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Invited Review

Trajectories of efficiency measurement: A bibliometric analysis of DEA and SFA

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ABSTRACT

This study surveys the increasing research field of performance measurement by making use of a bibliometric literature analysis. We concentrate on two approaches, namely Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA) as the most important methods to evaluate the efficiency of individual and organizational performance. It is the first literature survey that analyses DEA and SFA publications jointly, covering contributions published in journals, indexed by the Web of Science database from 1978 to 2012. Our aim is to identify seminal papers, playing a major role in DEA and SFA development and to determine areas of adoption. We recognized a constant growth of publications during the years identifying DEA as a standard technique in Operations Research, whereas SFA is mainly adopted in Economic research fields. Making use of document co-citation analysis we identify Airports and Supplier Selection (DEA) as well as Banking and Agriculture (SFA) as most influential application areas. Furthermore, Sensitivity and Fuzzy Set Theory (DEA) as well as Bayesian Analysis and Heterogeneity (SFA) are found to be most influential research areas and seem to be methodological trends. By developing an adoption rate of knowledge we identify that research, in terms of citations, is more focusing on relatively old and recent research at the expenses of middle-aged contributions, which is a typical phenomenon of a fast developing discipline.

1. Introduction

For more than three decades there is a growing interdisciplinary interest in performance in all its manifestations. Individual, group and organizational performance and its improvement are considered as highly important. Management by performance gains relevance to best utilize restricted resources and to sustain e.g. competitiveness in the private sector or to increase value for money, making government and policy more result-oriented. A competitive globalized world with interlaced finance markets and linked crises and shockwaves puts pressure on organizations of all kinds, demanding more resilience and more performance awareness especially concerning measurement, monitoring and hence the detection of its inefficiencies.

The growth in managerial interest in performance has been mirrored in the development of actual performance management practices and academic devotion. To conduct benchmarking between different organizations, "Decision Making Units" (DMUs) are commonly defined to measure relative efficiency, with a diverse species of approaches at hand.

By defining an efficient frontier, the inefficiency of a DMU is determined by measuring its distant to that hull, indicating its potential of an efficiency increase. On the one hand the frontier shows the maximum of diverse outputs with different input combinations; and on the other hand the minimal combination of necessary inputs for diverse outputs is viewed. DMUs below the frontier are understood as inefficient and DMUs on the frontier are regarded as efficient (Constantin, Martin, de Rivera, & Rivera, 2009). Beyond that, there are also methods that allow for both inputs and outputs to be simultaneously adjusted to move the DMU to the frontier.

To enable a more precise view on the method of efficiency measurement two important approaches for its measurement are analyzed in the following in a more detailed way: Data Envelopment Analysis (DEA) (Charnes, Cooper, & Rhodes, 1978) and Stochastic Frontier Analysis (SFA) (Aigner, Lovell, & Schmidt, 1977; Meeusen & van den Broeck, 1977). Table 1 states the most important differences between DEA and SFA. SFA is a **stochastic model** and therefore is able to differentiate between inefficiency and noise. On the other hand DEA is a **non-parametric** model and thus a function need not be defined. Therefore the effects of the form might not

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Table 1
Distinction between DEA and SFA. *Source*: Based upon Coelli, Rao, O'Donnel, and Battese (2005), Lan and Erwin (2003) and Lin and Tseng (2005).

	Data Envelopment Analysis (DEA)	Stochastic Frontier Analysis (SFA)
Elements	Multi outputs and inputs	Single input (output) and multiple output (input)
Algorithm	Linear programming	Regressions (typically using maximum likelihood estimation)
Consideration of noise	Noise is included in the efficiency score rather than accounted for directly (**deterministic model**)	Explicitly accommodates noise (**stochastic model**)
Functional form/input–output-relation	Not specified (everything that might be linearized)	Functional form is specified (e.g. linear, semi-log, double-log)
Factor weights	Individual factor weights for each unit (**non-parametric**)	No individual factor weights in the basic model (**parametric**)

Note: There are new methods within SFA research that allow for multiple inputs and multiple outputs.

get mixed with those of inefficiency (Fried, Lovell, & Schmidt, 2008).

Diverse state of the art articles in recent years indicate the relevance of that research field (e.g. Athanassopoulos, 1995a, 1995b; Seiford, 1990, 1996, 1997). First, bibliometric analyses demonstrate a wide adoption and diffusion of those techniques (Liu, Lu, Lu, & Lin, 2013a, 2013b; Sarafoglou, 1998). For the following reasons, our research goes beyond earlier analyses. To our knowledge we are the first analyzing not only DEA but also SFA, both pertinent performance measurement techniques. Our investigation focuses specifically on the following issues. We first analyzed the development of DEA and SFA research over time, clustering into different scientific disciplines. We see that performance measurement research relying on DEA and SFA in diverse industries and sectors can be characterized as being heterogeneous, fragmented and still evolving regarding its structure and sub-research fields. This study takes these variances into consideration. Therefore, we secondly quantitatively cluster real world and methodological contributions by document co-citation analysis to identify valid areas of research and their impact on the whole scientific field. Although the aim of several studies is to structure DEA research and further identify core research areas, these qualitative studies are based on the authors' personal experiences and judgments. So instead we utilize a bibliometric approach to combine the judgment of a huge number of experts in a field to identify and analyze different groups of closely connected articles mapping out major research areas of DEA and SFA science. We thirdly identify seminal papers according to two different approaches and display their persistence over time to derive their importance distinguishing between nominal and real seminals. Finally, to measure and compare how much progress in terms of methodological advance or practical expansion to other fields has taken place, we explicate and define an adoption rate. This measurement is applied to DEA and SFA research to analyze its substantial progress and its knowledge adoption over time.

The current paper is organized as follows. In the next section we describe the data and state the publication profile. Section 3 explains and conducts a document co-citation to quantitatively map out major research areas of DEA and SFA research. Section 4 concentrates on trajectories of DEA and SFA research. First, we make use of a rather simple numeric method, stating seminal articles and the change of ranking by counting citations (nominal seminals) in two different ways. Second, the progress of efficiency research is analyzed to identify seminal articles due to citation peaks (real seminals). Third, the adoption rate is defined and further analyzed to detect the resonance in literature. The final section concludes.

2. Data and publication profile

2.1. Data

We adopted Thomson Reuters Web of Science (WOS) as the data source of this study. WOS, covering over 10,000 high impact journals, as well as over 120,000 international conference proceedings is the world's leading citation database.

Papers on DEA and SFA were searched for and retrieved from this database with great care. This assignment started with a query of properly defined keywords. To only include key-articles of the two research fields in this study the keywords were set to "Data Envelopment Analysis" and "Stochastic Frontier Analysis". Papers containing these keywords in title, abstract, author keywords or Keywords Plus were retrieved for further examination.

The data were retrieved in March 2012 including a time span from 1987 to 2011. Overall 4782 publications were included in the dataset, 761 for SFA and 4021 for DEA. Among them, 4355 are articles (3687 DEA/668 SFA), 198 are proceedings papers (198 DEA/66 SFA), 48 are editorial materials (42 DEA/6 SFA), 115 are other document types (94 DEA/21 SFA); 4693 are English articles (3945 DEA/748 SFA), and 89 are in other languages (76 DEA/13 SFA).

2.2. Publication profile

Fig. 1 shows the increasing publication of articles over time of each method corresponding to their publication year. This illustration shows that DEA and SFA are popular instruments of managerial and economic research, especially in the last decade. Discontinuities are observed and accounted for, indicating special issues of journals (see Table 2 for a connection of a certain method and a journal) resulting in temporary increases of publication. Furthermore, the fact that special issues exist in this field of research indicates its increasing importance.

Table 2 shows the journals which present most of SFA/DEA research. Hence the top ten journals according to their DEA and SFA publications are stated. As there are differences in the top journals for DEA and SFA publications, respectively, they are further analyzed.

DEA seems to be mostly applied in "Operational Research" (OR) areas whereas SFA is a more widely used instrument in "Economics". WOS itself defines research categories for each article included in the database confirming this finding. 39.27% of DEA publications are allocated to "Operations Research Management Science" and 51.77% of SFA publications are categorized as "Economics" confirming the above finding. In summary, DEA is an approved permanent feature of OR and SFA for Economics research.

3. Impact of efficiency research contributions

In the following section we identify a detailed set of several research clusters that, when combined, represent the structure of DEA and SFA research. We differentiate the clusters according to sectoral and methodological segmentation. We first explain the method used, further visualize the results and state findings.

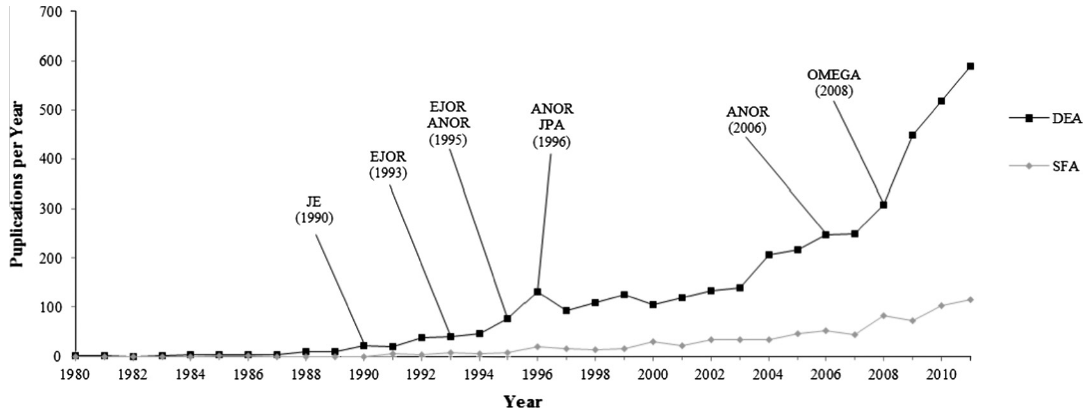

Fig. 1. DEA and SFA publications per year.

Table 2
Distribution of publicized articles corresponding to the journal published in.

Journal	Publications of DEA-articles			Publications of SFA-articles		
	Rating	Amount	Percent (%)	Rating	Amount	Percent (%)
European Journal of Operational Research (EJOR)	1	486	12.09	2–3	33	4.34
Journal of the Operational Research Society (JORS)	2	222	5.52	27–41	4	0.53
Journal of Productivity Analysis (JPA)	3	173	4.30	1	63	8.28
OMEGA International Journal of Management Science	4	123	3.60	17	6	0.79
Expert Systems With Applications (ESWA)	5	117	2.91	42–65	3	0.39
Applied Economics (AE)	6	97	2.41	2–3	33	4.34
Applied Mathematics and Computation	7	88	2.19	117–180	1	0.13
Annals of Operations Research (ANOR)	8	84	2.09	66–116	2	0.26
Computers Operations Research	9	60	1.49	66–116	2	0.26
International Journal of Production Economics	10	55	1.37	10–11	10	1.31
Energy Policy	11	47	1.17	6–7	12	1.58
Journal of Banking and Finance	17	35	0.87	4	17	2.23
Health Economics	60–64	10	0.25	5	16	2.10
Journal of Econometrics (JE)	44–46	14	0.35	6–7	12	1.58
Agricultural Economics	30–31	19	0.47	8	11	1.45
Applied Economics Letters	16	36	0.90	9	11	1.45
American Journal of Agricultural Economics	52–53	12	0.30	10	10	1.31

3.1. Method

Citation analysis is a major bibliometric approach (Osareh, 1996) following the use of citations as indicators of past and present activities of scientific effort (Garfield, Sher, & Torpie, 1964; Small, 1973). The major advantage of these approaches is that, unlike qualitative reviews, they do not represent the opinion of any single expert, but combine the judgment of a huge number of experts in a field. We build on the assumption that our data sample accurately reflects DEA and SFA research and its advances.

In a conventional bibliometric analysis articles are linked, when citing the same article, called bibliographic coupling. Here, we use the reverse method called co-citation coupling. This measurement reveals articles which are cited together. This "Document Co-citation Analysis" (DCA) was simultaneously and independently introduced by Small (1973) and Marshakova (1973). Linked articles are closely related to each other because of two reasons. They might be closely connected or they belong to the same research field (Cawkell, 1976; Garfield, Malin, & Small, 1978; Small, 1973).

Some aspects of this method require a cautious interpretation of the results. First, over time, some articles may become general knowledge and therefore may become part of newer publications without a citation. Second, negative citations (in terms of criticism) could weaken the results. A large data sample of articles as used here avoids these possible "noise" (Cawkell, 1976; Schildt, Zahra, & Sillanpaa, 2006).

3.1.1. Data cleaning

To enable a DCA and therefore the correct measurement of citations, misspellings and other mistakes when citing articles have to be eliminated. Because of the lack of digital object identifiers for authors and articles, the cleaning of the data was conducted alternatively (Lee, Kang, Mitra, Giles, & On, 2007). This sub-chapter explains the four steps used to clean the data.

To clean the authors, implying the detection of similar ones spelled differently in diverse journals the **first step** is to normalize all letters, meaning the change from capital to small letters. This step is conducted because the algorithm used to detect similar authors is case sensitive. The **second step** merges identical authors not perceived as identical ones by the computer program due to misspelling. We therefore make use of the Jaro-Winkler metric, a measure of similarity between two strings (author names) (Jaro, 1989, 1995; Winkler, 1999). It is rather intended for short strings and therefore suits our aim to detect duplicate authors (Cohen, Ravikumar, & Fienberg, 2003). The Jaro-Winkler metric is an advancement of the Jaro distance (d_j), based on the order and number of common characters (m) between two strings (s_1,s_2) and is defined as:

$$d_j = \frac{1}{3} * \left(\frac{m}{|s_1|} + \frac{m}{|s_2|} + \frac{m-t}{m} \right).$$

Here t states half the number of transpositions implying the matching but different ordered characteristics. Another assumption made is two characters (of s_1 and s_2) are only matching when they are not further than:

$$\left\lfloor \frac{max(|s_1|,|s_2|)}{2} \right\rfloor - 1.$$

The improved variant of this approach, called the Jaro-Winkler distance (d_w), is stated by Winkler (1990, 1999) as:

$$d_w = d_j + \left(\frac{P'}{10}(1 - d_j)\right).$$

The new parameter P' equals $max(P,4)$ implying P equates to the longest common prefix of the analyzed strings. Using the Jaro-Winkler distance we had values of different similarities using the labels of each node (author).

For our purposes, not only authors of articles but also authors included in the references of articles (to enable the correct display of citations) were tested by the Jaro-Winkler algorithm. We chose a Jaro-Winkler similarity of 60% to merge identical authors. A second threshold was set to 40% to further analyze suggested merges in the range between a 40% and 60% similarity. This was conducted to scan merges not automatically made but that almost occurred in comparison to the 60% threshold. This step was closed by analyzing the stated outcome to see if a manual merge was necessary.

Compared to other studies a threshold of 60% is quite small. This is done purposefully because the authors are not the restrictive character for citations whereas we prefer more rather than fewer merges.

The **third step** of data cleaning is to merge journals. As above this step is conducted to clean out misspellings or used abbreviations for journals in some references of articles. This was achieved by creating a document source merge table with the aid of an "Authoritative Journal Merging List" provided by the Sci^2 Team (2009) and implying several common names and abbreviations for journals. Afterwards the merging was viewed manually to exclude false and further merge absent merges.

The "cleaning" of the data was closed by the **fourth step**: matching citations to documents to exclude mistakes in the analysis by citations not found. The used algorithm considers a citation to match a document if and only if (Sci^2 Team, 2009):

- the citation author, page number, source, volume, and year are all provided and are valid;
- the citation author matches the first author of the document (provided by the second step);
- the citation page number matches the document beginning page;
- the citation source and document source are exactly the same source (provided by third step);
- the citation volume matches the document volume; and
- the citation year matches the document year.

This procedure does not take article titles into account and are therefore irrelevant for the analysis.

3.1.2. Document co-citation

To conduct the document co-citation analysis we utilize the Jaccard Index (Jaccard, 1901) as the relative measure of overlapping citations that two articles share. It places the co-citation count in relation to the sum of both partners' individual citations, less the co-citation count (Gmuer, 2003). Among others, this index is also used by Small and Greenlee (1980) and stated as:

$$S = \frac{\textit{Number of common citations to articles A and B}}{(\textit{Total citations to A} + \textit{Total citations to B} - \textit{Co} - \textit{citations of A and B})}.$$

The strength of the co-citation between two articles is measured with S ranging between 0, corresponding to no co-citation, and 1, corresponding to a perfect co-citation (e.g. when one article is cited another one is always cited as well). As the Jaccard Index is a normalized index it enables the comparison of co-citation strengths between articles cited relatively often and articles not cited relatively often. This analysis was conducted using the software tool Sci^2. (Sci^2 Team, 2009)

As recommended, we set a threshold to articles not having a significant impact (Small & Greenlee, 1980). Hence we neglected all articles with fewer than 15 citations for DEA and 10 citations for SFA, implicitly assuming that remaining articles are important to the research area. To further simulate the co-citation network we chose a rather "rough" method. We cut off the top edges (edges correspond to the strings between articles namely their co-citations) with respect to their Jaccard Index value and neglect others. We tried to find a threshold where the number of clusters would not change with a slight change of the threshold. For SFA, we chose the 100 top edges, implying a Jaccard Index threshold of 0.20. For DEA, we chose the top 400 edges implying a Jaccard Index threshold of 0.23077. Obviously we chose a higher amount of top edges because of the higher number of publicized articles, even though a higher Jaccard threshold is implied. Compared to other studies, the Jaccard Index is quite high (Schildt et al., 2006). This occurs because only articles focusing on DEA and SFA and their inter-citations are analyzed. This means that already related articles are analyzed to their relatedness, confirming our approach.

To give insight into the concentration of intellectual structures of clusters we deploy the Herfindahl index. We calculate it as:

$$\mathrm{HHI} := \sum_{i=1}^{N} a_i^2,$$

where a_i is the share of citations of the respective article in its cluster, and N is the number of all articles in a cluster.

3.2. Research clusters

This study aims to determine a quantitative categorization of the DEA and SFA research areas. Therefore we conducted a document co-citation analysis akin to that of Schildt et al. (2006) to reveal the different clusters of these research areas. Each group reflects a distinct theme in DEA and SFA research. Given that we are interested exclusively in the most cited and coherent groups of articles (and hence prior works), obviously some of the highly cited articles are excluded from this analysis due to their lacking affiliation to a cluster. Scilicet, some articles are excluded even though having high citations, when they are not relatively often cited together with other documents. In the following we differentiate between DEA and SFA methods and further distinguish between sectoral and methodological contributions. Each document is represented as a node and its size simulates the number of citations a document has. Edges represent the co-occurrence of articles in the reference of an article and its strength corresponds to the value of the Jaccard Index. Clusters smaller than or equal to 3 as well as clusters represented by a star are neglected. The resulting clusters are stated in Figs. 2–5.

Next, to the heading of each cluster, the value of the corresponding Herfindahl index is stated to identify increased concentrations on certain articles in clusters.

After presenting the sectoral contribution of DEA research, Fig. 3 depicts eleven sub-research fields of DEA adoption concentrating on the methodology.

The overall structure of clusters does not show high concentration of articles in particular clusters. This corresponds to the Herfindahl index of the intellectual structure of each cluster, which is low amongst clusters.

Due to insufficient co-citations, some seminal articles are not included in the clusters. We therefore want to at least mention that the pioneering work in the area of DEA and discriminant analysis (cluster II. 7) is Retzlaff-Roberts (1996). For cluster II. 11, concentrating on Super-efficiency we want to refer to Tone (2002) as one of the first contributions.

Two further extensions of DEA research, not included in the clusters, are briefly explained due to their relevance in science.

Dynamic DEA (DDEA), in which sub processes are interconnected in time, was originally developed by Fare and Grosskopf (1996). DDEA allows for time assessment incorporating concepts of quasi-fixed inputs and/or investment activities. DDEA surveys the performance of a DMU over time. The latest development in dynamic DEA includes the works of Chen (2009) and Tone and Tsutsui (2010). A more detailed literature survey of this area is stated by Cook and Seiford (2009), Cook, Liang, and Zhu (2010) and Castelli, Pesenti, and Ukovich (2010).

The second methodological approach is the nonradial (slacks-based) model. Historically, the radial models are represented by the CCR model (Charnes et al., 1978). In the input oriented case, this model only deals with a proportionate reduction of inputs. Hence the maximum rate of reduction with respect to the same proportion of inputs is yielded. The non-radial models represented by the slacks-based measure (SBM) (Tone, 2001) neglect the

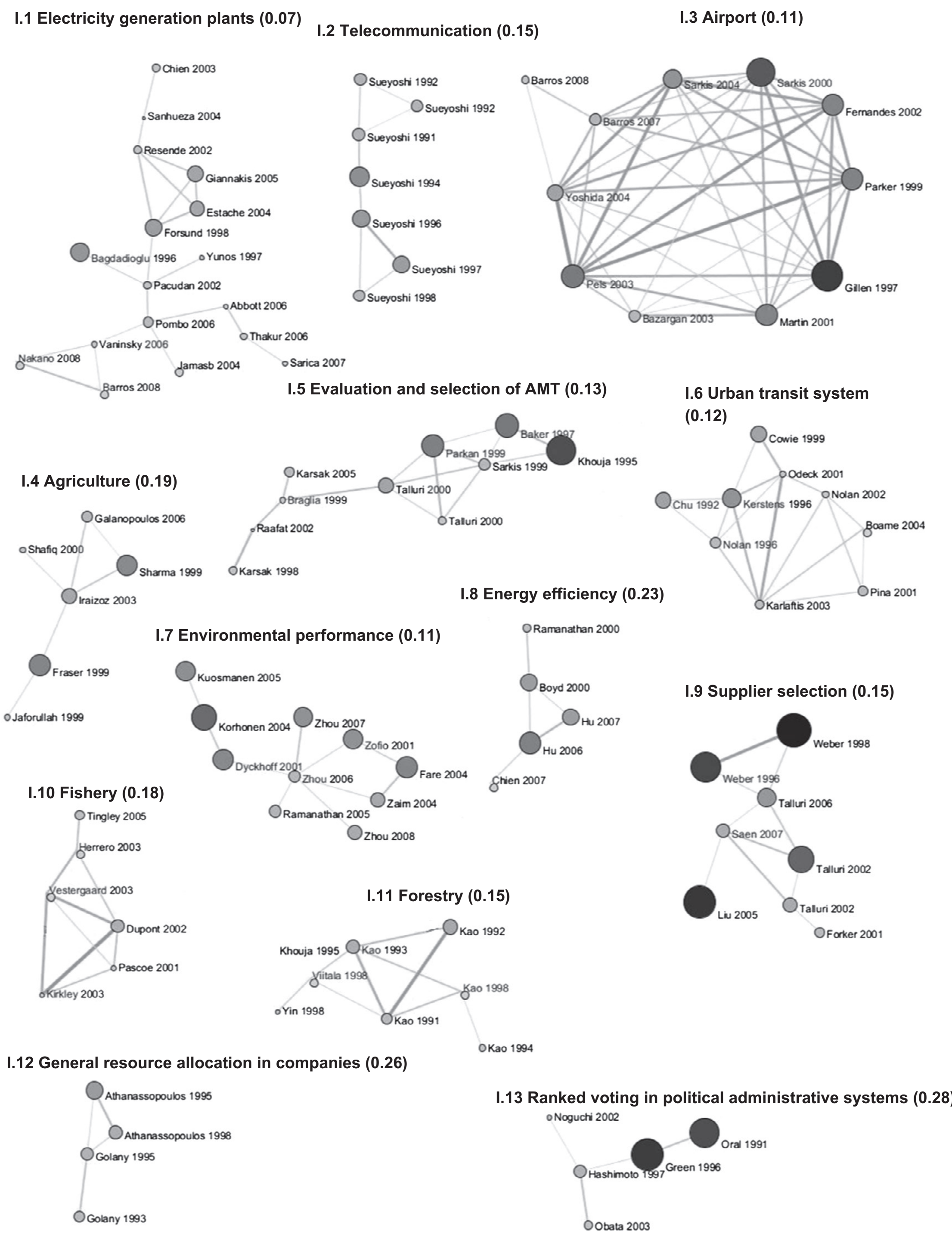

Fig. 2. Groups of highly cited DEA references – sectoral contribution – I (only first authors are named).

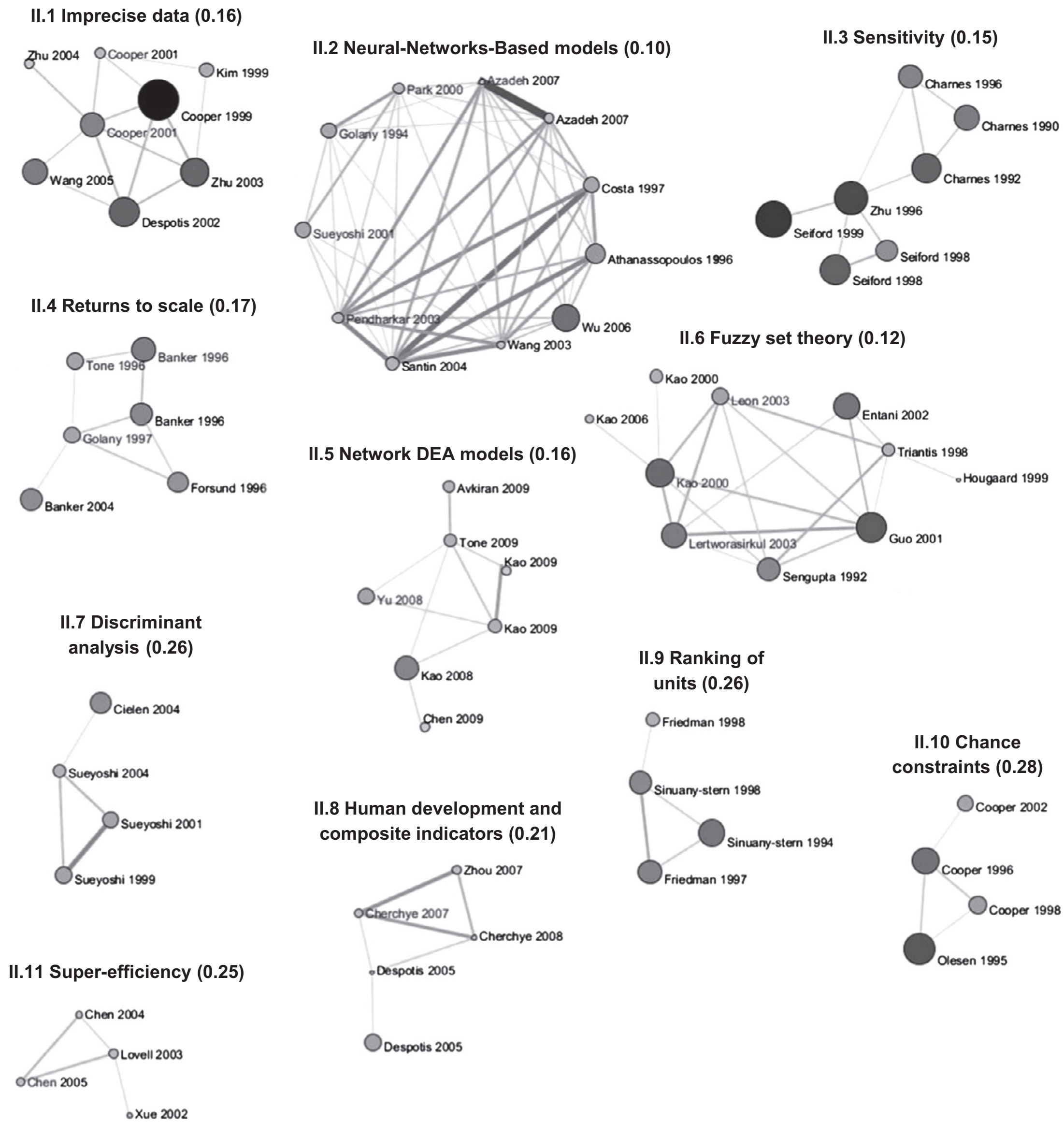

Fig. 3. Groups of highly cited DEA references – methodological contribution – II (only first authors are named).

assumption of a proportionate contraction in inputs. In summary, searching for the maximum rate of reduction in inputs that may reject varying proportions of the original input resources (in the input oriented view). A third extension, at least to be mentioned is the measurement of the relative balance by Ahn, Neumann, and Vazquez Nova (2012).

Figs. 4 and 5 constitute sub-research fields of SFA. Fig. 4 states sectoral directions, Fig. 5 shows methodological research fields of SFA literature.

The comparison of Figs. 2 and 4 show the different areas of focus of DEA and SFA research. The only sub-cluster concentrating on the same sector is fishery. Not only concentrating on the same sub-cluster but furthermore coinciding articles are included for the two research areas. This results in the adoption of both DEA and SFA to measure efficiency in the fishery sector. Hence this area seems appropriate to make comparisons and proves the connectedness of the two approaches. We further point out two articles connecting clusters III.1, III.2 and III.3 with each other. In terms of content, these two articles do not fit to either one of these clusters. First, Griffin and Steel (2007) concentrate on the implementation of Markov chain Monte Carlo methods to Bayseian analysis in SFA and make use of hospital and electricity utility companies' data. Therefore the methodological contribution seems to be the reason for its connection to these clusters. Second, Oum, Yan, and Yu (2008) analyze different ownership forms of airports which might be the linking reason for these articles.

As well as for DEA the Herfindahl index for SFA clusters is relatively low indicating no concentration of citations in particular clusters and therefore emphasizes the importance of the clusters in total. One exception is cluster III.2, displaying a relative high Herfindahl index. This cluster only includes two articles and is only included in Fig. 4, due to its connection to other clusters. Appendix A states the most cited articles of each cluster and describes their focus in bullet point form. Next to their citation count the corresponding percentage with respect to the associated cluster is stated. This gives evidence on major articles of each cluster and hence "must read" articles if interested in this topic.

To further evaluate the different clusters we state the citation count of each cluster and its percentage in proportion to sectoral or methodological contributions of the respective research area. Above that the percentage of each clusters' citations with respect to the entire research field (DEA or SFA) is given. Hence a ranking of the clusters' importance, according to their contribution area and further to their entire research field is given.

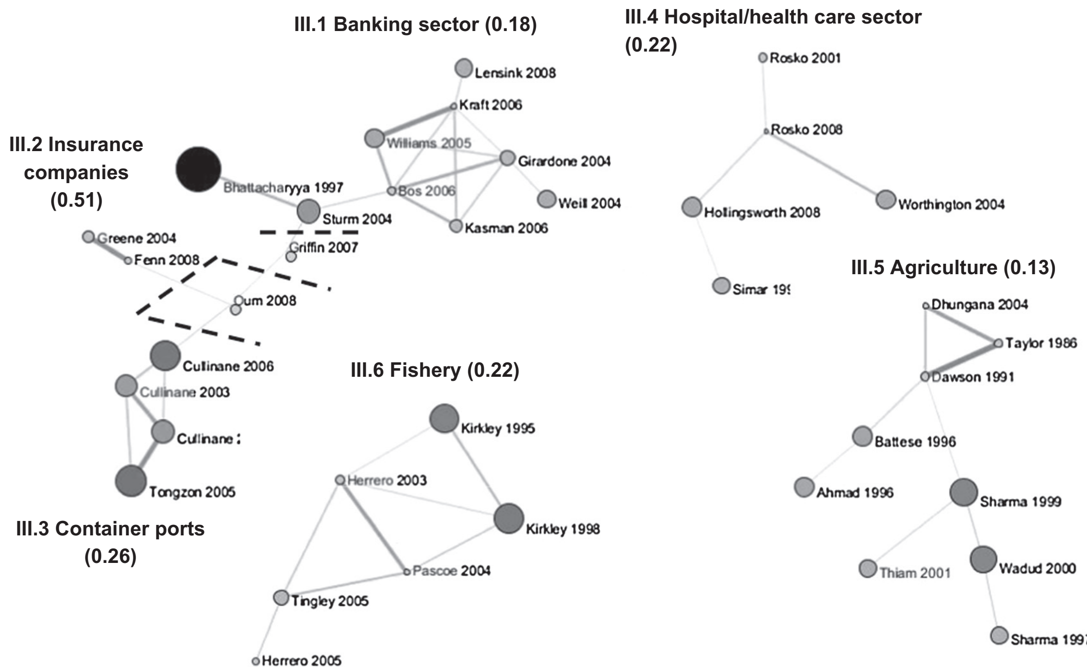

Fig. 4. Groups of highly cited SFA references – sectoral contribution – III (only first authors are named).

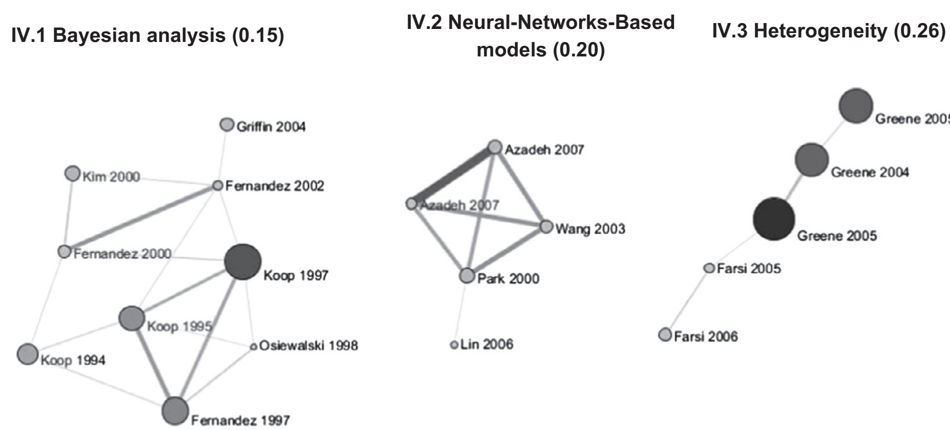

Fig. 5. Groups of highly cited SFA references – methodological contribution – IV (only first authors are named).

On the basis of these citation counts we detect the two most influential sectoral and methodological clusters. Most influential sectoral clusters are I.3 Airport (14.45%) and I.9 Supplier selection (12.82%) for DEA, and III.1 Banking sector (28.45%) and III.5 Agriculture (24.07%) for SFA. The most cited methodological clusters are II.3 Sensitivity (16.15%) and II.6 Fuzzy set theory (15.03%) for DEA, and IV.1 Bayesian analysis (44.58%) and IV.3 Heterogeneity (40.25%) for SFA.

Comparing methodological and sectoral contributions yields a higher influence of sectoral contributions for DEA as well as for SFA. 58% of DEA and 62% of SFA citations, with regard to articles included in our sample, cite articles belonging to sectoral clusters. Therefore, both methods are widely accepted in their application and represent a stable research area.

4. Trajectories

4.1. Seminals

To analyze the adoption of the DEA/SFA efficiency measurement methodology in literature we conduct a citation analysis by exploring the most cited articles of DEA and SFA research. Articles that embody the accepted principles of the area should always display high citation rates. These key papers are defined as nominal seminals. We see seminal articles represented in Table 3, emphazing the overall top 20 cited articles. Seminals are ranked according to two measures. First, we make use of the absolute number of citations as a measure of the overall impact of the work. Second, we use the average number of citations per year, mitigating the effect of the longer citation period of older articles.

For some of the highest ranked articles, the results are similar for both measures. Hence, these embody the accepted principles of the research area. For example Banker, Charnes, and Cooper (1984) are ranked first, independent of measurement used. However, the per year measure of citations gives different results for some articles. For SFA younger papers, such as Greene (2005a) or Banker and Natarajan (2008), move up in the rankings and show that performance measurement research has continued to develop new concepts. The same holds for DEA e.g. Tone (2001) and Simar and Wilson (2007).

Next to stating 'must read' articles in Table 3, the rankings suggest that for both SFA and DEA, new methods are continuously developed and adopted over time (because the per year citation ranking is very different to the total citation ranking). Both DEA and SFA research are therefore represented by a continuing development of new concepts.

4.2. Evolution over time

To further enable a better insight in the development of these methods, we define seminal articles with respect to the evolution of DEA and SFA over time. Therefore, we analyze the age structure of the cited articles adopting an approach from Schaeffer, Nevries, Fikus, and Meyer (2011). To further highlight if new concepts are developed over time and if publications influence the research over a long period of time, we separated the timespan into five subperiods named Period I (1987–1991) to V (2007–2011) for DEA each representing five years. (We did not list years before 1987 because very few publications to DEA (0.33%) and SFA (0.39%) were observed.) For SFA only four Periods (Period II–V) are presented because only 0.66% of the SFA publications occured in Period I itself. In Figs. 6 and 7, we chart the publication year of the cited articles and compare it to the number of citations. Thereby, we create an indication of the influence of recent and older research. For example, 15% of all citations made in Period I cite articles published in 1981 (Fig. 6 – DEA).

The spikes in Fig. 6 shows highly cited publication years. Even though these spikes decline over time, due to the increase of publication years, the importance of certain years for following research is obvious. For most of the citation spikes a small number of highly cited articles are responsible. These articles are of sustainable interest for new research, such as Charnes, Cooper, and Rhodes (1981) and Banker (1984), or Banker et al. (1984). Articles responsible for the citation peaks are referred to in Figs. 6 and 7. The above mentioned examples are also defined as seminals by Table 3 making use of a nominal approach. Furthermore, 'real' seminals, depicted by the peaks but not included in Table 3 exist. For DEA research 'real' seminals are Sherman (1984), Berg, Førsund, Hjalmarsson, and Suominen (1993), Tyteca (1996), Coelli and Perelman (1999), Cooper, Park, and Yu (1999) and Seiford and Zhu (1999) as well as Banker and Kauffman (2004).

For SFA literature (Fig. 7) Tyler and Lee (1979), Danilin, Materov, Rosefielde, and Lovell (1985), Taylor and Shonkwiler (1986), Dawson, Lingard, and Woodford (1991) and Sueyoshi (1991) as well as Banker (1993) are to be mentioned. Due to the two approaches (real and nominal seminals) several 'must read' articles for SFA and DEA research are identified. Detecting seminals not only using the nominal approach carves out additional ('real') seminals and thus rounds off the insight in key articles of the two research fields.

After working out seminal articles for the research area of DEA and SFA (the expressed citation peaks) we further analyze the citation behavior over time. Recent publications are the primary source of subsequent research, since the maximum number of citations lies five to eight years before the end of the period for DEA and four to seven years for SFA publications. This pattern is stable over all periods. Taking into account the lengthy process that extends from the development of a new research article to its publication, this shows that DEA and SFA research quickly takes recent knowledge into account (Schaeffer et al., 2011). To analyze the speed recent knowledge is taken into account we compare not only the different periods with each other but also DEA with SFA research.

Looking at Fig. 6, 16–37% of DEA research citations refer to articles published in the viewed period itself (whereas 23.45% belongs to Period I, 37.73% to II, 22.71% to III, 16.58% to IV and 22.28% to V). Those results are quite heterogeneous and do not reveal a constant trend. Another view shows that the 50% barrier of years (of

Table 3
Top 20 cited articles of DEA and SFA with regard to their total citation count (1979–2011).

Data Envelopment Analysis					Stochastic Frontier Analysis				
Article	# Citations		Rank based on			# Citations		Rank based on	
	Total	Per year	Total	Per year		Total	Per year	Total	Per year
Banker et al. (1984)	1975	68.10	1	1	Banker (1993)	219	10.95	1	2
Andersen and Petersen (1993)	532	26.60	2	3	Bhattacharyya, Lovell, and Sahay (1997)	103	6.44	2	9
Berger and Humphrey (1997)	416	26.00	3	4	Coelli (1995)	96	5.33	3	12
Charnes et al. (1981)	373	11.66	4	9	Greene (2005a)	93	11.62	4	1
Charnes, Cooper, Golany, Seiford, and Stutz (1985)	366	13.07	5	8	Fried, Lovell, Schmidt, and Yaisawarng (2002)	82	7.45	5	6
Simar and Wilson (1998)	253	16.87	6	5	Koop, Osiewalski, and Steel (1997)	73	4.56	6	13
Banker (1984)	249	8.59	7	15	Gong and Sickles (1992)	72	3.43	7	18
Seiford (1996)	229	13.47	8	6	Olesen and Petersen (1995)	67	3.72	8	16
Simar and Wilson (2007)	225	37.50	9	2	Greene (2005b)	66	8.25	9	4
Banker (1993)	219	10.95	10	10	Greene (2004)	64	7.11	10	7
Doyle and Green (1994)	201	10.58	11	12	Engle (2002)	62	5.64	11	10
Dyson and Thanassoulis (1988)	193	7.72	12	16	Cummins and Zi (1998)	59	3.93	12	15
Banker and Thrall (1992)	188	8.95	13	13	Reinhard, Lovell, and Thijssen (2000)	58	4.46	13	14
Charnes, Cooper, Wei, and Huang (1989)	165	6.88	14	18	Hjalmarsson, Kumbhakar, and Heshmati (1996)	57	3.35	14	19
Tone (2001)	161	13.42	15	7	Tongzon and Heng (2005)	56	7.00	15	8
Banker and Morey (1986)	160	5.93	16	19	Pels, Nijkamp, and Rietveld (2003)	55	5.50	16	11
Boussofiane, Dyson, and Thanassoulis (1991)	156	7.09	17	17	Bravo-Ureta and Rieger (1991)	54	2.45	17	20
Banker, Conrad, and Strauss (1986)	143	5.30	18	20	Cullinane, Wang, Song, and Ji (2006)	54	7.71	18	5
Allen, Athanassopoulos, Dyson, and Thanassoulis (1997)	143	8.94	19	14	Banker and Natarajan (2008)	53	10.60	19	3
Deng, Yeh, and Willis (2000)	141	10.85	20	11	Kirkley, Squires, and Strand (1998)	52	3.47	20	17

citations), with respect to Period I–III, are reached within two years before the starting point of the viewed Period (moving from recent to older publications). For more recent periods, namely Period IV and V, 50% are reached five years before the start of the Period. Hence older research takes more actual research into account.

Looking at SFA the citation behavior of Period III–V shows similarities. The percentage of citations referring to articles published in the period itself lies around 23–28%. For Period IV and V, 50% are reached within three years before the Periods start. Period III reaches 50% moving one year in front of the Period itself. Hence more actual citations take place when moving backwards in time, the same as for DEA publications. An even more significant result occurs when analyzing Period II. Here, 67% lie in the time span itself and 93% are reached when moving one year backward. This seems to be related to the low publication rates in the years before the period itself, meaning this method, or rather further research in it, was starting to spread only then.

Overall the citation analysis reveals that even though seminal papers dominate the citation behavior, DEA and SFA research is characterized by a research front that moves forward continuously.

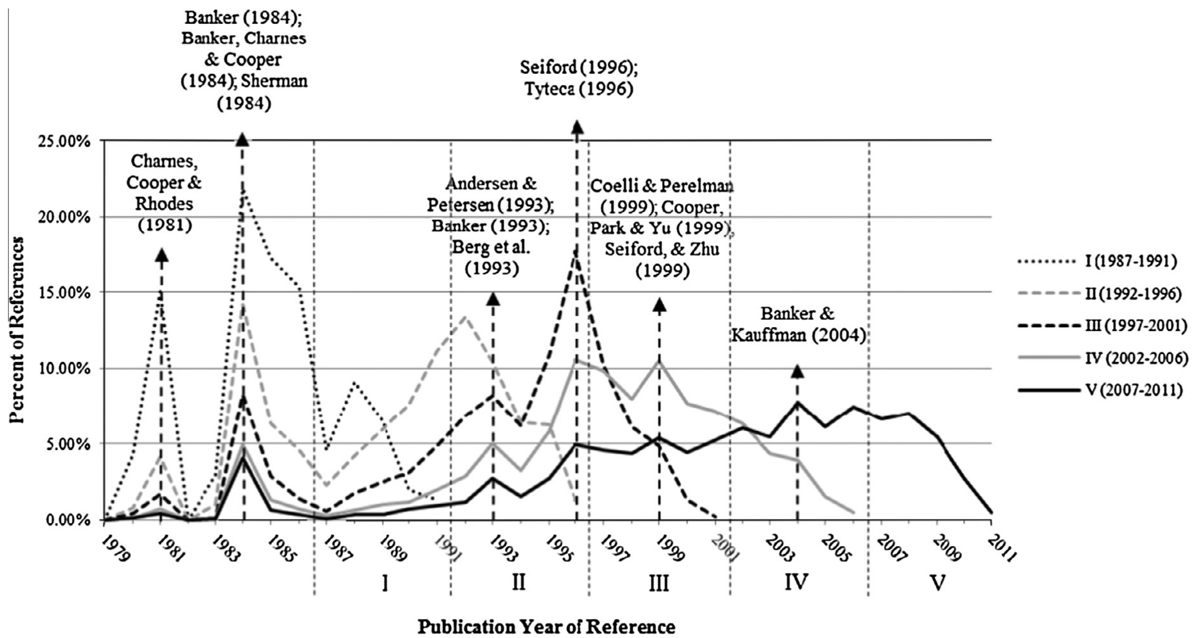

Fig. 6. Age structure of cited articles' publication dates – DEA. Note: 'Percent of References' is the percentage of citations in the respective year on the vertical axis, and the publication year of the cited article (Publication Year of Cited Article) on the horizontal axis. The dotted vertical lines indicate the period from which the citing articles are drawn from.

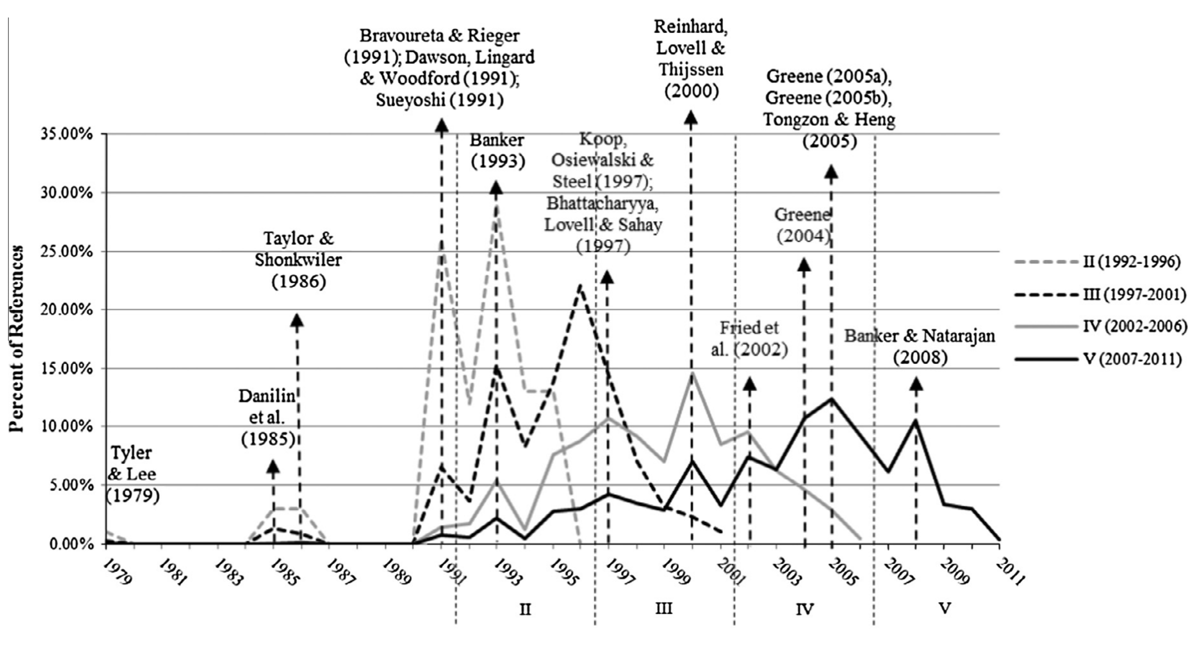

Fig. 7. Age structure of cited articles' publication dates – SFA. Note: 'Percent of References' is the percentage of citations in the respective year on the vertical axis, and the publication year of the cited article (Publication Year of Cited Article) on the horizontal axis. The dotted vertical lines indicate the period from which the citing articles are drawn from.

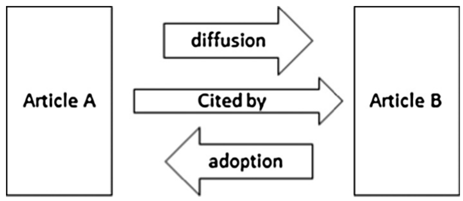

Fig. 8. The difference between adoption and diffusion.

Still, citations become relatively older when moving forward in time. Furthermore DEA science seems slower in knowledge adoption as SFA. The novelty of SFA and its accompanied slenderness, compared to DEA, might be the reason for this result. Therefore, DEA and SFA research are developing quite fast over time, concentrating on applications (shown by the dominance of sectoral contributions). To further shed light on the age structure of cited articles following sub-chapter analyzes the citation behavior of old and new articles in more detail.

4.3. Adoption rate

The above stated peak of citations, or rather the peaks of the publication years of citations, as used by Schaeffer et al. (2011) could be misleading because of its disregard of the whole distribution of publication dates. Another shortcoming of this method is its neglect of the evolution of the citation behavior over time. To overcome these problems we enhance this approach by using the adoption rate of science.

Therefore, we first differentiate between the term diffusion and adoption to enable a better understanding of the two perspectives.

> *"Diffusion is the process in which an innovation is communicated through certain channels over time among the members of a social system."* Rogers (2003)

Furthermore, diffusion describes the increase of adoption over time as the communication of the innovation changes (Järvenpää & Mäkinen, 2007). Until now in the bibliometric literature, mainly only diffusion is analyzed, see for example Sanni and Zainab (2011) and Førsund and Sarafoglou (1999) as well as Liu, Rafols, and Rousseau (2012). This approach is a forward oriented view in terms of the citing articles being considered. Instead, we concentrate on the adoption of knowledge, implying a backward oriented view. We therefore analyze cited articles, visualized in Fig. 8.

This approach is chosen to further analyze the rate of knowledge adoption. We compare the adoption behavior not only over time but also between DEA and SFA research. Figs. 9 and 10 'adopt' the data used in Figs. 6 and 7 but state the underlying publication dates of cited articles as cumulated percentage. Again, this is done separately for each analyzed period.

The embedded regression for the adoption behavior of the different periods shows a decreasing rate over time. Pollyannaish viewed this trend line is evidence for a decreasing rate of knowledge adoption for both DEA and SFA research. Assessing the goodness of fit of the regression the coefficient of determination (R^2) stabilizes the result. This finding is not surprising due to the excessive increase in publications over time (see Fig. 1) and seminals being cited over decades.

Our definition of the adoption rate is shown for the 60% threshold in Figs. 9 and 10. It states the delta between the start of a period and the achievement of the 60% threshold of citations with respect to the publication date of the corresponding publication. Hence the 60% threshold of citations of Period II is reached relatively shortly before the beginning of the period. Conversely 40% of the citations referred to are relatively recent. For Period IV, the 60% threshold is reached far earlier, represented by a longer fat grey line. This means 40% of the latest citations are more up to date for Period II compared to Period IV. In summary, Period II adopts more recent knowledge then Period IV. The same holds for SFA research (Fig. 10). For Period II the 60% level of citations is reached in the period itself implying an even higher rate of knowledge adoption. This might be due to SFA being a 'younger' research area than DEA.

To give an overview of the adoption behavior and its development over time, we calculate the deltas, the adoption rate, for the 20%, 40%, 60% and 80% thresholds (in years). In Figs. 11 and 12 those deltas and their evolution over time, with respect to the defined periods, are stated.

No clear trend is observed in Fig. 11 even though the average time needed for each threshold to be reached is increasing over the periods and therefore over time. Hence, on average citations refer to older articles when moving forward in time. The same holds for SFA (Fig. 12), again showing the importance of early seminal papers. This is confirmed when viewing the strong increase in years, needed to reach the 20% threshold of Period I–V.

We now analyze the behavior of DEA in more detail. For Period II and V, the 20% delta compared to the corresponding previous period increases rapidly. This gives evidence for the underlying knowledge of citations becoming relatively older for these two periods with respect to the 20% threshold. At the same time the delta for the 60% and 80% decreases compared to the previous periods. Hence, more relatively new research is cited. This gives evidence that the midfield of citations (in years of the underlying publications) decreases in importance. This is shown by a longer timespan needed to reach the same relative amount of midfield articles. This effect is even stronger for Period V, stated by a bigger

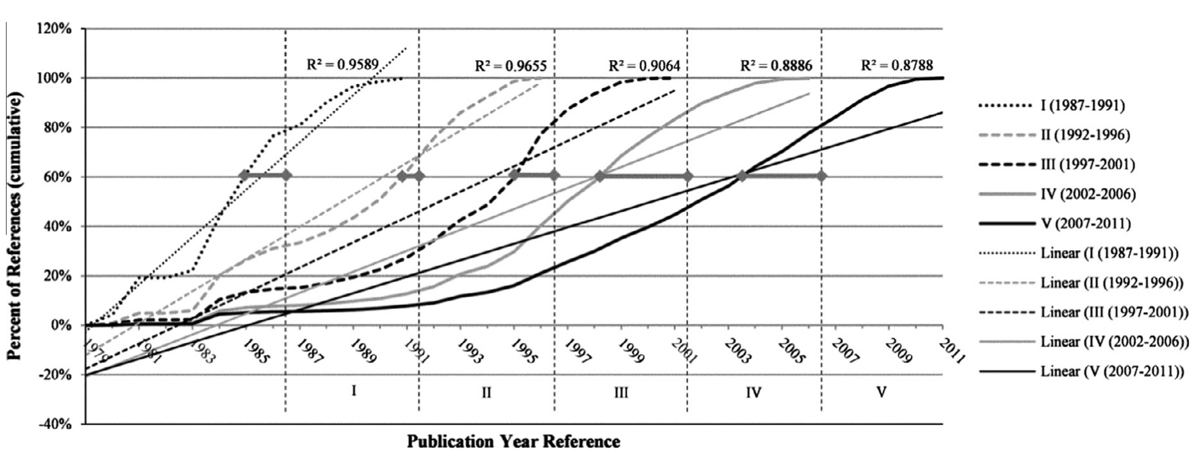

Fig. 9. Cumulated age structure of cited articles' publication dates – DEA.

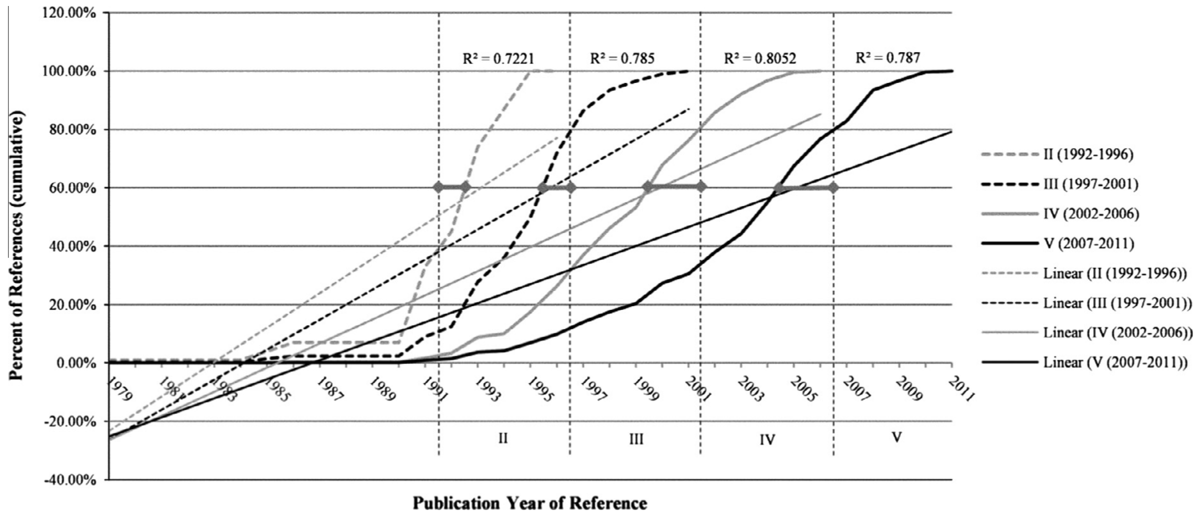

Fig. 10. Cumulated age structure of cited articles' publication dates – SFA.

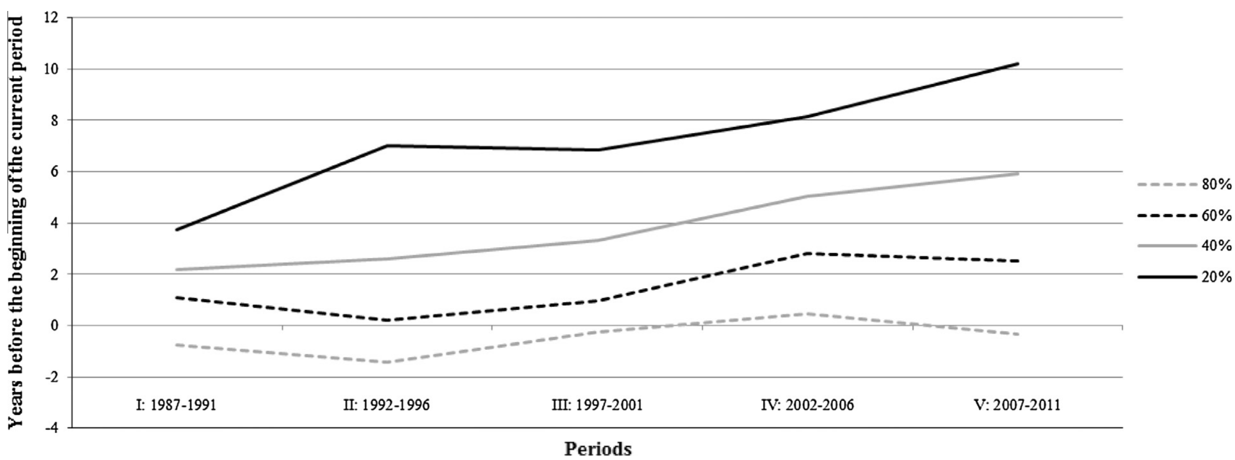

Fig. 11. Deltas of the reaching of a certain percentage level of cited publication dates corresponding to the different periods – DEA.

gap between the 60% and the 80% threshold. Concluding, seminal articles (in terms of early ones) as well as new research are taken more excessive into account in these two Periods compared to their previous ones.

The contrary is observed for Period IV. This is quite surprising because a constant trend in time should be anticipated. In other words, early research on DEA (Period II) and recent research on DEA (Period V) take more actual and older articles into account than the midfield (Period II and IV). The explanation behind this could be due to early research only having the chance to build upon relatively young articles due to the nascency of the research field. Therefore, this effect should be even stronger for Period I. We

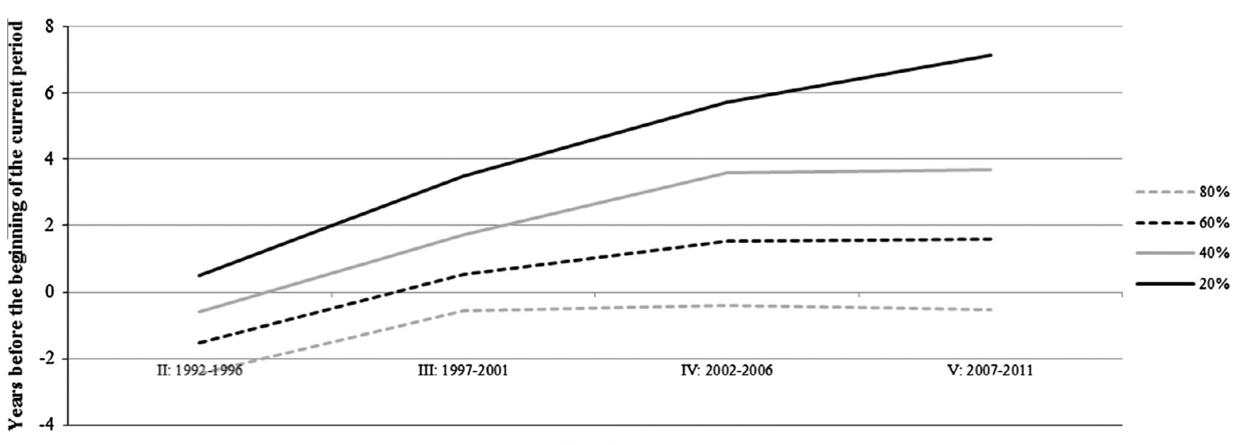

Fig. 12. Deltas of the reaching of a certain percentage level of cited publication dates corresponding to the different periods – SFA.

conclude that current research (Period V) concentrates more on citing recent research then the midfield of DEA research (Period III and V).

For SFA, the effect of increasing time spans between the Periods themselves and achieving the threshold increases not only on average (as explained above for DEA) but also absolutely (with one exception). The 80% threshold for Period V decreases compared to the previous Period implying a growth of importance of actual articles, namely 20% of the citations are more "up to date" ones relatively to the period before.

The flattening of the distribution on the one hand for the 60% and the 40% threshold, and a smooth decline of the 80% threshold as well as an increase for the 20% threshold on the other hand gives the same evidence as for DEA. Thus, both relatively old and relatively new articles are more important for contemporary research then the medium aged articles, compared to medium aged research. As seen in Figs. 11 and 12, this trend is obvious for the fifth Period of DEA and SFA (also for Period II of DEA research) and hence gives an idea of how the age structure of cited articles developed over time. This finding holds even though SFA publications are younger than the ones for DEA (see the explanation for Figs. 6 and 7). This effect is therefore irrespective of the age of a research area and thus is most influenced by the changing circumstances that research is subjected to. One reason might be the wide-spread internet use, resulting in a better availability and use of recent research leading to a superficial citation behavior. Concluding, middle-aged research falls into oblivion quite fast whereas the adoption of new ideas and references to relatively old articles increases over time, independently from the different age structure of DEA and SFA research.

5. Conclusion

The rapid growth in organizational and sectoral performance measurement research has led to the adoption of enhanced efficiency measurement methods in literature. We have thus reviewed the latest developments in the field and used a novel approach to do so. Specifically, we have focused on the application of DEA and SFA and we have presented a quantitative bibliometric analysis to get insights into growth trends. First, we have given evidence of the booming implementation of these methods in diverse research settings, identifying 4782 contributions (4021 DEA/761 SFA) from 1987 to 2012 in academic literature. The results reveal that DEA is strongly connected to Operations Research, while SFA appears to be more closely linked to Economics.

Clustering coherent fields of research, we have presented the first quantitative differentiation that indicates for which subjects (either thematic/sectoral or methodological) DEA and SFA are applied in the literature. By conducting a document co-citation analysis, we have differentiated 24 DEA and 9 SFA research areas. For DEA and SFA, citations of sectoral, and therefore real world applications, exceed (58% DEA/52% SFA) methodological contributions. This serves as a proof for a general acceptance of these techniques as a benchmarking tool in real world arrangements, measuring efficiency in different industries and sectors. Based on the citation counts we worked out the most influential sectoral and methodical clusters. For DEA, Airport and Supplier selection, as well as Sensitivity analysis and Fuzzy set theory, are identified. Major real world applications and methodological contributions for SFA are Banking and Agriculture as well as Bayesian Analysis and Heterogeneity. We further give evidence that there is no concentration of citations in particular clusters and therefore emphasize the importance of the clusters in total.

We have identified nominal as well as "real" seminal papers and analyzed the citation behavior over time. Overall, the citation analysis reveals that, even though seminal papers dominate the citation behavior, DEA and SFA research is characterized by a research front that moves forward continuously adopting new concepts. Evidence shows that DEA research activity is not as fast in the adoption of new concepts as SFA.

By defining an adoption rate, we were able to measure the rate of knowledge adoption and to analyze the evolution of DEA and SFA research over time. Evidence shows that current research focuses on building upon recent and older literature at the expense of middle-aged research. This trend is observed for DEA and SFA independent of their age structure. Hence, both research areas increase their rate of knowledge adoption in recent years. This effect is independent from the different age structures of DEA and SFA and therefore seems to be of structural nature. So, in SFA and DEA we see modern techniques, which are widely deployed and refined rapidly.

There are several limitations to this study. First, the dataset is taken from Web of Science. Although it is the largest citation-based academic database available, there are, certainly, some DEA and SFA papers published in journals not included in the WOS database. Interpretations of the results should incorporate a warning on the limitations of the data source.

Second, bibliometric studies are prone to the general criticism that not all references relevant to the article are always explicitly cited, and that not all citations are necessarily based on an intellectual link to the paper. Further potential effects might include citation networks among researcher groups, or citations made to please the potential reviewer or editor of the target journal. Furthermore, all citations are equally weighted, even though their importance may vary. These potential distortions should be mitigated due to the large number of articles this study is based on.

Third, it is hard to compile a complete dataset of all papers making use of SFA methods, given that literature measuring efficiency (especially in the context of (macro-) economic studies and econometric models) does not always reference their methods with "SFA", compared to DEA publications. To our knowledge, however, we are the first to analyze SFA adoption in economic and management science in this extend, measuring it́s publication performance.

As future work, we propose to transfer the concept of the "adoption rate" to other research fields, like innovation management, organizational behavior or accounting and finance research. In this way, we introduce a proper method to determine a scientific rate of knowledge adoption. By continuing our research arena we propose more analysis of the citations with respect to the cited research cluster to get further insight into how different clusters are developing.

Thus, the main contribution of this study is twofold. For the first time major research areas of DEA and SFA are quantitatively determined. This guides newcomers as well as 'old hands' to these research areas and supports to identify seminal and path breaking publications. Second, the analysis explains the rate of absorption of new methods and applications in DEA and SFA studies and gives insight into the development of research in this area. This should enhance future researchers' capability to identify research gaps and being aware of cutting edge research when building upon existing (methodological) knowledge.

Acknowledgement

The authors would like to thank Christoph Ihl for his valuable comments on earlier versions of this paper as well as four anonymous reviewers for their constructive comments.

Appendix A

See Tables B.1–B.4

Table B.1
Groups of highly cited DEA references – sectoral contribution – I.

DEA sectoral contributions (3565 citations/58% of DEA citations)		
Cluster name (number each cluster is cited /% of cites in proportion to sectoral DEA contributions (I)/% of cites in proportion to all DEA publications stated in the clusters (I and II))	Research topic	Amount each article is cited (% of cites in proportion to each cluster)
I.1 Electricity generation plants (390/10.94/6.36)	Comparison of different countries Yunos and Hawdon (1997)	18 (4.62)
	Comparison of public and private ownerships Bagdadioglu, Price, and Weyman-Jones (1996)	41 (10.51)
	Comparison of public and private ownerships, Scale efficiencies and different types of power plants (natural gas/coal/oil) Sarica and Or (2007)	18 (4.62)
	Impact of policies and Scale efficiencies Pacudan and de Guzman (2002) and Thakur, Deshmukh, and Kaushik (2006))	21 (5.38)
	Productivity Abbott (2006)	20 (5.13)
		20 (5.13)
	Productivity in the context of regulatory reforms and service quality Giannakis, Jamasb, and Pollitt (2005)	34 (8.72)
	Productivity in the context of regulatory reforms Nakano and Managi (2008)	16 (4.10)
	DEA vs SFA Estache, Rossi, and Ruzzier (2004)	33 (8.46)
	Differentiation between technical and technological change Barros (2008), Førsund and Kittelsen (1998)	16 (4.10)
		37 (9.49)
	Service centers Chien, Lo, and Lin (2003))	21 (5.38)
I.2 Telecommunication (228/6.40/3.72)	Data from 24 OECD countries Sueyoshi (1994)	44 (19.30)
	AT&T Sueyoshi (1991)	28 (12.28)
	Industrial efficiency of Chinese cities Sueyoshi (1992)	27 (11.84)
	Data from Nippon Telegraph & Telephone: Efficiency change via privatization Sueyoshi (1996) and Sueyoshi (1998))	26 (11.40)
	Returns to scale and scale economies Sueyoshi (1997)	37 (16.23)
	Managerial inefficiency/privatization (DEA and eight other methods) Sueyoshi (1996)	39 (17.11)
I.3 Airport (515/14.45/8.40)	Scale economies Pels et al. (2003)	55 (10.68)
	Operational efficiency Sarkis (2000)	72 (13.98)
	Spanish airports prior to privatization Martin and Roman (2001)	50 (9.71)
	Influence of environmental, structural and managerial variables Gillen and Lall (1997)	86 (16.70)
I.4 Agriculture (193/5.41/3.15)	Dairy farms Fraser and Cordina (1999)	49 (25.39)
	Pig farming, parametric and non-parametric approaches Sharma, Leung, and Zaleski (1999)	47 (24.35)
	Horticultural production, parametric and non-parametric approaches Iraizoz, Rapun, and Zabaleta (2003)	33 (17.10)
	Pig farming, factors affecting the efficiency Galanopoulos, Aggelopoulos, Kamenidou, and Mattas (2006))	26 (13.47)
I.5 Evaluation and selection of advanced manufacturing technology (AMT) (347/9.73/5.66)	Two-phase procedure Khouja (1995)	77 (22.19)
	Comparison of cross efficiencies and the two-phase procedure Baker and Talluri (1997)	56 (13.14)
	Comparison of the above study with newer approaches: A sequential dual use of DEA with restricted weights Braglia and Petroni (1999)	19 (5.48)
	A practical common weight multi-criteria decision-making mythology Karsak and Ahiska (2005)	24 (6.92)
	Multi-attribute decision-making and performance measurement methods are demonstrated and compared using data of the most cited article of this cluster Parkan and Wu (1999)	52 (14.99)
	Comprehensive bibliography on the techniques used in this area Raafat (2002)	17 (4.90)
I.6 Urban transit systems (238/6.68/3.88)	Impact of different factors: Average transit speed Boame (2004)	16 (6.72)
	Ownership in means of private or public, regulations and differentiating efficiency in managerial and organizational components Cowie and Asenova (1999)	35 (14.71)
	Ownership in means of private or public Odeck and Alkadi (2001)	19 (7.98)
	Ownership in means of private or public Pina and Torres (2001)	24 (10.10)
	Agency level technical efficiency Nolan (1996)	25 (10.50)
	Social efficiency Nolan, Ritchie, and Rowcroft (2002)	20 (8.40)
	Risk-sharing incentives in contracting, harmful impact of subsidies to efficiency and comparison of DEA and FDH Kerstens (1996)	42 (17.65)
	Effectiveness Chu, Fielding, and Lamar (1992)	35 (14.71)

(continued on next page)

Table B.1 (*continued*)

DEA sectoral contributions (3565 citations/58% of DEA citations)		
Cluster name (number each cluster is cited /% of cites in proportion to sectoral DEA contributions (I)/% of cites in proportion to all DEA publications stated in the clusters (I and II))	Research topic	Amount each article is cited (% of cites in proportion to each cluster)
I.7 Environmental performance (405/11.36/6.60)	Production of undesirable outputs and good	49 (12.10)
	Environmental performance index Fare, Grosskopf, and Hernandez-Sancho (2004)	32 (7.90)
	New definition of pollution intensity and its measurement Zaim (2004)	43 (10.62)
	Regulatory standards Zofio and Prieto (2001)	47 (11.60)
	Multi-dimensional value functions Dyckhoff and Allen (2001)	26 (6.42)
	Extensions to Slacks-based efficiency Zhou, Ang, and Poh (2006)	43 (10.62)
	Implication of non-radial approaches Zhou, Ang, and Poh (2007)	27 (6.67)
	Different DEA technologies Ramanathan (2005) and Zhou, Ang, and Poh (2008))	31 (7.65)
I.8 Energy efficiency (163/4.57/2.66)	China Hu and Wang (2006)	51 (31.29)
	Optimal efficient energy-saving targets for APEC economies Hu and Kao (2007)	37 (22.70)
	Linking productivity to energy efficiency Boyd and Pang (2000))	37 (22.70)
I.9 Supplier selection (457/12.82/7.45)	"Voting Analytic Hierarchy Process" Liu and Hai (2005)	89 (19.47)
	Enabling a selection with respect to ordinal and cardinal data – based on imprecise DEA Saen (2007)	30 (6.56)
	Multi-phase mathematical programming Talluri and Baker (2002)	65 (14.22)
	Extension of the former to enable performance monitoring Talluri and Sarkis (2002)	31 (6.78)
	Benchmarking of the best peer suppliers Forker and Mendez (2001)	24 (5.25)
	"Chance-Constrained Data Envelopment Analysis" – solves inherent variability of suppliers performance attributes Talluri, Narasimhan, and Nair (2006)	40 (8.75)
	A sub-topic of this cluster is the negotiation with suppliers: Identifying benchmark values on different criteria to enable the negotiation about those criteria with the suppliers Weber and Desai (1996)	80 (17.51)
	Three approaches for the negotiation and selection of suppliers in a non-cooperative environment Weber, Current, and Desai (1998))	98 (21.44)
I.10 Fishery (120/3.37/1.96)	Fixed or variables inputs (different species) and comparison of DEA and SFA Tingley, Pascoe, and Coglan (2005))	23 (19.17)
	Specialized maximization of output or output composition and its effects Herrero and Pascoe (2003)	16 (13.33)
	Different capacity measurement techniques Pascoe, Coglan, and Mardle (2001), Vestergaard, Squires, and Kirkley (2003))	18 (15.00)
		16 (13.33)
	Influences of managerial skills Kirkley, Squires, Alam, and Ishak (2003)	18 (15.00)
	Capacity utilization in a multi-species fishery Dupont, Grafton, Kirkley, and Squires (2002)	29 (24.17)
I.11 Forestry (157/4.40/2.56)	Sources of inefficiency: Yin (1998)	18 (11.47)
	Managerial style and support Viitala and Hanninen (1998)	16 (10.19)
	Management accomplishments Kao and Yang (1991)	25 (15.92)
	Reoganizing of forest districts Kao and Yang (1992)	32 (20.38)
	Differentiation in sub-districts (Kao, 1998)	16 (10.19)
I.12 General resource allocation in companies (121/3.39/1.97)	Target setting Athanassopoulos (1995a, 1995b, 1998)	38 (31.41)
		30 (24.79)
I.13 Ranked voting in political administrative systems (231/6.48/3.77)	Approaches to conduct the evaluation in the collective context and further perform an adequate selection are stated Hashimoto (1997), Noguchi, Ogawa, and Ishii (2002) and Obata and Ishii (2003)	27 (11.69)
		18 (7.79)
		22 (9.52)
	Collective evaluation and selection of industrial research & development projects Green, Doyle, and Cook (1996) and Oral, Kettani, and Lang (1991))	87 (37.66)
		77 (33.33)

Table B.2
Groups of highly cited DEA references – methodical contribution – II.

DEA methodological contributions (2569 citations/42% of DEA publications)		
Cluster name (s.a.number each cluster is cited/% of cites in proportion to methodical DEA contributions (II) /% of cites in proportion to all DEA publications stated in the clusters (I and II))	Research topic	Amount each article is cited (% of cites in proportion to each cluster)
II.1 Imprecise data (382/14.87/6.23)	Application of "Imprecise Data Envelopment Analysis" (IDEA) Cooper, Park, and Yu (2001a)	46 (12.04)
	"AR-IDEA" (Assurance Region) Cooper et al. (1999)	101 (26.44)
	IDEA with "Column Maximum DMU" (CMD) Cooper, Park, and Yu (2001b)	22 (5.76)
	Interval and/or fuzzy input–output environments Wang, Greatbanks, and Yang (2005)	49 (12.83)
	Linear programming equivalent referring to Cooper et al. (1999) and Despotis and Smirlis (2002)	61 (15.97)
II.2 Neural-network-based models (310/12.07/5.05)	Testing in: Public transport Costa and Markellos (1997)	29 (9.35)
	Banking sector Wu, Yang, and Liang (2006)	55 (17.74)
	Power generation sector Azadeh, Ghaderi, Anvari, and Saberi (2007a)	22 (7.10)
II.3 Sensitivity (415/16.15/6.77)	Examining the stability of efficiency scores (standard DEA) Charnes, Roussea, and Semple (1996), Seiford and Zhu (1998a, 1998b))	46 (11.08)
		40 (9.64)
		62 (14.94)
	Sensitivity in the additive-model Charnes, Haag, Jaska, and Semple (1992) and Charnes and Neralic (1990)	49 (11.81)
		61 (14.70)
II.4 Returns to scale (231/8.99/3.77)	Modify existing approaches Banker, Bardhan and Cooper (1996a) and Banker, Chang and Cooper (1996b)	43 (18.61)
	State alternative methods Banker, Bardhan, and Cooper (1996a) and Banker, Chang, and Cooper (1996b))	48 (20.78)
	Discuss returns to scale for available models Banker, Cooper, Seiford, Thrall, and Zhu (2004)	41 (17.75)
II.5 Network DEA models (183/7.12/2.98)	This group of articles reflects interrelations of processes within the system	26 (14.21)
	"Relational Network Model" Kao (2009) and Kao and Hwang (2008)	45 (24.59)
	"Multi-Activity Network DEA" Yu and Lin (2008)	30 (16.39)
	"Slacks Based Network DEA" Avkiran (2009) and Tone and Tsutsui (2009)	24 (13.11)
		26 (14.21)
II.6 Fuzzy set theory (386/15.03/6.29)	Dissolving of the problem of imprecise data	
	Construction of a membership function Kao and Liu (2000a)	26 (6.74)
	Triantis and Girod (1998))	25 (6.48)
	Fuzzy mathematical programming, fuzzy regression as well as fuzzy entropy are employed Sengupta (1992)	43 (11.14)
	Possibility approach, treating constraints as fuzzy events Lertworasirkul, Fang, Joines, and Nuttle (2003)	49 (12.69)
	Fluctuating data is represented as linguistic variables – furthermore these are fuzzy numbers Guo and Tanaka (2001)	64 (16.58)
	A-cut approach Kao and Liu (2000b) and Leon, Liern, Ruiz, and Sirvent (2003)	58 (15.03)
		31 (8.03)
	Two-level mathematical programming models (defining a lower and upper bound of efficiency and hence result in interval efficiency measures) Kao (2006)	20 (5.18)
	A special case of the above approach combines the original and the inverted DEA Entani, Maeda, and Tanaka (2002)	53 (13.73)
II.7 Discriminant analysis (126/4.90/2.05)	DEA-Discriminant Analysis" (DEA-DA) Sueyoshi (1999)	31 (24.60)
	"Extended DEA-DA" Sueyoshi (2001)	30 (23.81)
	Advanced by Sueyoshi (2004)	25 (19.84)
	Comparison of DEA to a rule induction model Cielen, Peeters, and Vanhoof (2004)	40 (31.75)
II.8 Human development and composite indicators (107/4.17/1.74)	Reassessment and measurement of the human development index for different countries Despotis (2005a, 2005b)	31 (28.97)
		17 (15.89)
	Construction of composite indicators using DEA Cherchye, Moesen, Rogge and van Puyenbroeck (2007), Cherchye et al. (2008) and Zhou et al. (2007))	20 (18.69)
		18 (16.82)
		21 (19.63)
II.9 Ranking of units (167/6.50/2.72)	Provide a full rank scaling Friedman and Sinuany-Stern (1997)	46 (27.54)
	Determine the meaningful variables in an analysis conducted	43 (25.75)

(continued on next page)

Table B.2 (*continued*)

DEA methodological contributions (2569 citations/42% of DEA publications)		
Cluster name (s.a.number each cluster is cited/% of cites in proportion to methodical DEA contributions (II) /% of cites in proportion to all DEA publications stated in the clusters (I and II))	Research topic	Amount each article is cited (% of cites in proportion to each cluster)
	with DEA Friedman and Sinuany-Stern (1998)	
	Academic departments, cluster analysis, new efficiency measures Sinuany-Stern, Mehrez, and Barboy (1994)	52 (31.14)
II.10 Chance constraints (184/7.16/3.00)	Chance constrained efficiency evaluation Olesen and Petersen (1995)	67 (36.41)
	Chance constrained programming Cooper, Deng, Huang, and Li (2002)	30 (16.30)
	Joint chance constraints are implemented Cooper, Huang, and Li (1996)	54 (29.35)
II.11 Super-efficiency (78/3.04/1.27)	Implications of the infeasibility in super-efficiency models and the potential to fully rank DMUs Chen (2005) and Xue and Harker (2002)	20 (25.64)
	New and modified super-efficiency models are introduced Chen (2004) and Lovell and Rouse (2003)	18 (23.08)
		19 (24.36)
		21 (26.92)

Table B.3
Groups of highly cited SFA references – sectoral contribution – III.

SFA sectoral contributions (1051 citations/62% of SFA publications)		
Cluster name (number each cluster is cited/% of cites in proportion to sectoral SFA contributions (III)/% of cites in proportion to all SFA publications stated in the clusters (III and IV))	Research topic	Amount each article is cited (% of cites in proportion to each cluster)
III.1 Banking sector (299/28.45/17.62)	The effect on efficiency of: Capital strength and non-performing loans in the balance sheet Girardone, Molyneux, and Gardener (2004)	23 (7.69)
	Privatization of banks Kraft, Hofler, and Payne (2006)	14 (4.68)
	Foreign ownership (differences in institutional quality and institutions between the host and the home country) Lensink, Meesters, and Naaborg (2008)	27 (9.03)
	Macroeconomic and financial sector conditions Kasman and Yildirim (2006)	20 (6.69)
	Changes in bank governance Williams and Nguyen (2005)	30 (10.03)
	Foreign bank entry Sturm and Williams (2004)	38 (12.71)
	Temporal, ownership and random noise component Bhattacharyya et al. (1997)	103 (34.45)
III.2 Insurances companies (IC) (34/3.24/2.00)	Firm size and market structure of IC Fenn, Vencappa, Diacon, Klumpes and O'Brien (2008))	15 (44.12)
	Effect of cost efficiency on the profitability of IC Greene and Segal (2004)	19 (55.88)
III.3 Container ports (182/17.32/10.72)	Private sector, deregulation policies Cullinane and Song (2003)	35 (19.23)
	Additionally port size Cullinane, Song, and Gray (2002))	37 (20.33)
	DEA and SFA to compare results of important influential factors as for example private sector involvement Cullinane et al. (2006)	54 (29.67)
	Private sector involvement Tongzon and Heng (2005)	56 (30.77)
III.4 Hospital/health care sector (114/10.85/6.72)	Different depths are analyzed: Reviewing 317 published articles Hollingsworth (2008)	30 (26.32)
	Best practice results of 20 SFA studies are compared against previously used methods Rosko and Mutter (2008)	13 (11.40)
	Statistical analysis Simar (1996)	26 (22.81)
	Review of empirical techniques and selected applications Worthington (2004)	29 (25.44)
III.5 Agriculture (253/24.07/14.91)	Concentrating on agriculture, various types of measurement techniques are analyzed and compared: Different types of efficiency Sharma et al. (1999)	47 (18.58)
	Exogenous influences Wadud and White (2000)	46 (18.18)
III.6 Fishery (169/16.08/9.96)	As the references show this cluster is almost similar to the one stated for DEA. Hence a comparison of methods lies in the foreground: Fixed or variable inputs, different methods Tingley et al. (2005))	23 (13.61)
	Different output compositions Herrero and Pascoe (2003)	16 (9.47)
	Comparison of methods and managerial skills Herrero (2005)	15 (8.88)
	Managerial skills Kirkley, Squires and Strand (1995) and Kirkley et al. (1998)	52 (30.77)
		49 (28.99)

Table B.4
Groups of highly cited SFA references – methodical contribution – IV.

SFA methodological contribution (646 citations/38% of SFA citations)		
Cluster name (number each cluster is cited/% of cites in proportion to methodical SFA contributions (IV)/% of cites in proportion to all SFA publications stated in the clusters (III and IV))	Research topic	Amount each article is cited (% of cites in proportion to each cluster)
IV.1 Bayesian analysis (288/44.58/16.97)	Application and findings of reduced computational difficulties – Osiewalski and Steel (1998)	14 (4.86)
	Monte Carlo and Gibbs sampling Koop et al. (1997)	73 (25.35)
	Comparison between classical and Bayesian approaches Kim and Schmidt (2000)	23 (7.99)
	Gibbs sampling methods for posterior inferences in SFA Koop, Osiewalski, and Steel (1995)	41 (14.24)
	Panel data Fernandez, Osiewalski, and Steel (1997)	47 (16.32)
IV.2 Neural-network-based model (98/15.17/5.77)	New approach Wang (2003)	20 (20.41)
	Better performance of neural-network approaches compared to conventional methods Azadeh, Ghaderi, Anvari, Saberi and Izadbkhsh (2007b) and Azadeh et al. (2007a)	22 (22.45)
		18 (18.37)
IV.3 Heterogeneity (260/40.25/15.32)	Examining several approaches on data from:	64 (24.62)
	The World Health Organization Greene (2004)	66 (25.38)
	U.S. banking industry Greene (2005b) and Greene (2005a)	93 (35.77)
	Swiss railway companies Farsi, Filippini, and Greene (2005)	17 (6.54)
	Regional bus companies Farsi, Filippini, and Kuenzle (2006)	20 (7.69)

Appendix B

The data set used in this study can be downloaded at bit.ly/1nMAokL for DEA and at bit.ly/QECqbV for SFA.

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