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A survey of DEA applications

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ABSTRACT

The literature of data envelopment analysis (DEA) encompasses many surveys, yet all either emphasize methodologies or do not make a distinction between methodological and application papers. This study is the first literature survey that focuses on DEA applications, covering DEA papers published in journals indexed by the Web of Science database from 1978 through August 2010. The results show that on the whole around two-thirds (63.6%) of DEA papers embed empirical data, while the remaining one-third are purely-methodological. Purely-methodological articles dominated the first 20 years of DEA development, but the accumulated number of application-embedded papers caught up to purely-methodological papers in 1999. Among the multifaceted applications, the top-five industries addressed are: banking, health care, agriculture and farm, transportation, and education. The applications that have the highest growth momentum recently are energy and environment as well as finance. In addition to the basic statistics, we uncover the development trajectory in each application area through the main path analysis. An observation from these works suggests that the two-step contextual analysis and network DEA are the recent trends across applications and that the two-step contextual analysis is the prevailing approach.

1. Introduction

The value of data envelopment analysis (DEA) lies in its capability to relatively evaluate the individual efficiency or performance of a decision making unit (DMU) within a target group of interest that operates in a certain application domain such as the banking industry, health care industry, agriculture industry, transportation industry, etc. All these industries practically adopt DEA for a variety of reasons, as Golany and Roll [85] pointed out that it can be applied to: identify sources of inefficiency, rank the DMUs, evaluate management, evaluate the effectiveness of programs or policies, create a quantitative basis for reallocating resources, etc. Some 30 years after the publication of the influential paper by Charnes et al. [1], the application domain for DEA has grown to such an extent that almost no one in the DEA research community is able to keep track of its development and in particular on how widely DEA is applied to real world applications.

Most previous general literature surveys for DEA place their emphasis on the methodologies, as the following examples show. Seiford and Thrall [2] reviewed early-stage DEA development. Seiford [3] traced the evolution of DEA for the period 1978 through 1995. Cooper et al. [4] evaluated some DEA models and measures. Cook and Seiford [5] performed a comprehensive survey on 30 years of DEA developments since 1978. Liu et al. [6] conducted a citation-based survey and depicted the main DEA development paths. All these surveys have elaborated on methodological topics such as generic DEA models, network models, multiplier restrictions, considerations on the status of variables, data variation, etc.

As we are aware of, the literature offers no survey in regards to the development of DEA applications. The closest comments in the literature on how DEA is applied are: "In total, 67%[1] of the (DEA) articles presented a real-world application" [7] and "Banking, education (including higher education), health care, and hospital efficiency were found to be the most popular application areas" [8]. These comments provide some information, yet a more extensive survey is needed in order to benefit DEA researchers and practitioners. After all, the main purpose for developing the DEA method is to apply it.

In the development of any discipline, assessing what has been done can provide practical information in setting up strategies ahead of the next stage for various types of researchers. For

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[1] We believe that the author meant 57% and that 67% is a typographical error.

example, basic statistics such as the number of application papers suggest the overall usefulness of the developed methodology. Theoreticians may need to find ways to improve their methods upon seeing that they are not frequently applied. Other statistics such as the major application area can inspire theoreticians to develop methods to specifically meet the needs of these areas. In addition, information on how each individual model was applied in applications indicates the trend in methodology adoption and thus helps users of the methods to catch up with the latest technology. A newcomer to a discipline would certainly be eager to know the set of "must read" papers to determine his/her research direction in that discipline.

The purpose of this study is to provide the above statistics and information in the DEA application area through a rigorous analysis. We pursue the answers to the following questions: What is the proportion of application papers in the DEA literature? Exactly how widely is DEA applied to real world applications? What are the major DEA applications? What is the trend of the methodological approach for each application area? Lastly, what are the development trajectories for each application area? Through these research questions, this study contributes to the DEA literature in three major aspects. First, it differentiates between methodological articles and application articles and provides basic statistics on application articles, in contrast with previous similar studies [7,8] that present statistics on the whole set of DEA literature. Second, it provides information on the most-cited methodological works in each application area. Third, through the main path analysis, it identifies papers that stand out in the important historical development path of each major application area.

In order to answer these questions, we classify a set of DEA papers into methodological and non-methodological works and then further segment the empirical works based on the real world problem that is discussed, tested, and validated within each work. After the classification, the basic statistics are summarized. We then present a list of the most-cited methodological papers for each of the five most popular application areas. In the end, the citation-based main path analysis as described in Liu et al. [6] is applied to these five most popular application areas to uncover their development trajectories.

This paper is organized as follows. In the next section we describe the dataset and the method of analysis. Section 3 discusses the basic statistics for the DEA applications. Section 4 presents the most-cited methodological works for the five major DEA applications. Section 5 introduces the main paths of the five most popular application areas. The last section draws conclusions, including implications and insights from the analysis results.

2. Data and methodologies for analysis

2.1. Data

The data we adopt to start the analysis are the same as that collected in the previous survey [6], consisting of 4936 DEA papers carefully retrieved from the ISI Web of Science (WOS) database. WOS is the world's leading citation database with multi-disciplinary coverage of over 10,000 high impact journals in science, social sciences, as well as international proceedings for over 120,000 conferences. Databases within WOS selected for this study are science citation index expanded (SCIE), social sciences citation index (SSCI), conference proceedings index-science (CPI-S), and conference proceedings index-social science and humanities (CPI-SSH). The data were retrieved in August 2010 and the begin time is set to 1978, which is the year Charnes et al. [1] published their paper. The data contain virtually all types of studies on DEA, whether theoretical or empirical, single or multilevel models, fixed or time series data, certain or uncertain data, etc.

We next conduct a selection process to obtain data suitable for further analysis. Since the focus of this study is DEA application, our goal is to choose papers that contain real world applications and separate them from methodological papers. An issue was encountered immediately: many DEA papers touch on both methodologies and real world problems. In fact, as indicated in Gattoufi et al. [9], there are basically three types of DEA papers: purely-methodological, application-centered, and theory-together-with-empirical-data. The first type, purely-methodological, elaborates on mathematics and models, but does not relate to empirical data, although occasionally some simulated data are used to test the theory. Examples are Banker et al. [86], who presented only mathematics, and Tone [87], who illustrated the proposed model with a set of artificial data. The second type, application-centered, applies an already developed approach to a real world problem. The focus is mainly on application. Examples are Karkazis and Thanassoulis [88] and Ma et al. [89], who applied existing DEA models to study the efficiencies of Greece's public investment and China's iron and steel industry, respectively. In-between the two extremes is the third type, theory-together-with-empirical-data. This type proposes a methodological innovation and then validates or tests the proposed method with a set of empirical data. It may put strong emphasis on the application or simply adopt a previous empirical data to test the model. Examples for the former case are Sahoo and Tone [90] and Kao and Huang [91], whereas for the latter include Cook and Zhu [92] and Chen et al. [93]. The contribution to the theory also varies widely in these studies. Practically, it is not easy to differentiate between the second- and the third-type works as there is a wide spectrum on how the authors balance the weight between the models and applications. In the screening process, we label both of them as application-embedded papers. Thus, our main research target is application-embedded papers, which include both application-centered and theory-together-with-empirical-data papers.

After screening out the purely-methodological papers, the next step is to classify the application-embedded papers. Gattoufi et al. [9] proposed a taxonomy scheme for the DEA literature, where there are four main classes. Each class is based on keys of data source, type of frontier, the purpose of analysis, and the nature of study, respectively. To keep the matter simple, this taxonomy scheme is not followed herein. We classify the set of papers simply according to the industry to which the real world problem belongs. These industries can be banking, health care, agriculture, transportation, etc. Some papers specifically address management issues in a specific industry—for example, supply chain management, human resources management, technology management, etc.; some address these issues without mentioning an industry. We classify the former type of papers according to the industry mentioned and the latter type to the special category "disciplines", because the latter type's focus is on management disciplines and no specific industry can be identified.

It is rather tempting to automatize the selection and the classification process with computer tools. Nevertheless, we recognize the importance of this study and would rather keep the results as genuine as possible. We also believe that human judgment is better than a computer in this regards. Therefore, each paper is hand-picked and classified by one of the authors. The classification work is time consuming, but it definitely makes the results of this study more trustworthy.

2.2. Methodologies

In addition to counting the papers, this study uses paper citation information in three ways. First, we compute the

h-index/*g*-index [10,11] of journals that publish DEA application papers to determine their influence. Second, for each methodological paper we count the citations it receives from other papers in each of the five major applications. This helps us comprehend how methodological works were used in each of the five major DEA applications. Third, we obtain the main paths for each application to highlight the well-recognized application-embedded papers in that area.

Main path analysis is one form of citation analysis that works on citation networks. Citation networks are constructed by observing the citation relationships among the documents in a target discipline, in which a node represents a document and a link indicates citation relationships among any two nodes. A link's direction points from the cited document to the citing document. This convention indicates that knowledge in the cited document disseminates to the citing document. The method has been applied to several science and technology disciplines to uncover their development trajectories, or from a different perspective, knowledge flow paths [6,12,13]. The best feature of the method is that it simplifies a complicated citation network by extracting out important paths in the network. It is like providing a bird's-eye view to the citation network, in which only significant paths remain and paths of lesser significance disappear.

We use a simple citation network in Fig. 1 to demonstrate how the method works and in particular how the weight (search path count, SPC) for each individual link in a citation network is calculated. One defines a 'source' as a node that is cited, but cites no other nodes; and a 'sink' as a node that cites other nodes, but is not cited. In other words, sources are the origins of knowledge, while sinks are the end points of knowledge dissemination. The network in Fig. 1 has two sources, A and B, and four sinks, C–F. There are many alternative paths to go from the sources to the sinks. Assuming that one exhausts all efforts in searching out all paths from all the sources to all the sinks, the SPC for each link is defined as the total number of times the link is traversed. For example, link J-C has SPC value of 2, because paths A-H-J-C and B-H-J-C pass through it. Link B-I's SPC value is 4 as it is traversed by 4 paths: B-I-F, B-I-G-D, B-I-G-E, and B-I-E. In the example network, B-I and H-J have the largest SPC value. The larger the SPC value is, the more significant the link's role is in transmitting the knowledge.

After SPCs for all the links are calculated, Hummon and Doreian [12] suggested to begin the main path search from all the sources by applying the "priority first search" algorithm, which has that, at any node, one always chooses the next link in the path with the highest SPC as the outgoing link. By applying the choice rule repeatedly until hitting a sink, a main path is constructed. The resulting main paths for the simple citation network are B-I-G-E and B-I-G-D. One notices that the main paths begin with B-I, because it is the link with the largest SPC value among all links emanating from all the sources.

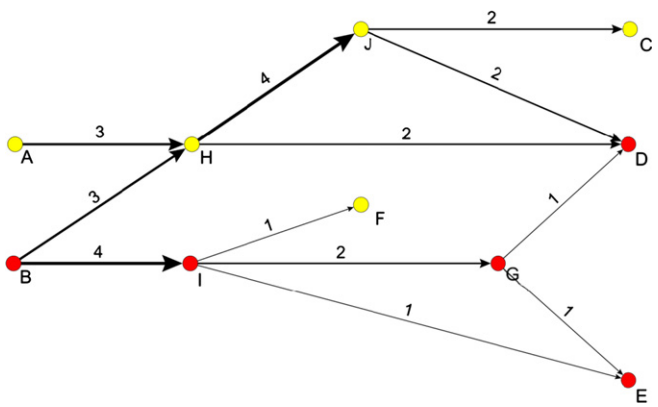

Fig. 1. A simple citation network example.

Liu et al. [84] extended their method in several ways, in particular suggesting a different type of main path called the key-route main path. Unlike the "priority first search" method, the key-route main path is constructed by first selecting the link(s) with the largest SPC values as the key-route(s); then searching forward from the end node of the key-route(s) until a sink is hit; next searching backward from the start node of the key-route(s) until a source is hit. The procedure guarantees that the "key-routes" are included in the main paths. A nice feature of the scheme is that one is able to 'zoom' in or out to examine different levels of detail by selecting the number of key-routes. The more key-routes selected, the greater is the detail observed of the paths. In this study we use the key-route main paths to trace the development trajectories of several DEA application areas.

On the main paths are works that stand out at an important juncture of the historical development of a field. Many of them have very high citation counts, especially those published in the early stage of the field development. However, a high citation count does not guarantee a position on the main path, because the citation count presents only direct influences, whereas the main path analysis also takes indirect influences into account.[2]

3. Basic statistics

DEA started out as a theoretical method and then found its way into a broad spectrum of applications. Along the course of its development, its methodological extension has seemed to endlessly discover a burgeoning amount of new areas and new applications. Our analysis shows that among the total of 4936 papers, 36.5% (1802) are purely-methodological and 63.5% (3134) are application-embedded, or roughly one-third purely-methodological and two-third application-embedded. Please keep in mind that purely-methodological papers are those that do not include real world empirical data and application-embedded papers are those that do.

This one-to-two ratio between types is not how it was during the early stage of the DEA evolution. Purely-methodological articles outnumbered application-embedded papers in the first 20 years of the development. It was not until 1999 that the accumulated number of application-embedded papers caught up to the number of purely-methodological papers. The rapid growth of application-embedded papers may very likely be caused by the availability of software tools. Fig. 2 shows the growth trend of both categories.

Table 1 lists the applications in order according to their total number of application-embedded papers. It provides answers to the following two research questions: How widely is DEA applied to real world applications? What are the major DEA applications? A total of 24 types of applications have at least 20 published papers in the WOS database. The types of industry these applications address range from traditional industries such as agriculture and manufacturing to modern industries such as software, e-business, etc. According to the total number of application-embedded papers, banking ranks number one, followed by health care, agriculture and farm, transportation, and education. These five applications make up 41.0% of all application-embedded papers. As to why certain application areas gain more popularity than the others, we suggest three possible causes. First and most is the

[2] Consider three papers A, B, and C, where paper C cites paper B, and paper B cites paper A. The influence of paper B on paper C is direct and obvious, whereas the influence of paper A on paper C is indirect and less obvious. The main path method takes the indirect influence of paper A on C into account.

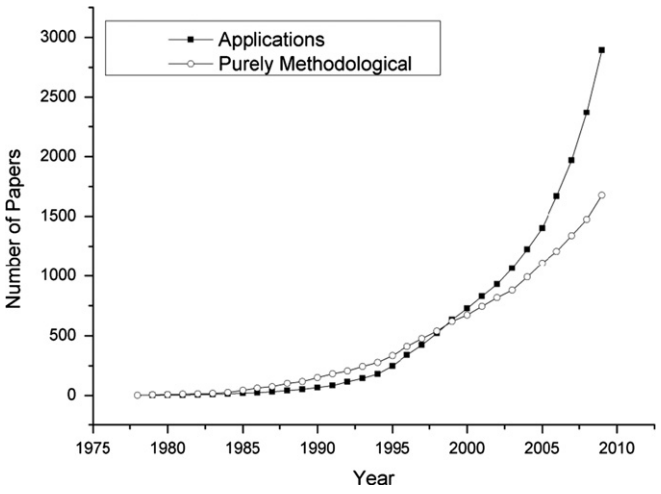

Fig. 2. Accumulated number of purely theoretical and application DEA papers.

Table 1
Number of papers for DEA applications.

Real world applications	Total no. of papers	Percentage (%)	No. of papers 2005–2009	Fraction of total papers (%)
Banking	323	10.31	147	45.5
Health care	271	8.65	107	39.5
Agriculture & farm	258	8.23	140	54.3
Transportation	249	7.95	131	52.6
Education	184	5.87	75	40.8
Power	156	4.98	87	55.8
Manufacturing	146	4.66	75	51.4
Energy & environment	109	3.48	75	68.8
Communication	70	2.23	28	40.0
Finance	51	1.63	33	64.7
Insurance	44	1.40		
Tourism	42	1.34		
Petroleum	41	1.31		
Fishery	39	1.24		
Sport	31	0.99		
Construction	29	0.93		
Automobile	28	0.89		
Retailing	28	0.89		
Forestry	27	0.86		
Water	27	0.86		
Real estate	25	0.80		
Software	25	0.80		
E-business	22	0.70		
Mining	22	0.70		
Miscellaneous	351	11.20		
Disciplines	536	17.10		

Note: The table lists only industrial applications with 20 or more number of papers; applications otherwise are labeled as miscellaneous or disciplines. Under the item miscellaneous are industrial applications with less than 20 papers. The item disciplines includes papers focusing on topics such as supply chain management, human resources management, operations management, technology management, logistics, government, development, etc. without referring to specific industries. Percentage represents the fraction of the non-theoretical papers (total 3134).

need for performance measurement. Several application areas, for example, banking and health care, have a strong need either from government or from individual organizations to check the effect of their policies. Second, data accessibility makes a lot of difference. Researchers who need empirical data to prove their models may take a more convenient path to obtain data. Some of the application areas, banking for example, certainly have better data accessibility than other applications. Third, the support of application journals also plays a role. For example, banking applications have good support from one of the top journals in its discipline. Journal of Banking & Finance has published a relatively large number, a total of 40, of DEA application articles and also published the first DEA application article on banking [14].

Some applications such as education and health care blossomed in the early days of DEA, while other applications, on the other hand, have just begun to apply DEA fairly recently. In general, all applications show a growing trend, but for the last several years not all applications have the same growth momentum. The two right-most columns of Table 1 display the number of papers and its fraction for the top 10 applications during the period 2005–2009. Among the top 10 applications, health care, education, and communication take up relatively small percentages of new papers than the others in this time frame. In contrast, the recent growth in energy and environment and finance papers is at a pace faster than the other application areas. This hints that they may become the next areas of focus for DEA applications.

One may also be interested in answering the question of where these application articles are published. Table A.1 in Appendix A[3] lists the top 20 most influential journals that publish DEA application articles. The journals are listed in order according to their *g*-index, followed by *h*-index and the total number of articles. The top five journals are: *European Journal of Operational Research*, *Management Science*, *Journal of Banking & Finance*, *Journal of Productivity Analysis*, and *Omega-The International Journal of Management*.

The list also includes the percentage of application articles among all DEA articles. All the top five journals, with the exception of *Journal of Banking & Finance*, have a balanced proportion of purely-methodological and application-embedded articles. Several application-oriented journals, such as *Journal of Banking & Finance*, *Transportation Research Part A-Policy and Practice*, *Medical Care*, *Transportation Research Part E-Logistics and Transportation Review*, *Energy Policy*, *Agricultural Economics*, *Health Services Research*, and *Energy Economics*, publish only application papers. It should be noted that, among the top ten journals, only one journal, *Journal of Banking & Finance*, is application specific. The rest are a general type of journal.

4. Most-cited methodological works for the five major applications

Methodological works provide the base for DEA applications. This section discusses how methodological works were used in each of the five major DEA applications. We do a simple count for each methodological paper on the citations it received by each of the five major applications. For each of the five major applications, we then pick the two most cited methodological papers published each year (since 1978). To make sure that the paper has some significance, we keep only those papers with an overall citation number greater than 2 and an application-specific citation number greater than 1. Appendix B presents the results, listing important methodological works year by year and application by application. Appendix C lists a complete summary of these methodological papers.

The two most-cited methodological papers each year for each application are virtually the same, especially in the early years of DEA's evolution. Although no obvious preferences for each of the applications are observed, a general trend for the adoption of certain methodological approaches across applications does exist. Works related to network DEA and two-step contextual analysis

[3] Appendices are put separately as electronic supplementary material.

are repeatedly cited by empirical works across all applications in recent years.

5. Development paths of the five major applications

This section presents the main development trajectories of the five major DEA applications. For each application, we present the local key-route main paths. All the paths shown are drawn with Pajek software [15]. In the figure the arrow indicates the direction of knowledge flow, and the line thickness reflects the SPC value. The thicker the line is, the more significant the route is. In the following subsections, we briefly note the content of each paper located on the main paths. As we shall see, many of the papers on the main path are those that initiate new research directions through applying a new method or proposing a new concept.

5.1. Banking

Fig. 3 presents the key-route main paths for the banking application. All papers on the main paths study the performance of banks in countries all over the world. Nevertheless, the DEA models they use and the foci of their studies vary.

The leading paper on the main path, Sherman and Gold [14], is the first paper that applies DEA to study bank efficiency [16]. It used the classical CCR model [1] to compare operating efficiencies among 14 branch offices of a savings bank. Their claim, that DEA results provide meaningful insights not available from other techniques, invited a series of subsequent DEA studies. Parkan [94] is another early work that examined the efficiency of branches of a Canadian bank. A significant work following Sherman and Gold [14] is Rangan et al. [18], which was the first to introduce the two-step contextual DEA method to the banking application.

Three studies follow Rangan et al. [18] – Elyasiani and Mehdian [19], Berg et al. [20], and Berg et al. [21] – and attempt to examine the efficiency changes in time. Among them, Berg et al. [20] and Berg et al. [21] applied the Malmquist index to study banks' productivity growth in Norway and Nordic countries.

A subsequent work, Favero and Papi [22], studied 174 Italian banks with the two-step contextual method. Thompson et al. [23] introduced several assurance region (AR) concepts to the banking study.

Berger and Humphrey [24] and Thanassoulis [25] motivated researchers by reflecting on the development of DEA in the banking application. Berger and Humphrey [24] was a survey study and Thanassoulis [25] was an introductory type of article that elaborated on banking issues that have been addressed and can be addressed in the future through DEA.

The last three studies – Seiford and Zhu [30], Luo [31], and Lo and Lu [32] – are similar in that they all applied the two-stage process concept to a banking study. Bank operation is separated into profitability and marketability stages, and efficiencies in both stages are evaluated thoroughly and separately.

The studies on the main paths overall reflect the methodological development of DEA. The method adopted appears in sequence from the classical CCR model, to the two-step contextual DEA, to the Malmquist index, then to AR DEA, etc. The forefront of the studies, as indicated by the last three studies on the main path, emphasize the two-stage production process, which is a basic form of the network DEA model.

5.2. Health care

Fig. 4 shows the main paths of the health care application. With few exceptions, most of the papers on the main paths studied hospital performance, although nursing homes, primary care, and care programs are among many other subjects of study.

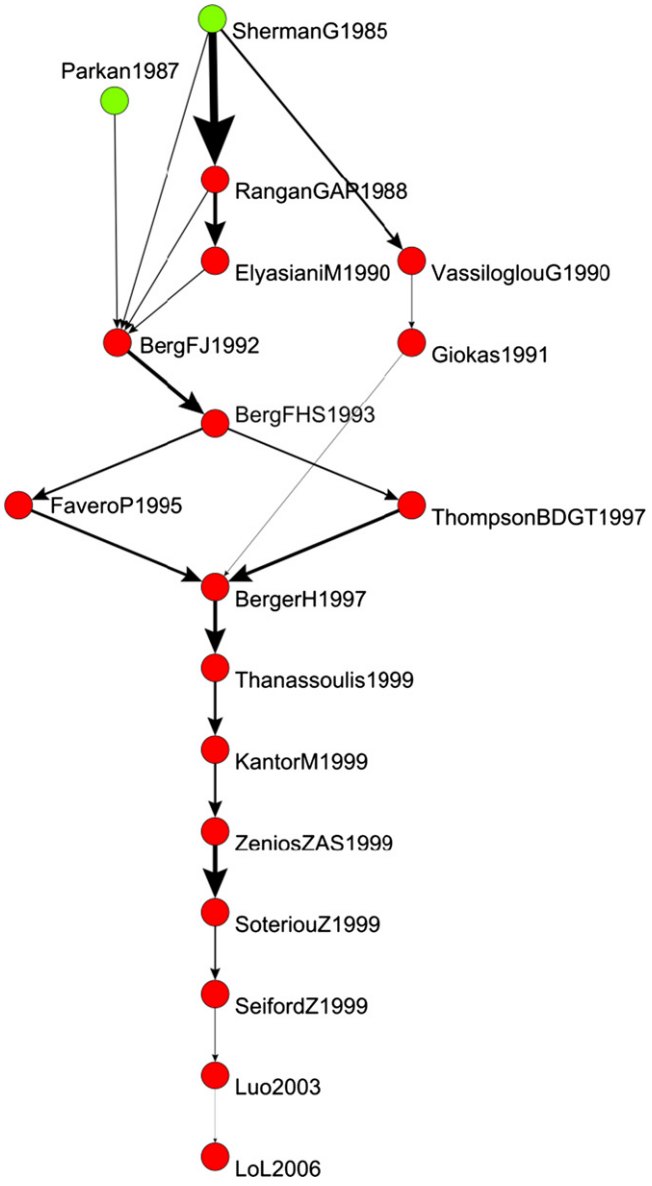

Fig. 3. Banking main paths. Link weights are indicated with different line thickness. Thicker lines indicate heavier weights. The network is drawn with Pajek software.

Two independent studies, Nunamaker [39] and Sherman [35], lead the DEA study in the health care area. Nunamaker [39] was the first published paper in this category, focusing on nursing service efficiency. Sherman [35] began as early as 1981 [36], but was not published until 1984. The study 'tested' DEA by applying it to a group of teaching hospitals and concluded that "DEA is, therefore, suggested as a means to help identify and measure hospital inefficiency …"

Several studies on the main paths are concerned about method comparison. Banker et al. [95] applied and compared the translog and DEA models using a sample of North Carolina hospitals. Linna [43] and Giuffrida and Gravelle [33] investigated the efficiency of hospital and primary care services, respectively, with both the DEA and stochastic frontier analyses. Two studies close to the end of the main paths are a survey type of literature. Worthington [46] reviewed the health care literature that applies frontier

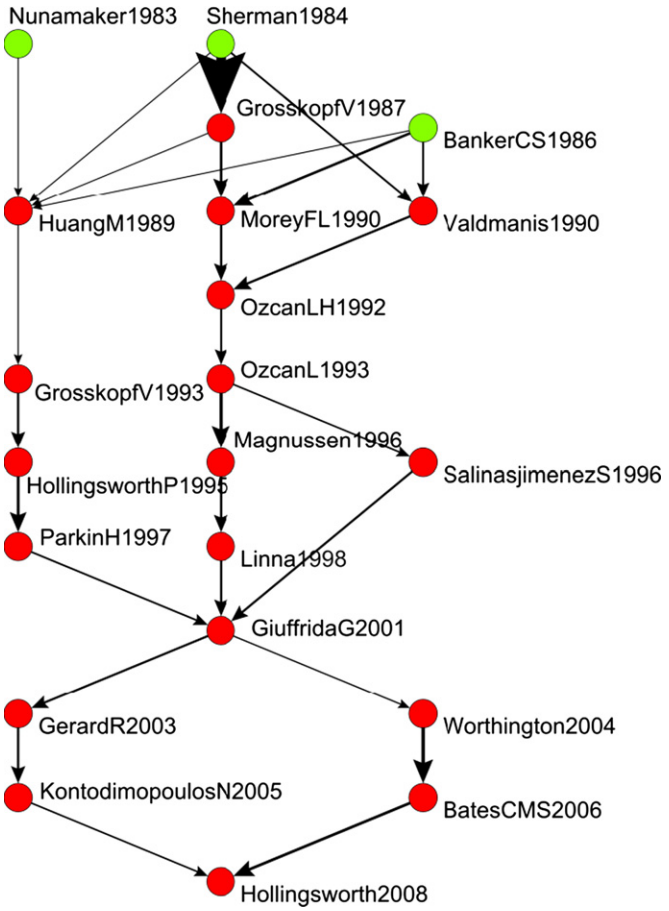

Fig. 4. Health care main paths. Link weights are indicated with different line thickness. Thicker lines indicate heavier weights. The network is drawn with Pajek software.

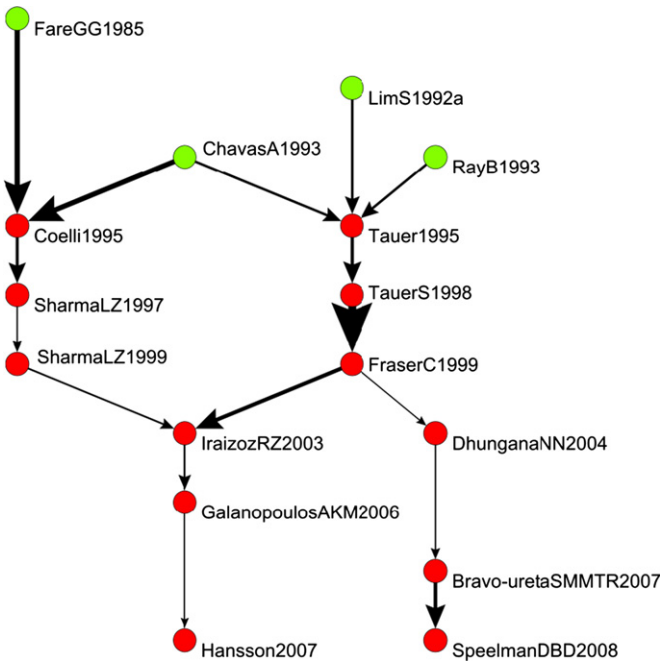

Fig. 5. Agriculture and farm main paths. Link weights are indicated with different line thickness. Thicker lines indicate heavier weights. The network is drawn with Pajek software.

efficiency measurement. Hollingsworth [34] summarized the latest development of DEA application in the health care category.

Overall, as pointed out in Hollowgsworth [34], the techniques used in efficiency studies in the health care area are mainly based on DEA, but there is some usage of parametric stochastic frontier analysis, which is outside the scope of this study.

5.3. Agriculture and farm

From the main paths shown in Fig. 5, we can see that there are two quite different paths separately applying DEA to the agriculture sector before merging to Iraizoz et al. [48].

One of the knowledge disseminating paths begins from the emergence of studies by Fare et al. [55] and Chavas and Aliber [50] to that of Coelli [56]. Fare et al. [55] was the first study to apply the frontier concept to investigate agriculture economics. Ceolli [56] surveyed the literature on the estimation of frontier functions and the measurement of efficiency and proposed their potential applications in agriculture economics. Sharma et al. [57] and Sharma et al. [58] used DEA and the stochastic frontier production function to measure the productive efficiency of the swine industry in Hawaii. They suggested that, DEA is more robust in measuring the efficiencies than the parametric approach.

The other knowledge-disseminating path starts in the early 1990s where several works, such as Lim and Shumway [49], Chavas and Aliber [50], and Ray and Bhadra [51], applied DEA to the agriculture sector to identify whether economic efficiency is coming from scale or scope efficiency, or from minimizing costs or maximizing profits. The subsequent works of Tauer [52], Tauer and Stefanides [53], and Fraser and Cordina [54] investigated efficiencies of dairy farms. The above two paths merge to Iraizoz et al., which assessed the technical efficiency of horticultural production in Spain.

Close to the end of the paths, Dhungana et al. [96], Speelman et al. [60], Galanopoulos et al. [61], and Hansson [62] all applied the two-step contextual analysis in which Tobit analysis is applied after efficiency evaluation to detect the environmental factors that are correlated to the efficiencies. This indicates that the two-step contextual analysis is gradually becoming a trend in the agriculture and farm area.

5.4. Transportation

Under the transportation category, the main paths – as shown in Fig. 6 – consist of two independent streams of works. All of the works on the left-hand side studied the performance of airlines, airports, or airport authorities. The works on the right-hand side examined the efficiencies of ground transportation systems such as railway and bus.

Schefczyk [63] is the leading article for air transportation, measuring the operational performance of 15 international airlines. This article laid out the model for future efficiency studies on the airline industry. Other articles in this stream applied standard and variations of the DEA model to examine efficiencies. Oum and Yu [66], which studied the efficiency of the railway system in 19 OECD countries, leads the stream for ground transportation systems studies. Subsequent works, with the exception of Cowie and Riddington [97], studied the efficiencies of bus systems. Methodologically, two studies, Gillen and Lall [98] and Barros and Dieke [70], adopted the two-step contextual analysis.

5.5. Education

Education is the application that attracts the most attention in the early days of DEA development. This is probably due to

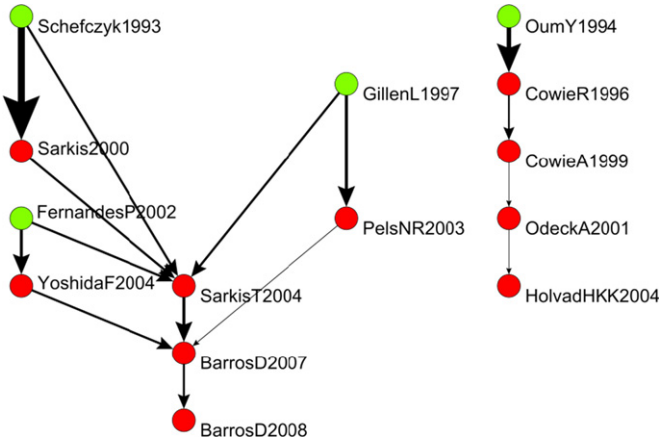

Fig. 6. Transportation main paths. Link weights are indicated with different line thickness. Thicker lines indicate heavier weights. The network is drawn with Pajek software.

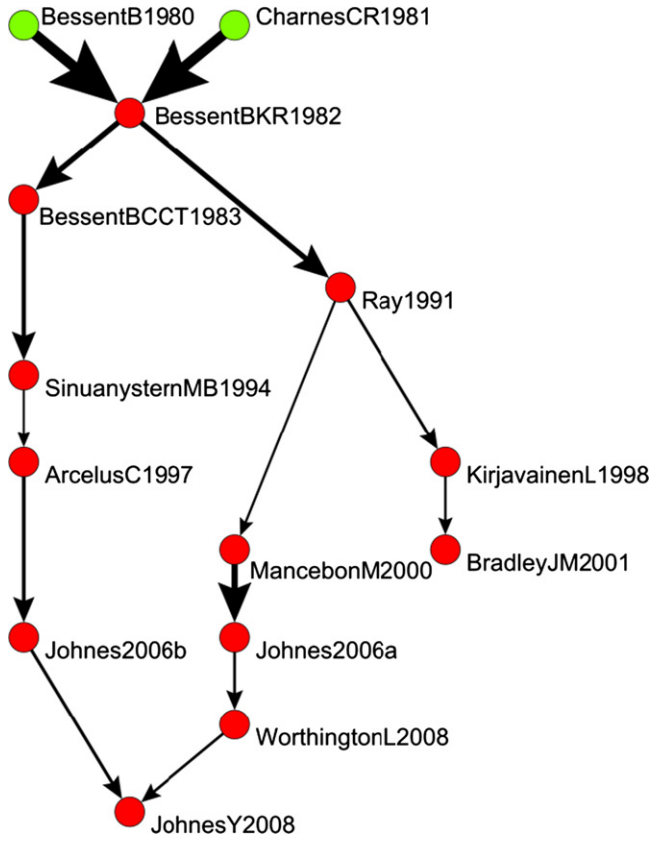

Fig. 7. Education main paths. Link weights are indicated with different line thickness. Thicker lines indicate heavier weights. The network is drawn with Pajek software.

Charnes himself who applied DEA to evaluate the efficiency of program follow through, which is a large-scale social experiment in public school education [72]. From the main paths in Fig. 7, one can see that up through 1983 there are already four important DEA educational studies: Bessent and Bessent [73], Charnes et al. [72], Bessent et al. [74], and Bessent et al. [75]. Charnes et al. [72], Bessent et al. [74] and Bessent et al. [75] are particularly influential, not only to educational applications, but to DEA development in general, as they are all on the main path of grand DEA development [6].

After Bessent et al. [74], there appears to be two streams of literature in the main paths. The one on the left side of Fig. 7 studies the efficiency of higher education. This stream includes Bessent et al. [75], Sinuanystern et al. [76], Arcelus and Coleman [77], Johnes [78], and Johnes and Yu [79]. The other stream examines that of basic education, including Ray [80], Mancebon and Molinero [81], Kirjavainen and Loikkanen [99], and Bradley et al. [100]. Towards the end of this stream, Johnes [82] and Worthington and Lee [83] shift their focus to higher education. The two streams finally merge to Johnes and Yu [79], which measured the research performance of Chinese regular universities.

The recent trend of efficiency studies in the education category clearly focuses on the higher education sector as all articles close to the end of the main paths evaluate the performance of universities. Methodologically, basic education studies show preference for the two-step contextual DEA method. Ray [80], Mancebon and Molinero [81], Kirjavainen and Loikkanen [99] and Bradley et al. [100], all adopted this approach.

6. Conclusion

We have filled a gap in the DEA literature by conducting a systematic survey on DEA applications. This survey covers DEA papers listed in the Web of Science database from 1978 through August 2010. The results show that, during the period, a total of around two-thirds of all DEA studies embed applications, i.e., use real world data as the main subject of study or the target of methodological validation, but this high number was not so in the early days of DEA development. There were more purely-methodological than application-embedded studies in the early days. The fast growth of application-embedded studies in the mid-1990s pushed the total amount of these studies to exceed that of purely-methodological ones in 1999.

This study has identified five major applications: banking, health care, agriculture and farm, transportation, and education. They take up a total of 41.09% of all application-embedded papers. Among all the applications, the highest growth momentum recently has been in energy and environment as well as finance.

A cross citation examination suggests that there are no obvious methodological preferences for each of the five major applications, but a common trend for the adoption of certain methodological approaches across applications does exist. Works related to network DEA and two-step contextual analysis are repeatedly cited by empirical works in all applications.

Three interesting phenomena are observed from the main path analysis on the five major applications. First, there is a pattern of technology-adoption process by DEA application researchers. Early adopters start with the classical DEA models and cautiously suggest the usefulness of the methodology. After DEA is accepted in the field, researchers tend to adopt the newly developed approaches and models once they are available. The phenomenon is particularly apparent in banking and health care applications. Second, two-step contextual analysis is the prevailing approach across applications. A typical two-step contextual study first obtains efficiency scores through DEA and then correlates these scores with various contextual factors through regression analysis. Many papers on the main paths of all five major applications adopt this approach. Third, the two-stage process model, a simple form of the network DEA model and not to be confused with the two-step contextual analysis, has drawn much attention lately across applications.

The interpretation of these survey results should nevertheless take the following limitations into consideration. First, the dataset is from the WOS database and does not include all DEA papers published in journals. Second, papers are categorized manually by one of the authors; some judgmental mistake may occur, but this should be reduced to a minimum. Third, application studies discussed herein include application-centered and theory-together-with-empirical-data papers. Some of them may not be real applications in the sense that there is no engagement put into practice, because one can write a highly theoretical DEA paper and decide whether or not to include an application based on data availability or the author's preference. Furthermore, they may also be duplications of previous studies where the data are used to illustrate a new method as opposed to a new application. Fourth, the results of the main path analysis are subject to citation noise, which is a general limitation of the citation analysis. Finally, each application area is treated as one broad research area. Some of the application areas may be heterogeneous in nature, such that certain development streams of the area are left out by the main path method.

Looking forward, the development on DEA methodologies and applications continue to flourish. Recent innovations on methodologies include DEA with streaming data [101], a general two-stage network DEA based on game approach [102], super-efficiency based on a modified directional distance function [103], and a new slack-based super-efficiency model [104]. On the other hand, there are many innovative applications that adopt new DEA methodologies. These include studies in risk management problems applying three-stage network DEA [105], environment issues using latent variable model and range adjusted measure [106,107], loan quality of bank branches adopting full proportional slack methodology [108], measuring economies of scope with DEA cost model [109], and predicting corporate failure and success through a DEA based assessment index [110]. Interesting works also exist on organizational decision and performance issues that integrate DEA with methodologies such as data mining [111] and balanced scorecard [112]. Further development of DEA requires cooperation between theoreticians and practitioners. Only with the help of theoreticians can practitioners put the method into practice to meet their needs, and with the feedback from practitioners, theoreticians can refine their theories to make further contributions. Currently, many of the DEA models proposed were explored marginally by practitioners. One of the main reasons is that these models are difficult or take time to implement. One suggestion that may help in cooperation inside the DEA community is that theoreticians should attempt to make their models operational and available by providing standalone software or an add-in to existing commercial software such as DEAFrontier [64] and DEA-Solver [65]. This will attract practitioners to use the model, offer feedback on issues of the model, and eventually turn the development process into virtuous cycles.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.omega.2012.11.004.

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