 13(2):549
93. RezaHoseini A, Rahmani Z, BagherPour M (2021) Performance evaluation of sustainable projects: a possibilistic integrated novel analytic hierarchy process-data envelopment analysis approach using z-number information. Environ Devel Sustain 1–60 (2021)
94. Banihashemi SA, Khalilzadeh M (2021) Evaluating efficiency in construction projects with the topsis model and IDEA method considering environmental effects and undesirable data. Iran. J Sci Technol - Trans Civ Eng
95. Wang C-N, Dang T-T, Tibo H, Duong D-H (2021) Assessing renewable energy production capabilities using dea window and fuzzy topsis model. Symmetry 13(2):334
96. Karasakal E, Eryılmaz U, Karasakal O (2021) Ranking using promethee when weights and thresholds are imprecise: a data envelopment analysis approach. J Operat Res Soc 1–18
97. Hoseini SA, Fallahpour A, Wong KY, Antuchevičienė J (2021) Developing an integrated model for evaluating r &d organizations’ performance: combination of dea-amp. Technol Econ Dev Econ 27(4):970–991
98. Lee Z-Y, Chu M-T, Wang Y-T, Chen K-J (2020) Industry performance appraisal using improved mcdm for next generation of Taiwan. Sustainability 12(13):5290
99. Karami S, Ghasemy Yaghin R, Mousazadegan F (2021) Supplier selection and evaluation in the garment supply chain: an integrated dea-pca-vikor approach. J Textile Instit 112(4):578–595
100. Mei M, Chen Z (2021) Evaluation and selection of sustainable hydrogen production technology with hybrid uncertain sustainability indicators based on rough-fuzzy bwm-dea. Renew Energy 165:716–730
101. Lee SK, Mogi G, Hui K (2013) A fuzzy analytic hierarchy process (ahp)/data envelopment analysis (dea) hybrid model for efficiently allocating energy r &d resources: In the case of energy technologies against high oil prices. Renew Sustain Energy Rev 21:347–355
102. Zelenyuk V (2020) Aggregation of inputs and outputs prior to data envelopment analysis under big data. Eur J Oper Res 282(1):172–187
103. Lee C-Y, Cai J-Y (2020) Lasso variable selection in data envelopment analysis with small datasets. Omega 91:102019
104. Chen Y, Tsiomas MG, Zelenyuk V (2021) Lasso plus dea for small and big wide data. Omega-Int J Manag Sci 102
105. Limleamthong P, Guillen-Gosálbez G (2018) Mixed-integer programming approach for dimensionality reduction in data envelopment analysis: application to the sustainability assessment of technologies and solvents. Indus Eng Chem Res 57(30):9866–9878
106. Davoudabadi R, Mousavi SM, Sharifi E (2020) An integrated weighting and ranking model based on entropy, dea and pca considering two aggregation approaches for resilient supplier selection problem. J Comput Sci 40:101074
107. Deng F, Xu L, Fang Y, Gong Q, Li Z (2020) Pca-dea-tobit regression assessment with carbon emission constraints of china’s logistics industry. J Clean Prod 271:122548
108. Smirlis YG, Maragos EK, Despotis DK (2006) Data envelopment analysis with missing values: an interval dea approach. Appl Math Comput 177(1):1–10
109. Azizi H (2013) A note on data envelopment analysis with missing values: an interval dea approach. Int J Adv Manuf Technol 66(9):1817–1823
110. Kuosmanen T (2009) Data envelopment analysis with missing data. J Operat Res Soc 60(12):1767–1774
111. Tao X, An Q, Xiong B, Chen Y, Goh M (2022) Benchmarking with nonconvex production possibility set through data
envelopment analysis: an application to china’s transportation system. Expert Syst Appl 198:116872

112. Ren X-T, Fukuyama H, Yang G-L (2022) Eliminating congestion by increasing inputs in r & d activities of Chinese universities. Omega 110:102618

113. Shen W, Yang G, Zhou Z, Liu W (2019) DEA models with Russell measures. Ann Oper Res 278(1):337–359

114. Aldamak A, Zolfaghari S (2017) Review of efficiency ranking methods in data envelopment analysis. Measurement 106:161–172

115. Wanke P, Barros CP, Emrouznejad A (2018) A comparison between stochastic DEA and fuzzy DEA approaches: revisiting efficiency in angolan banks. RAIRO-Oper Res 52(1):285–303

116. Ahmed NNSAM, Talib MA, Jani R (2022) A fuzzy data envelopment analysis model for measuring efficiency of Malaysian public research universities, Palestine. J Mathem 11:109–124

117. Chen Y, Cook WD, Li N, Zhu J (2009) Additive efficiency decomposition in two-stage DEA. Eur J Oper Res 196(3):1170–1176

118. Cook WD, Hababou M (2001) Sales performance measurement in bank branches. Omega 29(4):299–307

119. Wang K, Huang W, Wu J, Liu Y-N (2014) Efficiency measures of the chinese commercial banking system using an additive two-stage DEA. Omega 44:5–20

120. Seiford LM, Zhu J (1998) Sensitivity analysis of DEA models for simultaneous changes in all the data. J Operat Res Soc 49(10):1060–1071

121. Zhou P, Ang B, Poh K (2006) Slacks-based efficiency measures for modeling environmental performance. Ecol Econ 60(1):111–118

122. Choi Y, Zhang N, Zhou P (2012) Efficiency and abatement costs of energy-related CO2 emissions in China: a slacks-based efficiency measure. Appl Energy 98:198–208

123. Tone K, Tsutsui M (2014) Dynamic DEA with network structure: a slacks-based measure approach. Omega 42

124. Azadi M, Jafari M, Saen RF, Mirhedyatian SM (2015) A new fuzzy DEA model for evaluation of efficiency and effectiveness of suppliers in sustainable supply chain management context. Comput Oper Res 54:274–285

125. Lozano S, Gutiérrez E (2011) Efficiency analysis and target setting of spanish airports. Netw Spat Econ 11(1):139–157

126. Souto JE, Rodriguez A (2015) The problems of environmental-ally involved firms: innovation obstacles and essential issues in the achievement of environmental innovation. J Clean Prod 101:49–58

127. Lee K-H, Saen RF (2012) Measuring corporate sustainability management: a data envelopment analysis approach. Int J Prod Econ 140(1):219–226

128. Liang L, Wu J, Cook WD, Zhu J (2008) The DEA game cross-efficiency model and its nash equilibrium. Oper Res 56(5):1278–1288

129. Chauhan NS, Mohapatra PK, Pandey KP (2006) Improving energy productivity in paddy production through benchmarking-an application of data envelopment analysis. Energy Convers Manage 47(9–10):1063–1085

130. Wang Y-M, Chiu K-S (2010) A neutral DEA model for cross-efficiency evaluation and its extension. Expert Syst Appl 37(5):3666–3675

131. Falagario M, Sciancalepore F, Costantin N, Pietroforte R (2012) Using a dea-cross efficiency approach in public procurement tenders. Eur J Oper Res 218(2):523–529

132. Vázquez-Rowe I, Villanueva-Rey P, Iribarren D, Moreira MT, Feijoo G (2012) Joint life cycle assessment and data envelopment analysis of grape production for vinification in the rias baixas appellation (nw spain). J Clean Prod 27:92–102

133. Li H, Shi J-F (2014) Energy efficiency analysis on chinese industrial sectors: an improved super-sbm model with undesirable outputs. J Clean Prod 65:97–107

134. Yang L, Ouyang H, Fang K, Ye L, Zhang J (2015) Evaluation of regional environmental efficiencies in china based on super-efficiency-dea. Ecol Ind 51:13–19

135. Mirhedyatian SM, Azadi M, Saen RF (2014) A novel network data envelopment analysis model for evaluating green supply chain management. Int J Prod Econ 147:544–554

136. Lozano S, Gutiérrez E, Moreno P (2013) Network DEA approach to airports performance assessment considering undesirable outputs. Appl Math Model 37(4):1665–1676

137. Dotoli M, Falagario M (2012) A hierarchical model for optimal supplier selection in multiple sourcing contexts. Int J Prod Res 50(11):2953–2967

138. Eilat H, Golany B, Shhtub A (2008) R & d project evaluation: An integrated DEA and balanced scorecard approach. Omega 36(5):895–912

139. Liu W, Meng W, Zhang D (2008) Two-level DEA approaches in research institute evaluation. Omega 36(6):950–957

140. Azadeh A, Ghaderi S, Maghsoudi A (2008) Location optimization of solar plants by an integrated hierarchical DEA approach. Energy Policy 36(10):3993–4004

141. Azadeh A, Ghaderi S, Nasrollahi M (2011) Location optimization of wind plants in Iran by an integrated hierarchical data envelopment analysis. Renew Energy 36(5):1621–1631

142. Azadeh A, Rahimi-Golkhandan A, Moghaddam M (2014) Location optimization of wind power generation-transmission systems under uncertainty using hierarchical fuzzy DEA: A case study. Renew Sustain Energy Rev 30:877–885

143. Shen Y, Hermans E, Ruan D, Wets G, Brijs T, Vanhoucke M (2011) A generalized multiple layer data envelopment analysis model for hierarchical structure assessment: a case study in road safety performance evaluation. Expert Syst Appl 38(12):15262–15272

144. Kumar A, Jain V, Kumar S (2014) A comprehensive environmental friendly approach for supplier selection. Omega 42(1):109–123

145. Kuo RJ, Wang YC, Tien FC (2010) Integration of artificial neural network and mada methods for green supplier selection. J Clean Prod 18(12):1161–1170

146. Egilmez G, Kucukvar M, Tatari O, Bhutta MKS (2014) Supply chain sustainability assessment of the us food manufacturing sectors: a life cycle-based frontier approach. Resour Conserv Recycl 82:8–20

147. Pels E, Nijkamp P, Rietveld P (2003) Inefficiencies and scale economies of European airport operations. Transp Res Part E: Logist Transp Rev 39(5):341–361

148. Cullinan DWSK, Wang TF, Ji P (2006) The technical efficiency of container ports: comparing data envelopment analysis and stochastic frontier analysis. Transp. Res. Part A Policy Pract 40(4):354–374

149. Li M-J, Tao W-Q, Tian FC (2010) Integration of artificial neural network and mada methods for green supplier selection. J Clean Prod 18(12):1161–1170

150. Sadjadi SJ, Omrani H (2008) Data envelopment analysis with uncertain data: an application for Iranian electricity distribution companies. Energy Policy 36(11):4247–4254

151. De Witte K, López-Torres L (2017) Efficiency in education: a review of literature and a way forward. J Operat Res Soc 68(4):339–363

152. Linna M (1998) Measuring hospital cost efficiency with panel data models. Health Econ 7(5):415–427

153. Han Y, Geng Z, Zhu Q, Qu Y (2015) Energy efficiency analysis method based on fuzzy DEA cross-model for ethylene production systems in chemical industry. Energy 83:685–695
238. Parameshwaran R, Srinivasan P, Punniyamoorthy M, Charunyanath S, Ashwin C (2009) Integrating fuzzy analytical hierarchy process and data envelopment analysis for performance management in automobile repair shops. Eur J Indus Eng 3(4):450–467
239. Hwang S-N, Chen C, Chen Y, Lee H-S, Shen P-D (2013) Sustainable design performance evaluation with applications in the automobile industry: focusing on inefficiency by undesirable factors. Omega 41(3):553–558
240. Wang C-N, Tibo H, Nguyen HA (2020) Malmquist productivity analysis of top global automobile manufacturers. Mathematics 8(4):580
241. Viitala E-J, Hänninen H (1998) Measuring the efficiency of public forestry organizations. For Sci 44(2):298–307
242. Bogetoft P, Thorsen BJ, Strange N (2003) Efficiency and merger gains in the Danish forestry extension service. For Sci 49(4):585–595
243. Şafak MEAMGMKI, Gül AU, Portakal S (2014) Efficiency determination of the forest sub-districts by using fuzzy data envelopment analysis (case study: Denizli forest regional directorate). Int J Fuzzy Syst 16(3)
244. Limaei SM (2013) Efficiency of Iranian forest industry based on DEA models. J For Res 24(4):759–765
245. Li L, Hao T, Chi T (2017) Evaluation on China’s forestry resources efficiency based on big data. J Clean Prod 142:513–523
246. Lu C-C, Lin I-F, Wu D, Zhang X (2021) The effect of forestry on energy efficiency in EU countries: a non-oriented dynamic slack-based data envelopment analysis. Energy Sci Eng
247. Lambert DK, Dichev D, Raffiee K (1993) Ownership and sources of inefficiency in the provision of water services. Water Resour Res 29(6):1573–1578
248. Thanassoulis E (2000) DEA and its use in the regulation of water companies. Eur J Oper Res 127(1):1–13
249. Chancellor W, Lu W (2016) A regional and provincial productivity analysis of the Chinese construction industry: 1995 to 2012. J Constr Eng Manag 142(11):05016013
250. Li J, Chiang YH, Choi TN, Man KF (2013) Determinants of efficiency of contractors in Hong Kong and China: Panel data model analysis. J Constr Eng Manag 139(9):1211–1223
251. Li K, Ma Z, Zhang G (2019) Evaluation of the supply-side efficiency of China’s real estate market: a data envelopment analysis. Sustainability 11(1):288
252. Liu X-X, Liu H-H, Yang G-L, Pan J-F (2021) Productivity assessment of the real estate industry in China: a two-stage malmquist productivity index. Int J Strateg Prop Manag 25(2):146–168
253. Liu X-X, Song Y-Y, Liu H-H, Yang G-L (2021) Regional efficiency of the real estate industry in 35 large and medium-sized cities in China a meta-frontier SMB approach. Post-Communist Econ 1–33
254. Serrano-Cinca YF-CC, Mar-Molinero C (2005) Measuring DEA efficiency in Internet companies, vol 38. Elsevier
255. An Q, Meng F, Xiong B, Wang Z, Chen X (2020) Assessing the relative efficiency of Chinese high-tech industries: a dynamic network data envelopment analysis approach. Ann Oper Res 290(1):707–729
256. Zhu J, Paradi JC (2018) List of DEA software about the authors
257. Barr RS (2004) DEA software tools and technology. In: Handbook on data envelopment analysis, Springer, pp 539–566
258. “Data Envelopment Analysis: Ali Emrouznejad’s DEA Homepage, The Most Comprehensive Source of Data Envelopment Analysis!!” Data Envelopment Analysis: Ali Emrouznejad’s DEA Homepage, The Most Comprehensive Source of Data Envelopment Analysis!!, https://www.deazone.com/. Accessed 2 June 2022.

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.