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The tale of two research communities: The diffusion of research on productive efficiency ☆

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Abstract

The field of theoretical and applied efficiency analysis is pursued both by economists and people from operational research and management science. Each group tends to cite a different paper as the seminal one. Recent availability of extensive electronically accessible databases of journal articles makes studies of the diffusion of papers through citations possible. Research strands inspired by the seminal paper within economics are identified and followed by citation analysis during the 20-year period before the operations research paper was published. The first decade of the operations research paper is studied in a similar way and emerging differences in diffusion patterns are pointed out. Main factors influencing citations apart from the quality of the research contribution are reputation of journal, reputation of author, number of close followers; colleagues, "cadres of protégés", Ph.D. students, and extent of network ("invisible college"). Such factors are revealed by the citing papers. In spite of increasing cross contacts between economics and operations research the last decades co-citation analysis reveals a relative constant tendency to stick to "own camp" references.

Keywords: Farrell efficiency measures; Data envelopment analysis; DEA; Bibliometry

1. Background

There is a special relationship between economics and operations research. According to Mirowski (1999) the rise of operations research had an important influence on the development of post second world war economics. A core concept in OR developed during the war was the production function as appearing in neoclassical economics

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(Mirowski, p. 692). When outsiders (engineers, physicists, computer scientists) "invade" a field it is often the case that the "trespassers [are] oblivious of their predecessors" (Mirowski, p. 692). This is a description that applies to how two contributions in the field of efficiency and productivity of production activities are cited in the literature. The two papers, published with a span of 20 years difference, are now both classical;[1] "The measurement of productive efficiency" by Farrell (1957), having 1061 citations in the web-based Social Science Citation Index (SSCI), (http://www.isinet.com) by medio March 2004 and "Measuring the efficiency of decision making units" by Charnes et al. (1978) (CCR), having 1044 (the latter paper will also have many citations in the Science Citation Index, SCI).

The two papers are rooted in two different research environments, economics and operational research or management science (OR/MS). The motivation for the present paper is that there seems to be too little knowledge among OR/MS researchers studying efficiency of the contributions of Farrell and the research inspired by him in the 20 years before CCR (1978) was published, and too little "cross-camp" contacts afterwards, resulting in unnecessary parallel research efforts. However, it is not the objective of this paper to track repetitions or delay in scientific progress. We will prepare the ground for such deeper studies by focussing on the overall diffusion of citations of the two papers and related contributions. The existence now of databases of citations based on the bulk of published journal papers like the SSCI makes it possible to track the diffusion of Farrell and CCR and reveal citation patterns for evidence of cross-camp contacts. The specific purpose of this paper is to document both the broader activity of efficiency analysis of the period between Farrell (1957) and CCR (1978) and the continuing influence of Farrell (1957) after the publication of CCR (1978). The diffusion of Farrell and CCR through citations over time and distribution through journals will be used to give an impression of the scope of diffusion. Special emphasis will be put on the diffusion of Farrell up to the publication of CCR, and the diffusion of CCR the first decade. The researchers citing the two papers will be used to show the responses of OR/MS and economics. The different nature of the diffusion of the two papers will then be revealed. To show the extent and development of cross-camp contacts we will make use of joint citation analysis.

To set the following citation analysis in the right perspective one should be aware of the fact that about $\frac{2}{3}$ of journal papers in general never earn any citations except self citations. Impact factors of journals, i.e., expected number of citations in other journals per journal article per year, and half-life, i.e. estimate of number of years a paper in a journal will be quoted, varies a lot with journals. Citation peaks have been found to be typically 5–7 years after publication, with a long tailing off (see e.g., Price (1976) and Johnson (1997) for studies of diffusion distributions). However, the bulk of the citations of the two papers we are investigating are from the last decade, underlining the observation made by Johnson (1997) that "old capital" should not be depreciated too quickly when measuring influence.

The number of citations does not necessarily measure the "true" value of journal contributions, but papers achieving classical status should have a high probability of having advanced new paradigms, or new methods. With papers of such large impact there is the danger now that their advancement of knowledge has become intrinsic. It is referred to as "obliteration by incorporation" in Zuckerman (1987, p. 331). The key concepts are used without reference, becoming canonical knowledge or household expressions, like *Walras law*, or the *Cobb–Douglas* production function[2] (Johnson, 1997). One could, of course, ask whether it is necessary to refer to seminal classical papers if we only want to signal the use of some concepts or techniques, such as Farrell efficiency measures or the DEA model. However, we take the temerity to suggest that quite a number of papers while just referring to the classics now,

[1] In bibliometrics a paper becomes classical when the number of citations exceeds 500.

[2] This mathematical function was actually introduced to economics by Wicksell (1893), (Grubbström (1995), Sandelin (1976).

would have benefited even more had the authors studied the cited papers. There is the well-known danger of citations following "success breeds success" (Price, 1976), with little real knowledge accumulation signified by the citations.

A word of caution is necessary as to the quality of the SSCI database. It does not encompass all relevant journals, and mistakes and oversights may exist, further complicated by the trivial reason that authors occasionally misspell their references. When using the database it is important to know that it is dynamic in the sense that new journals are included and already included journals updated continuously. Therefore the date of accessing the database must be given.

It was shown in Førsund and Sarafoglou (2002) that main milestones in the efficiency research the first two decades after Farrell (1957) were based on ideas already presented there, although this connection was not so readily recognised. The perspective of this paper is different, focussing not only on the broad picture of diffusion through citations of the two key papers, but also on related milestones up to the present.[3]

The plan of the paper is as follows: In Section 2, we will motivate the need for our study by demonstrating lack of sufficient recognition in many OR/MS papers within the field of efficiency of Farrell and his legacy. In Section 3, the Farrell contributions are briefly reviewed. Section 4 portrays the pattern of diffusion of Farrell over time and also across journals based on citations prior to the publication of CCR. For a comparison the diffusion of citations of CCR for its first decade is also studied in a similar way. The total development of citations up to now is shown for Farrell and CCR and also for some additional papers representing milestones in the development of the field of efficiency studies. In Section 5, explanations for the different patterns of diffusion are offered. In Section 6, the pattern of joint references is investigated to analyse the contacts between the camps and the change in interrelations. Differences in diffusion across types of journals are illustrated. Concluding remarks are offered in Section 7.

2. The neglect by the OR/MS camp

Among OR/MS researchers studying efficiency the general opinion seems to be that the Data Envelopment model or Analysis was introduced by CCR (1978), where the term DEA was coined. Referring to answers from 25 researchers about the most influential DEA publications, Seiford (1996, p. 104) states:[4]

> A few researchers listed Farrell (1957) among the ten most influential papers, while one *more accurately* [our Italics] characterised it as one of the ten least influential!

Gattoufi et al. (2004a, footnote 1) expressed the same sentiment recently:

> There is a widespread agreement that Charnes et al. (1978) represents the "official birth" of DEA.

This point of view also prevails in the International Journal of Production Economics (IJPE), which we will use as an example for an in depth investigation. IJPE is No. 6 (together with Management Science) of 490 journals publishing the most DEA papers in the period 1995–2000 with 26 DEA publications, according to the definition (not explicitly stated) of DEA publications used in Gattoufi et al. (2004c).

The detailed results are shown in Table 1. The 19 DEA papers (defined as entering "DEA" or "data envelopment analysis" among the key words) we found published in IJPE between 1995 (a special issue on DEA appeared in this volume) and 2001 are classified as to whether they refer to Farrell (1957) and/or CCR (1978), and whether Farrell or CCR is cited as the originator of the DEA model. No one refers to Farrell as the originator of DEA and only six (1/3) refer to Farrell at all, although all papers are concerned with calculating or using Farrell efficiency

[3]However, some overlaps may be unavoidable due to self containment, and will be pointed out.

[4]See Sarafoglou (1997) for a bibliometric scrutiny of Seiford's "top ten" list of DEA contributions.

Table 1
References to Farrell (1957) and Charnes et al. (1978) in DEA articles in International Journal of Production Economics 1995–2001[a]

DEA article	Citing Farrell	Farrell original	Citing CCR	CCR original
Banker and Chang (1995)	No	No	Yes	Yes
Bogetoft (1995)	No	No	Yes	Yes
Färe et al. (1995)	No	No	No	No
Gong and Sun (1995)	Yes	No	Yes	Yes
Lovell (1995)	No	No	No	No
Olesen (1995)	No	No	Yes	Yes
Olesen and Petersen (1995)	No	No	Yes	Yes
Thompson et al. (1995)	Yes	No	Yes	Yes
Tulkens and van den Eeckhaut (1995)	No	No	No	No
Hartman and Storbeck (1996)	No	No	Yes	Yes
Ritchie and Rowcroft (1996)	Yes	No	No	No
Chen (1997)	No	No	Yes	Yes
Chandra, Cooper et al. (1998)	No	No	Yes	Yes
Talluri et al. (1999)	No	No	Yes	Yes
Park and Lesourd (2000)	Yes	No	Yes	Yes
Talluri and Yoon (2000)	No	No	Yes	Yes
Homburg (2001)	No	No	Yes	Yes
Uri (2001)	Yes	No	Yes	Yes
Murillo-Zamorano and Vega-Cerevera (2001)	Yes	No	Yes	Yes

[a]Only papers mentioned in the text are entered in the References.

measures in some way or other. All but four of the 19 papers refer to CCR, and cite it as the originator of DEA. Of the four papers, one takes the knowledge of DEA as given (Ritchie and Rowcroft, 1996), one is concerned more about the frontier technology as such (Tulkens and van den Eeckhaut, 1995), one considers only papers from "own circle," although a DEA model is set up (Färe et al., 1995), and one (Lovell, 1995) uses FDH on a macro level (though the Farrell efficiency concept is utilised without reference). Without actually going through all the DEA papers (over 1800) reported in Gattoufi et al. (2004a) we have the feeling that a similar pattern as revealed by Table 1 for IJPE is representative for OR/MS journals.

The DEA papers sampled in IJPE are remarkable in the sense that among the 35 authors we have top ranked DEA writers according to the ranking of "Top twenty" DEA authors per August 2001 in Gattoufi et al. (2004c); No. 1 William Wager Cooper, No. 3 Rolf Färe, No. 5 Shawna Grosskopf, No. 7 C. A. Knox Lovell, No. 8 Rajiv D. Banker, No. 14 Robert M. Thrall, and No. 19 Russell G. Thompson. Within the DEA group of the OR/MS camp neither Cooper nor Banker refers to Farrell. More surprisingly, this is also the case for the economists; Färe, Grosskopf, Lovell and Tulkens. However, they do not refer to CCR either! It is only Thompson and Thrall from the OR/MS camp among the top 20 authors that refer to Farrell, but not as an originator.

3. The contributions of Farrell

Farrell's efficiency concepts are still the basic definitions in use today. The estimation methods for both the non-parametric and parametric frontier introduced by Farrell are the foundation for later contributions. A brief review of Farrell's contributions therefore seems appropriate.[5] The fundamental assumption of Farrell was the possibility of inefficient operations, immediately pointing to a *frontier production* function concept as the benchmark, as opposed to a notion of *average performance* underlying most of the previous econometric literature on the production function.

[5]See also Førsund and Sarafoglou (2002).

Inspired by the activity analysis of Koopmans (1951),[6] he worked with a piecewise linear frontier function technology. Using as a point of departure Debreu (1951), analysing efficient use of resources at a macro level using a "coefficient of resource use," Farrell introduced—at the micro level—a radial contraction/expansion connecting inefficient observed points for production units with (unobserved) reference points on the production frontier as the basis for the measure of *technical efficiency*. Two more measures were defined, the *allocative*, or price efficiency measure showing the inefficiency due to choice of input mix only at existing input prices, and overall efficiency as the product of technical and allocative efficiency.

The illustration of the Farrell efficiency measures is shown in Fig. 1 (Farrell's original figure). The definitions, using the inefficient observation P and measuring relative to the theoretical frontier unit isoquant SS', are:

Technical efficiency: inputs needed at best practice to produce observed outputs relative to observed input quantities, keeping observed input ratios; OQ/OP.

Allocative- or *Price efficiency*: costs of producing observed output at observed factor prices, assuming technical efficiency, relative to minimised costs at the frontier; OR/OQ.

Overall efficiency: costs of producing observed output if both technical efficiency and price efficiency are assumed relative to observed costs; OR/OP = (OQ/OP) (OR/OQ).

In the choice of a production frontier benchmark Farrell adopts a most practical approach, starting with engineering considerations and ending up with recommending observed best practice. He used a *piecewise linear* envelopment of the data as the most pessimistic estimation of the frontier, in the sense of the function being as close to the observations "as possible," as illustrated in Fig. 2 (Farrell's original figure).

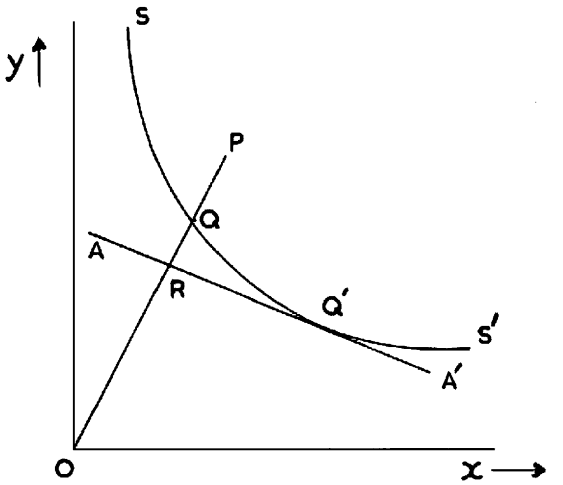

Fig. 1. The definition of Farrell's technical efficiency measures (note that y and x are input coefficients).

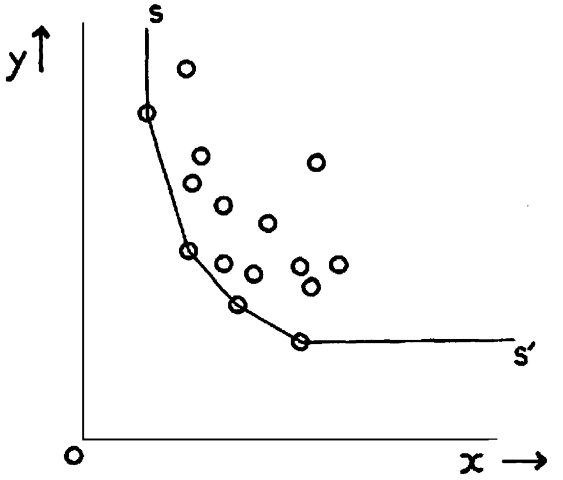

Fig. 2. Estimation of the observed best practice piecewise linear production frontier (unit isoquant SS') (note that y and x are input coefficients).

Concerning the calculation of the efficiency measures Farrell set up a system of linear equations that in principle would yield the efficiency scores also for multiple outputs. However, his empirical application to US agricultural farms on a state level used only a single output, and four inputs. As far as we know the solution algorithm for the multiple output case that he offered has never been tried, may be because in the

[6]Farrell knew activity analysis and Koopmans well from a visit at Cowles Commission 1951–1952, see Farrell (1954). It is interesting to note that Malmquist, Ruist, Cooper, Thrall and Shephard were also visiting the Cowles Commission at around that time.

discussions of Farrell's paper, Hoffman (1957) made the very crucial intervention that the newly developed algorithm for solving linear programmes (LP) could be used. This LP idea was implemented in Farrell and Fieldhouse (1962), but the application was still for the single output case, although the paper indicated how a general multiple output case could be set up.

The key contributions of Farrell concerned the definition of efficiency measures, the specification of the frontier production function and the computational methods for estimation the frontier function and/or the efficiency measures. We will now turn to how these topics were developed in the literature citing Farrell (1957).

4. The diffusion patterns the first decades

4.1. The diffusion of Farrell (1957) prior to CCR (1978)

There seems to be a widespread misunderstanding, and not only in the DEA group of the OR/MS community, that Farrell was forgotten until CCR was published. A typical attitude is expressed by the following quotation:

> The seminal concept of *technical efficiency* was introduced by Farrell (1957). It was the seed for later exploitation, following its rediscovery by Charnes et al. (1978) and subsequent relabelling as "CCR-efficiency" under the broader heading of "data envelopment analysis" (DEA)…."
> Stone (2002, p. 405)

On the contrary Farrell received quite a widespread attention *prior* to the publication of CCR. The number of citations per year, the authors, and the journals were the citations appeared, are set out in Table 2. Economist both from Europe and U.S made early citations of Farrell.

The first citation came in 1959, and was not very enthusiastic, as revealed by the evaluation:

> Mr. Farrell's work has the virtue of making a start—though perhaps a false start—where previously little had been done.
> Hall and Winsten (1959, p. 85)

The next reference was in 1960 by Hicks, and then in 1961 by Ruist.[7] Within the first five years,[8] Farrell received four citations, including one self-citation, distributed on three journals. The next five-year period brought the total number of citations up to nine, distributed on seven journals. The journals having citations the first ten years reflect the heterogeneity of the diffusion, and they are all well reputed (they now have on average high impact factors) like Economic Journal, Econometrica[9] and Review of Economics and Statistics.

Note that an early citation came in 1964 by an OR scientist (Amey), and was, quite interestingly, a consequence of 1963 being officially designated as a National Productivity Year in England. The conference theme of the National Conference of the Operational Research Society was "Productivity Criteria: Their use and abuse". Amey (1964) was read at the meeting. However, this exposure did not create any measurable reaction from the OR community.

The group of researchers citing Farrell (1957) was heterogeneous both regarding nationality and research profile, ranging from econometricians, agricultural economists and mainstream economists to management- and OR scientists. Concerning the latter group it should be remarked that there are only two citations, in 1964 and in 1976. By and large the OR/MS community missed out on Farrell before CCR.

In the first decade the first development of the Farrell approach was by Farrell himself, in Farrell and Fieldhouse (1962). Here the constant returns to scale assumption used in Farrell (1957) was generalised within a single output framework, and a linear programming (LP) format adopted, following the advice by Hoffman in the Discussion (1957).

Agricultural economists at Berkeley picked up Farrell's approach. At a symposium in 1966, the group staged a "Farrell revival" workshop. Five

[7] Ruist (1960) referred to Farrell in a booklet in Swedish covering the same ground as Ruist (1961).

[8] Remember that it takes 5–7 years for an average paper's citations to peak.

[9] But notice that in the survey of Walters (1963) there is only a passive reference to Farrell (1957).

Table 2
Journals with Farrell (1957) citations 1957–1977[a]

Year	Authors	Journal	No. of citations	Cum. no. of citations	Cum. no. of journals
1959	Hall and Winsten[b]	Economic Journal	1	1	1
1960	Hicks[b]	Economic Journal	1	2	1
1961	Ruist[b]	Productivity Measurement Review	1	3	2
1962	Farrell and Fieldhouse	Journal of the Royal Statistical Society-A	1	4	3
1963	Walters	Econometrica	1	5	4
1964	Amey	Operational Research Quarterly	1	6	5
1967	Clague	Review of Economics and Statistics	1		
	Boles, Bressler[b]	Western Farm Economics Association Proceedings	2	9	7
1968	Aigner and Chu	American Economic Review	1		
	Clemhout[b]	Review of Economics and Statistics	1		
	Clemhout[b]	Review of Economic Studies	1	12	9
1970	Seitz	American Journal of Agricultural Economics	1		
	Bessell	Journal of Agricultural Economics	1		
	Nadiri	Journal of Economic Literature	1		
	Nabb	Journal of the Royal Statistical Society-D	1	16	12
1971	Lau and Yotopoulos	American Economic Review	1		
	Seitz, Timmer	Journal of Political Economy	2		
	Førsund	Swedish Journal of Economics	1		
	Pearson and Page	Bulletin of the Oxford University Institute of Economic and statistics	1		
	Merewitz	Journal of the American Statistical Association	1	22	16
1972	Afriat[b]	International Economic Review	1		
	Hanoch and Rothschild	Journal of Political Economy	1		
	Carlsson	Swedish Journal of Economics	1		
		Economic Journal	1	26	17
1973	Yotopoulos and Lau	American Economic Review	1		
	Teague and Eilon	Applied Economics	1		
	Kalish and Gilbert	Journal of Industrial Economics	1		
	Kalish and Gilbert	Journal of Finance	1		
	Leibenstein	Journal of Political Economy	1	31	20
1974	Muller, Lin, Dean and Moore	American Journal of Agricultural Economics	2		
	Caves	Economica	1		
	Levin	Public Finance Quarterly	1		
	Førsund and Hjalmarsson	Swedish Journal of Economics	1		
	Pack	Oxford Economic Papers	1		
	Dunnin	Journal of World Trade	1	38	24
1975	O'Connor and Hammonds	American Journal of Agricultural Economics	1		
	Keating and Keating	Review of Social Economy	1		
	Färe	Zeitschrift für Nationalökonomie	1	41	26
1976	Araji	American Journal of Agricultural Economics	1		
	Ahmed	Economic and Social Review	1		
	Weston	European Journal of Marketing	1		
	Toda	Review of Economics and Statistics	1		
	Goldstein and Ehrenberg	Southern Economic Journal	1	46	29
1977	Shapiro and Muller	Economic Development and Cultural Change	1		
	Todd[b]	Economic and Social Review	1		
	Meeusen and Broeck	International Economic Review	2		
	Førsund and Jansen				
	Sejak	Politicka Ekonomie	1		
	Aigner et al.	Journal of Econometrics	1	52	32

Sources: SSCI ("In print" 1961–1980, CD-ROM 1981–1990, WEB-based 1991–March 2004, http://www.isinet.com), JSTOR: http://www.jstor.org.

[a]Only papers mentioned in the text are entered in the References.

[b]Not in SSCI.

contributions (Boles, Brown, Seitz, Sitorus and Bressler) were published in the symposium volume in 1967, but only two explicitly referred to Farrell's publications (Boles and Bressler). Boles (1967) restated and interpreted the LP formulation in Farrell and Fieldhouse (1962), and gave concrete indications for how a multiple output case could be formulated. He completed this task in a working paper (Boles, 1971), which never made it into a journal paper. As far as we know, it has only been referred to once in a journal article (Hanoch and Rothschild, 1972). As pointed out in Førsund and Sarafoglou (2002) the LP formulation in Boles (1971) is identical to what was later to become known as the "CCR DEA model". A mainframe programme was developed by Boles (1967, 1971) and used by Seitz (1970, 1971).

The next decade saw quite another level of activity regarding citations. The reason is the development of methods for estimating the frontier function introduced by Farrell (1957).[10] The first paper out was Aigner and Chu (1968). The non-parametric approach of Farrell was dropped, but the programming format was kept for the calculation of the parameters of the Cobb–Douglas frontier function (and the efficiency score). The key feature of the formulation of the estimation problem was a *one-sided deviation* from the frontier function. This was handled by inequality constraints on each observation expressing the production function on a logarithmic form. An influential follow-up was Timmer (1971) with a potential link to Charnes and Coopers' concept of chance constraints by introducing a possibility to overshoot the frontier.[11]

Afriat (1972) was the next milestone. He elaborated further ideas from Farrell (1957) and what came up during the discussion of Farrell's paper. A statistical framework was formulated for finding maximum likelihood estimators for the parameters of frontier functions, leaving the pure programming format. But Afriat (1972) also contributed within the non-parametric framework of piecewise linear frontier functions by formulating the model with variable returns to scale (in the single output case). This was later referred to as the *BCC* model (Banker et al., 1984) by the DEA group of the OR/MS community (without reference to Afriat).

A "crowning piece" concerning statistical estimation of parametric frontier functions was the composed error approach, allowing overshooting the frontier due to "white noise," but keeping the one-sided error term capturing inefficiency, published independently at the same time by Aigner et al. (1977) and Meeusen and Broeck (1977).[12]

Developments of the efficiency frontier and efficiency measures themselves were performed in Førsund (1971), Førsund and Hjalmarsson (1974, 1979) in a setting of a general production function exhibiting the "Regular Ultra Passum Law" of Frisch (1965). The input- and the output-oriented efficiency measures and scale efficiency measures needed for the general case of a variable returns to scale (VRS) production frontier were introduced. Färe (1975) pointed out the equality between Shephard's (1953) concept of distance function and Farrell's measure of technical efficiency.[13]

The total number of citations of Farrell (1957) for the 20-year period is 52, distributed over 32 journals. There is a fairly even spread on journals, top journals like Journal of Political Economy and American Economic Review having three citations each, the same as a general journal like Swedish Journal of Economics (later Scandinavian Journal of Economics). It is interesting to note that the first methodological advance came in American Economic Review and then several developments in International Economic Review and first in the last year did a methodological contribution appear in a specialised econometrics journal (Journal of

[10]Notice, however, that Førsund and Sarafoglou (2002) expose a clear lack of explicit appreciation of the ideas in Farrell (1957), and especially the ideas generated by the published discussion of Farrell's paper.

[11]However, his so-called probabilistic approach boiled down to dropping enough frontier observations until a given percentage overshoot was reached.

[12]Meeusen and Broeck (1977) were soon "driven out" of the citation market, illustrating the "Matthew effect". Notice that Battese and Corra (1977) is not a parallel discovery, but refers to Aigner et al. (1977) as pointed out in Førsund and Sarafoglou (2002).

[13]This contribution of Färe (1975) was overlooked in Førsund and Sarafoglou (2002), but they are in good company since Färe and Lovell (1978) also overlooked the paper.

Econometrics). As pointed out earlier agricultural economists was the only group trying to develop the non-parametric approach of Farrell. The citations in agricultural journals numbers eight distributed on three journals, two of them with potentially high impact, thus constituting the most marked sector diffusion of Farrell. Otherwise there is no marked applied profile judging from the involved journals.[14]

4.2. The diffusion of Charnes et al. (1978) the first decade

The CCR (1978) paper had a more rapid diffusion than Farrell (1957), as shown in Table 3.

During the first five years there are 25 references distributed on 16 journals. However, there is a marked presence of self-citations, 8 (32 percent), but this is not so much "advertising" as further development and applications of the method by the originators and their associates. CCR achieved almost as much in the first four years as Farrell did in 11 as regards citations and journal diffusion. During the remaining years of the first decade the citations of CCR and diffusion over journals increased rapidly all years but two, ending up with a total of 79 citations distributed on 44 journals. Notice that the spread on journals is higher with a factor of 1.45 for one decade compared with what Farrell had for two. The activity of the originators for the whole decade is revealed by the 18 papers written and co-authored by Charnes and Cooper with self-citations. The second most important source for CCR citations in the first decade is Banker with nine citations. Other early Ph.D. students are also contributing.

As to type of journal CCR (1978) is clearly diffused among OR/MS journals. Only six journals are typical economics journals (and one applied economics journal in Danish in addition). The first economic journals citations came in 1983 (Färe and Grosskopf, Färe et al., and Lovell and Sickles), coinciding with the first citation by economists in an OR/MS journal (Färe and Grosskopf). The only DEA paper by Charnes and Cooper and associates in an economics journal appeared in 1985 in Journal of Econometrics (Charnes et al., 1985). Management Science and European Journal of Operational Research have the highest number of their accumulated citations with 13 and 8 respectively, but otherwise the citations are evenly distributed. Judging form the titles of journals CCR in the first decade was probably cited in many applied papers especially in the fields of education and health.[15]

Concerning important theoretical developments in the first decade it may be reasonable to consider contributions opening up for applications. In the OR/MS community it is customary to name the model approach that is followed, using the names of the authors of seminal papers. The two basic ones are the "*CCR* model" and the "*BCC* model," the constant returns to scale model being developed in CCR (1978) and the extension to variable returns to scale model in Banker et al. (1984). The appropriateness of the usage of the term CCR model has already been dealt with. As mentioned above the special form of a piecewise linear model set up in Banker, Charnes and Cooper was actually introduced already in Afriat (1972) (although for the case of a single output). Moreover, it was empirically implemented in the case of single output in Färe et al. (1983). References to these, and especially the last, are almost completely overlooked in the OR/MS literature.[16] We may also add that a key concept, when using variable returns to scale frontier functions, is *optimal scale*. This concept, introduced in the economics production theory literature already in the thirties by Frisch (1965), termed *Technically Optimal Scale*, and the related concept in economics called Minimum Scale Size (MSS) were both overlooked in Banker (1984) and BCC and in the DEA OR/MS literature afterwards, exclusively

[14]It would be interesting to classify all citing papers as to type of contribution as suggested in Reisman (1992) and Gattoufi et al. (2004d), using the taxonomy of Gattoufi et al. (2004b). However, this is beyond the scope of this paper.

[15]Footnote 14 also applies here.

[16]The paper has 13 citations in total of which five are in OR journals mainly on the topic of electricity.

Table 3
Journals with Charnes et al. (1978) citations 1978–1988[a]

Year	Authors	Journal	No. of cit.	Cum per year	Cum. no. of journ.
1979	Charnes, Cooper and Rhodes (CCR)	European Journal of Operational Research	1	1	1
1980	Charnes and Cooper (CC)	Accounting, Organizations and Society	1		
	Bessent and Bessent	Educational Administration Quarterly	1		
	Banker	European Journal of Operational Research	1		
	Morey and Mccann	Management Science	1	5	4
1981	Schaible	European Journal of Operational Research	1		
	Sojka	Ekonomicky Casopis	1		
	Banker and CCR, CCR	Management Science	2	9	5
1982	Sengupta	International Journal of Systems Science	1		
	Bessent et al.	Management Science	1		
	CC and Schinnar, Lewin et al.	Omega	2		
	Lindsay	Review of Educational Research	1		
	CC and Seiford et al.	Socio-Economic Planning Sciences	1	15	9
1983	Bessent, CC et al.	Educational Administration Quarterly	1		
	Färe and Grosskopf	European Journal of Operational Research	1		
	Nunamaker	Health Services Research	1		
	Shakun and Sudit	International Journal of General Systems	1		
	Bessent et al.	Management Science	1		
	CC et al.	Operations Research Letters	1		
	Parks	Policy Studies Journal	1		
	Lovell and Sickles	Review of Economics and Statistics	1		
	Färe et al.	Resources and Energy	1		
	Färe and Grosskopf	Zeitschrift für Nationalökonomie	1	25	16
1984	CC, Banker, Boyd and Färe	European Journal of Operational Research	3		
	Bessent et al.	Interfaces	1		
	Banker and CC, Byrnes et al.	Management Science	2		
	Sherman	Medical Care	1		
	Sherman	Sloan Management Review	1	33	19
1985	Danilin and Lovell et al.	Economica	1		
	Capettini and Dittman and Morey	Journal of Accounting and Public Policy	1		
	Sherman and Gold	Journal of Banking & Finance	1		
	CC et al.	Journal of Econometrics	1		
	CC et al.	Journal of Marketing	1		
	Nunamaker	Managerial and Decision Economics	1		
	Morey, Capettini and Dittman	Policy Sciences	1	40	26
1986	Grosskopf	Economic Journal	1		
	Stern	Education and Urban Society	1		
	Baxter et al.	Energy Economics	1		
	CC and Sueyoshi	European Journal of Operational Research	1		

Table 3 (*continued*)

Year	Authors	Journal	No. of cit.	Cum per year	Cum. no. of journ.
	Thompson and Thrall et al.	Interfaces	1		
	Lewin and Minton, Banker and Maindiratta, B and Morey, B et al., Färe and Hunsaker	Management Science	5		
	Pedersen	Nationaløkonomisk Tidsskrift	1		
	Banker and Morey	Operations Research	1		
	CC and Thrall	Operations Research Letters	1		
	Macmillan	Papers of Regional Science Association	1		
	Miller	Systems Research	1	55	35
1987	Macmillan	Environment and Planning A	1		
	Thanassoulis et al., Bowlin	Journal of Operational Research Society	2		
	Grosskopf and Valdmanis	Journal of Health Economics	1		
	Smith and Mayston	Omega	1		
	Jesson, Mayston and Smith	Oxford Review of Education	1	61	38
1988	Glover et al.	Decision Science	1		
	Banker and Maindiratta	Econometrica	1		
	Thompson et al.	Interfaces	1		
	Borden	Journal of Accounting and Public Policy	1		
	Kamakura	Journal of Consumer Research	1		
	Golany, Dyson and Thanassoulis	Journal of the Operational Research Society	2		
	Färe et al.	Journal of Public Economics	1		
	Sengupta, Ahn and CC	Managerial and Decision Economics	2		
	Sengupta	Management Decision Economics	1		
	Golany, Kamakura	Management Science	2		
	Bessent et al.	Operations Research	1		
	Woodhouse and Goldstein	Oxford Review of Education	1		
	Ray, Ahn and CC (2)	Socio-Economic Planning Science	3	79	44

Sources: SSCI (“In print” 1961–1980, CD-ROM 1981–1990, WEB-based 1991 –March 2004, http://www.isinet.com), JSTOR: http://www.jstor.org.

[a]Only papers mentioned in the text are entered in the References.

referring to the Banker concept of MPSS (most productive scale size).[17]

A third significant development of the DEA model was inspired by a real life problem. The standard CCR model did not seem to offer practical solutions to the problem of locating a high-energy physics laboratory in Texas. Thompson et al. (1986) increased the realism in applications by introducing bounds on the shadow prices (called “multipliers” by the OR community) associated with the output- and input constraints of the LP problem on “envelopment” form.[18] They introduced the concept of “assurance region” and this concept is later also called the “cone-ratio” approach. Within the first decade the

[17]We should add that Frisch operated with a single output, while Banker dealt with multiple outputs. Rajiv D. Banker is now well aware of the contribution of Frisch, but this does not seem to be the case for the standard OR/MS DEA researcher.

[18]It has become customary to name the LP problem where the efficiency score is the objective function for the envelopment form, and the dual LP problem for the “multiplier” form.

approach was followed up in Dyson and Thanassoulis (1988).

The introduction of bounds on multipliers is a good example of the research philosophy among many people developing DEA, especially (the late) Abraham Charnes and William W. Cooper: *application-driven* theoretical development. Theoretical developments are inspired by real life problems (see Cooper (2002) for a historic account of this research philosophy).

Among other innovations of current importance for DEA users during the first decade we may mention introduction of discretionary variables (Banker and Morey, 1986a), and categorical variables (Banker and Morey, 1986b).

4.3. The diffusion of Farrell (1957) and CCR (1978) up to year 2003

The diffusion of the central papers is set out in Table 4 and presented in Fig. 3. Although the diffusion of citations was much more rapid for CCR than Farrell, we see from Fig. 3 that for the same time period there is a remarkable similarity of development. Up to 1994 the citations of Farrell actually outnumber those of CCR, with the reverse occurring afterwards. There is a marked jump in citations from 1996 and then an almost constant average level for both papers to 2003 with some ups and downs with parallel movements for both but with CCR receiving consistently more citations. The role of special issues may be important for explaining the local peaks in the development. Farrell citations certainly obtained a boost from the special issue of Journal of Econometrics in 1980. Its next special issue on efficiency topics was in 1990, and now we see the effect of also inviting DEA researchers to contribute. Both Farrell and CCR citations dramatically increased. One factor behind the significant increase in citations in the nineties is the appearance of Journal of Productivity Analysis (JPA) from 1989, but not included in the SSCI until 1996, and Annals of Operational Research included in the SSCI from 1995. According to Gattoufi et al. (2004c) JPA has the second highest number of DEA papers for the period 1978–2001, about half the number of European Journal of Operational Research (EJOR) being No. 1.

The development of co-citations of Farrell (1957) and CCR (1978) is also shown in Fig. 3. The share of co-citations is high the first decade with a low number of citations for CCR, and in 1987 the share is 100 percent (of the lowest number of separate citations). But when the absolute number of citations starts to increase significantly for both papers the share of co-citations actually goes down, and stays at about 50 percent on average. By studying in detail the papers citing both papers one could establish characteristics about papers just citing one of the papers and both. A conjecture is that papers utilising either only parametric frontier estimation techniques or non-parametric techniques will tend to quote only one paper if the emphasis is on methodology, while a paper using non-parametric techniques focussing on efficiency would tend to also refer to Farrell for the introduction of the efficiency measure concepts.

4.4. Diffusion of other key milestones

The first contribution on methods for computing parametric frontier functions, Aigner and Chu (1968), received an attention paralleling Farrell's paper at that time, but was made "technologically redundant" by the contribution of Aigner et al. (1977) nine years later. The redundancy shows up by citations for Aigner, Lovell and Schmidt becoming higher already in 1978, and then clearly outpacing Aigner and Chu from the latter part of the eighties. The relative low citations of Afriat compared with Aigner, Lovell and Schmidt that has become a classic (a total accumulated of 151 compared with 575 for Aigner et al. by 2003), in spite of his importance, may reflect that the paper was rather long and not easily accessible, and philosophical rather than providing a ready-made method to apply. It appeared rather unedited. Aigner et al. (1977) on the other hand were more accessible, and presented a method that could readily be applied by researchers and econometrically inclined Ph.D. students.

The development of citations of Banker et al. (1984) picked up from a slow start to a level of on

Table 4
Diffusion of Farrell, CCR and main contributions 1957–2000

Year	Farrell	Aigner and Chu	Afriat	Aigner, Lovell and Schmidt	CCR	BCC	Thompson and Thrall et al.	Banker and Morey (a)	Banker and Morey (b)
1957	0								
8	0								
9	1								
1960	1								
1	1								
2	1								
3	1								
4	1								
1965	0								
6	0								
7	3								
8	3	0							
9	0	0							
1970	4	4							
1	6	4							
2	4	1	1						
3	5	1	0						
4	6	4	1						
5	3	3	0						
6	5	3	0						
7	6	5	2	1					
8	8	5	1	4	0				
9	11	7	4	4	1				
1980	17	6	**5**	9	4				
1	8	0	2	3	3				
2	10	0	2	9	6				
3	13	0	2	6	10				
4	11	0	1	7	8	0			
5	7	0	2	3	7	0			
6	23	8	4	11	16	5	0	0	0
7	12	1	2	8	6	3	0	0	1
8	21	6	5	11	18	6	0	1	1
9	17	4	4	15	14	10	1	3	4
1990	30	4	10	13	20	9	7	6	9
1	23	5	6	17	22	8	4	2	3
2	26	4	4	18	27	7	2	3	2
3	35	6	8	23	32	18	1	2	3
4	36	6	10	28	39	14	4	1	1
5	37	9	8	32	44	28	5	7	3
6	77	14	7	44	97	50	8	12	5
7	75	7	15	34	79	52	12	6	8
8	63	10	4	34	83	57	4	12	4
9	67	9	7	43	94	59	9	13	5
2000	68	8	5	52	81	47	7	7	2
1	73	11	5	47	102	63	7	6	6
2	71	8	11	47	80	59	8	8	3
03	84	6	13	52	88	57	8	6	6
Total[a]	974	169	151	575	981	552	87	95	66

Sources: JSTOR http://www.jstor.org, SSCI (“In print” 1961–1980, CD-ROM 1981–1990, WEB-based 1991–March 2004, http://www.isinet.com), Tables 2 and 3.

[a]Column sums, may differ from number for total period in SSCI.

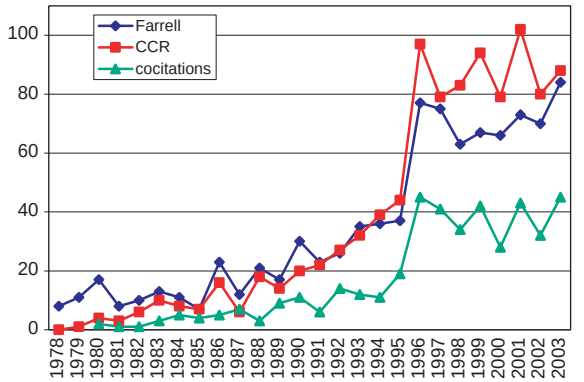

Fig. 3. The development of Farrell and CCR citations and co-citations.

the average 10 from six to nine years after publication, and then to 18 in 1993, and 50 in 1996, mainly due to a special issue that year. It is the second most quoted paper in DEA and is a classic, as seen in Table 4 from the total accumulated count of 552 in 2003. The innovative papers of Thompson et al. (1986) and Banker and Morey (1986a, b) have much lower impacts with an accumulated count of 87, 95 and 66 respectively in 2003.

4.5. *Diffusion of additional innovative contributions*

In addition to the mainly methodologically oriented extensions of both parametric and non-parametric estimation methods of the two first decades and first decade respectively for Farrell and CCR, citations of other significant contributions up to the present are set out within type of topic in Table 5.

The first topic is elaborations on the notion of efficiency measures. We have entered early contributions only. Only economists have early papers within this topic. The paper by Førsund (1971) has made a quite insignificant impact, especially when we add that of the total of eight citations seven are self-citations. The work on establishing an axiomatic basis for efficiency measures (Färe and Lovell, 1978) has had the highest impact. Later contributions based on measuring efficiency in other directions than proportional changes are not considered here. It seems that only the directional efficiency measure (Chambers et al., 1998) may have a potential.

The theoretical developments of both the parametric approach and the programming approach continued after the periods covered in detail in Tables 2 and 3. We will not go into details, but just mention some highlights. Within the econometric approach a panel data model was introduced in Pitt and Lee (1981), and extended in papers by Battese and Coelli and others to model change in the efficiency distribution over time. The paper by Cornwell et al. (1990) has the highest number of citations (for a complete story see the survey of parametric frontier models in Kumbhakar and Lovell (2000)).

The measurement of scale properties of non-parametric frontiers has been widely discussed in the literature (see Banker et al. (2004), Førsund and Hjalmarsson (2004a, b) for recent surveys). Banker (1984)[19] and Banker and Thrall (1992) are clearly leading in citations. Another paper relevant for scale issues is Banker et al. (1984) with 598 citations per medio March 2004, but probably most of these concern the variable returns to scale model.

The use of non-parametric frontiers within productivity analyses is based on the theoretical contribution in Caves et al. (1982). This paper has a high citation total of 209. Among the early contributions Färe et al. (1994) in American Economic Review stands out with a high citation. We clearly see the importance of publishing in journals with high impact factors. The fact that important contributions came as chapters in books (Charnes et al. (1994) containing the seminal contribution of Färe et al. (1989) of using the DEA model to calculate the Malmquist productivity index, extending the index calculation to inefficient units decomposing the productivity change into a technology shift component and a catching-up component following Nishimizu and Page (1982) in a parametric frontier setting, and Fried et al. (1993)) may distort the true influence of the early journal contributions. Only economists have contributed to the early literature on

[19]For Banker (1984) there may be many citations only referring to the MPSS concept.

Table 5
Citations of some innovative contributions[a]

Topic	Author	Journal	Year	No. of citations
Efficiency measures	Førsund	Swedish Journal of Economics 73, 225–240	1971	8
	Førsund and Hjalmarsson	Swedish Journal of Economics 76, 141–154	1974	44
	Färe and Lovell	Journal of Economic Theory 19(1), 150–162	1978	126
	Førsund and Hjalmarsson	Economic Journal 89, 294–315	1979	54
Panel data	Pitt and Lee	Journal of Development Economics 9(1), 43–64	1981	118
	Battese and Coelli	Journal of Econometrics 38(3), 387–399	1988	127
	Cornwell et al.	Journal of Econometrics 46, 185–200	1990	151
	Kumbhakar	Journal of Econometrics 46 (1–2), 201–211	1990	64
	Battese and Coelli	Journal of Productivity Analysis 3, 153–169	1992	100
	Battese and Coelli	Empirical Economics 20, 325–332	1995	131
Scale elasticity	Färe, Grosskopf and Lovell	Scandinavian Journal of Economics 85, 181–190	1983	26
	Banker	European Journal of Operational Research 17, 35–44	1984	103
	Färe and Grosskopf	Scandinavian Journal of Economics 87, 594–604	1985	35
	Banker and Thrall	European Journal of Operational Research 62, 74–84	1992	92
	Førsund	Journal of Productivity Analysis 7(2–3), 283–302	1996	11
Malmquist productivity index	Caves, Christensen and Diewert	Econometrica 50(6),1393–1414	1982	209
	Färe et al.	Resources and Energy 12(4), 383–398	1990	10
	Färe and Grosskopf	Economic Journal 102(410), 158–160	1992	18
	Färe et al.	Journal of Productivity Analysis 3, 85–101	1992	59
	Berg et al.	Scandinavian Journal of Economics 94(S), 211–228	1992	14
	Berg et al.	Journal of Banking and Finance 17(2–3), 371–388	1993	42
	Färe et al.	American Economic Review 84(1), 66–83	1994	168
Influential peer	Andersen and Petersen	Management Science 39(10), 1261–1264	1993	110
	Wilson	J. of Business and Economic Statistics 11, 319–323	1993	13
	Wilson	Journal of Productivity Analysis 6, 27–45	1995	29
	Torgersen et al.	Journal of Productivity Analysis 7, 379–398	1996	17
Sensitivity	Charnes et al.	Annals of Operations Research 2, 139–156	1985	193
Statistical foundation	Banker	Management Science 39 (10), 1265–1273	1993	97
	Banker	Journal of Productivity Analysis 7(2/3), 139–159	1996	37
	Simar	Journal of Productivity Analysis 7(2/3), 177–185	1996	16
Boot-strapping	Simar	Journal of Productivity Analysis 3, 167–203	1992	27
	Ferrier and Hirschberg	Journal of Productivity Analysis 8 (1), 19–33	1997	11
	Simar and Wilson	Management Science 44(11), 49–61	1998	52
	Simar and Wilson	Journal of Productivity Analysis 13, 49–78	2000	26
	Simar and Wilson	Journal of Applied Statistics 27(6), 779–802	2000	12

Source: SSCI, March 2004, http://www.isinet.com.

[a]Only papers mentioned in the text are entered in the References.

the Malmquist productivity index, but the bulk of citations to Caves et al. (1982) are now found in non-parametric applications of the Malmquist index.

The non-parametric approach is essentially building on efficient outlier observations. But a problem is distinguishing between relevant outliers and unreasonable ones. The most cited paper is Andersen and Petersen (1993), although the purpose was to rank efficient units.

Sensitivity analysis has a tradition within linear programming that can be applied to the DEA analysis (see Cooper et al. (2000) for a survey). DEA applications have also developed its own sensitivity approach with a high citation of Charnes et al. (1985b).

One reason why the programming approach has not been much developed within economics may be the lack of statistical measures for the quality of the point estimators of efficiency scores. Indeed, the programming approach was often characterised as deterministic. Of course, a programming format is also a way of estimating the unknown frontier production function. The problem has been lack of statistical test procedures for choosing the scale nature of the function, or for studying choice of variables, and the difficulties of finding the properties of point estimators for efficiency scores. Banker (1993) has done a start, followed by Simar (1996), Kittelsen (1998) and Simar and Wilson (1998, 2000). Banker (1993) is the dominating paper in terms of citations.

Papers by Simar and Wilson have introduced bootstrapping to provide confidence intervals for the efficiency scores. The early contribution by Simar (1992) has had a modest diffusion. A paper that really set the profession working on bootstrapping is the paper by Ferrier and Hirschberg (1997), but this paper has received very modest citations. But in working out the right way to bootstrap Simar and Wilson (1998) appears as the most influential bootstrap paper with 52 citations already, followed by Simar and Wilson (2000) with half the number of citations. It is interesting to note that the most cited statistical contributions have not appeared in econometrics journals, but in Management Science and a specialised productivity journal, Journal of Productivity Analysis.

Seitz (1967, 1971) pioneered a two stage approach for explaining inefficiencies dating back to Nerlove (1965) within a parametric approach. Variables not specified in the model when calculating efficiency scores, are utilised in a second stage regression as explanatory variables for the efficiency scores. This may be dubious from a theoretical point of view, but is followed in a number of practical applications within non-parametric approaches. Banker and Natarajan (2001) give theoretical conditions that may support the practice. Simar and Wilson (2003) provide a thorough critical discussion of the two stage approach and point out more sound statistical ways to go forward. These two last papers are still unpublished working papers.

A link between non-parametric and parametric frontier approaches may be represented by estimating parametric distance functions (see e.g. Coelli and Perleman (2000) and references there). A distance function contains all information about the technology, also the frontier. However, there are still some unresolved problems with formulating the appropriate data generating mechanism, e.g. determining the appropriate estimating equations.

5. Explanations of diffusion patterns

Main factors influencing citations apart from the quality of the research contribution are reputation of journal, reputation of author, number of close followers; colleagues, "cadres of protégés" (Zuckerman, 1987, p. 332), Ph.D. students, and extent of network ("invisible college"). We will look into these factors regarding the diffusion of Farrell and CCR as revealed by Tables 2 and 3.

5.1. Journal outlets

The journal Farrell published in was well known in England, but not so in US, where the journal was not included in the social science databases. He himself had a good reputation, although not a prolific journal contributor, but he had no group of Ph.D. students around him (although he was in

touch with Seitz and Sitorus when he visited Berkeley in 1965). The Cambridge location should not be a disadvantage from a network point of view. It may be of significance that he did not himself participate so much in the development of his ideas. The first and only self-citation—in general a possible sign of advertising—came quite naturally in a follow-up paper five years later on scale issues of the frontier function (Farrell and Fieldhouse, 1962).

CCR had a better start. They were older (in their 60 s as to Farrell being 31 years old) and well established as world authorities within the field of programming, with a better reputation as to publishing record than Farrell (he had six journal publications prior to the 1957 one, see the bibliography in Fisher (1976)), and were influential within a sizeable group of Ph.D. students, as documented below. But their outlet, European Journal of Operations Research, was new and not so well known. They participated very actively in the development of their own ideas. Table 3 reveals that of the 79 citations the first decade 18 are self-citations, or 23 per cent.

5.2. The impact of Ph.D. students

Thesis advising is one channel for asserting influence and promoting own research, and securing citations through successful followers (a vehicle for "promoting your own genes," to borrow an analogy from biology). Here the profile of Farrell, and Charnes and Cooper are quite different. Farrell had a few collaborators, but no Ph.D. student in the productivity/ efficiency field with a significant "take off" of his own.[20] Charnes and Cooper, on the other hand, had a sizeable group of followers. The entry "Thesis adviser" available in the UMI Dissertation Abstracts (University Microfilms International (UMI) available on the web; www.lib.umi.com/dissertations/, from 1987) reveals that Charnes had been thesis adviser for 13 between 1987 and 2000, and Cooper 10 (with some formally overlapping), but they both initiated and assisted many more dissertations at University of Texas. Some of their first students within DEA are among the leading contributors to the DEA field today, like Banker, Schinnar, Seiford, Sueyoshi and Golany.[21] Using the database on for the period 1976–2000 we see from Table 6 that DEA and production frontier themes are about equal until the nineties.

Then there is an explosion in DEA-related dissertations and a marked decline in the number of frontier production function dissertations. It must be underlined that this database is mainly covering US and not Europe.

Foreign Ph.D. students of Charnes and Cooper continued DEA research in their home countries on returning home, especially in Asia. In the Nordic countries followers of the production theory school of Frisch and Johansen (see Førsund (1999) for a survey) cited Farrell more than CCR. Researchers located at business schools, like Warwick in England dominated the growth in citations in Europe of CCR, cf. the early citations in Thanassoulis et al. (1987) and Dyson and Thanassoulis (1988).

5.3. Ease of application

Farrell struggled to compute the efficiency measures for his illustration, consisting of only 48 units and five variables. Employing one of the earliest electronic computers in Europe, the EDSAC computer[22] in Downing Street, Cambridge, up to 60 hours for one run is reported (Farrell, 1957, p. 265). (EDSAC had probably less computing capacity than a modest pocket calculator of today!). In contrast, Charnes and Cooper

[20]In fact, since Farrell did not have a Ph.D. himself, he would not officially be a main supervisor of Ph.D. students in Cambridge, although he advised some students in econometrics broadly defined. He had a heavy teaching load and had to cope with a polio paralysis after 1957. Notice that the idea of an English economist doing a Ph.D. in economics at that time was not a familiar (or even welcome) culture outside the science disciplines (private communication from Harry Burley).

[21]Morey, Bessent and Lewin were not formal students, but learned about DEA from Charnes and Cooper (private communication from W.W. Cooper).

[22]Electronic Delay Storage Automatic Calculator (EDSAC) is claimed to be the world's first fully operational computer, and was inaugurated 6 May 1949 (Renfro, 2004). In 1958 it was replaced by EDSAC 2, which was used in Farrell and Fieldhouse (1962). See also Brown et al. (1953) for an account.

Table 6
Ph.D. Dissertations with DEA and frontier production function as search words

Year	DEA	Frontier production function
1976	0	1
7	0	1
8	1	0
9	0	1
1980	1[a]	2
1	3	1
2	0	2
3	5	1
4	2	5
5	5	2
6	8	2
7	5	3
8	7	1
9	1	9
1990	10	3
1	9	6
2	8	2
3	10	8
4	9	8
5	10	8
6	10	11
7	22	4
8	22	8
9	14	5
2000	26	3
Total	187	97

Source: Dissertations Abstracts UMI (CD-ROM, and WEB-based; www.lib.umi.com/dissertations/).

[a]Banker's 1980 dissertation cannot be found in the database using DEA as a search word because it is occurring neither in the title nor abstract.

and associates could offer easily accessible computer LP codes to be run on speedy mainframes.[23] The first commercial software for PCs, IDEAS, appeared in 1989. This is probably an important factor behind the success of DEA in the nineties. The econometric follow-ups of Farrell's ideas the first two decades involved a lot more difficult computational work. Although improvements in calculation techniques benefited the following up of both the parametric and non-parametric approaches, the threshold is probably higher for applying econometrics packages than LP- ones.

[23]The computing work for the empirical application in the dissertation of Edwardo Rhodes was done by applying a standard LP routine the required number of times (private communication from Edwardo Rhodes).

5.4. Networks

The extent and type of networks are obviously important for the diffusion of new ideas. Followers of Farrell and CCR started out operating within different networks or invisible colleges, which we can call the OR/MS and the economics efficiency networks. The OR/MS DEA community had several national and international conferences where ideas were presented and exchanged. In the late nineties electronic networks were established. Special issues devoted partially or fully to efficiency and/or DEA have had a significant impact on citations, especially for CCR because close associates often edited special issues. Among the special issues we have European Journal of Operational Research 1993, 1995, 1997, Annals of Operations Research 1985, 1996, 1997, Journal of Productivity Analysis 1992, 1996, 1997, Computers and Operational Research 1997, Journal of Banking and Finance 1993, and Journal of Econometrics, 1980, 1990.

Farrell did not so actively create a network as Charnes and Cooper, but through being well known among Oxford and Cambridge economists his ideas had possibilities of being spread. He also visited Cowles Commission in 1951–1952 and established contacts with Debreu and Koopmans, as well as meeting with Charnes and Cooper at Carnegie Mellon. His activity approach to efficiency measurement was inspired by this exposure, and the Cowles Commission group should have known his 1957 paper. Farrell also visited Berkeley in the sixties and met with agricultural economists there. As stated previously this group organised a special workshop on Farrell's approach in 1966. The diffusion through agricultural economists can be seen in Table 2.

Leif Johansen of Oslo University made Farrell's efficiency paper known in Scandinavia. He had spent a year in Cambridge 1959–1960 and brought

home a reprint of the Farrell paper. We see the Nordic influence in Table 2.[24]

6. Convergence of invisible colleges?

As a natural consequence of competition among different research groups some frictions are evident in the literature, and were observed at conferences, and unfair selection felt practised in refereeing processes. After a period of some frictions at DEA streams of ORSA/TIMS meetings and informal workshops organised by Ali Dogramaci at Rutgers University from early eighties, a series of events at the end of the decade lead to the different networks establishing extensive cross-links. A "peace conference" was organised at Chapel Hill in 1988 with proceedings published in Journal of Econometrics 1990. Charnes and Cooper at Austin arranged a broadly based conference of participants from the two "camps" in 1989. The conference volume was out as a book in 1994 (Charnes et al., 1994). The Journal of Productivity Analysis was started in 1989, springing out of the enthusiastic work over many years of Ali Dogramaci at Rutgers University, arranging informal workshops on efficiency and productivity, documented in several books. Also the electronic network PARN (http://www.sam.sdu.dk/parn/parninfo.htm), started in 1992, should be mentioned.

One way of measuring interaction and convergence between the camps is to inspect combinations of joint citations. The pattern of cross-references is set out in Table 7 for a few selected years. Naturally the number of papers citing both Farrell and CCR has clearly increased over time with the increase in total numbers. But as already commented upon previously, the share of the total citations of the two papers as the share of the paper with the smallest number of citations has gone down from a share above $\frac{2}{3}$ in the first half of the eighties to from 1988 to around $\frac{1}{2}$ on average for the years after. For the chosen years in Table 7, the shares varies from 0.3, 0.6, 0.4 and 0.4, respectively. The data does not support hypothesis of convergence. In order to establish in more detail the nature of joint citations the individual papers have to be inspected for the reason for citations, as was done in Section 2 for a sub-sample of papers.

The two OR/MS papers CCR and BCC have a very high overlap. We see that in 1986 the share of co-citation relative to the BCC citations is 0.8, and then 1, 0.78 and 0.85. Regarding the seminal econometric papers one would expect a high co-citation between papers developing the methods for estimating parametric frontiers. But the overlap between the econometric papers is rather weak. Thematically Afriat (1972) and Aigner et al. (1977) are closest, but here the ratios of co-citations relative to the paper with the lowest citations are 0.5, 0.2, 0.25 and 0.2. The idea of an "Afriat School" as introduced in Thompson and Thrall (1993) corresponds poorly with the overlap of citations. There is a markedly higher overlap between Aigner and Chu and Aigner, Lovell and Schmidt developing different approaches of 1, 0.2, 1 and 0.4, respectively for the four periods. The joint citations between the three main papers within the "Afriat School" are very poor indeed, and adding Farrell to the comparison makes the joint citations going further down to almost zero. There are only two papers jointly citing Farrell (1957) and all the parametric frontier papers for the four years represented in Table 7.

7. Concluding remarks

We started out by postulating that OR/MS efficiency researchers have tended to overlook the contributions of Farrell (1957). It may be of interest to note that the importance of Farrell (1957) was not really seen by his contemporary colleagues, even 20 years later in spite of the fact that our citation analysis reveals an extraordinary diffusion of his ideas during this period. Both in the obituary in The Times 1975 (October 30) and in Fisher (1976) a paper on how increasing returns to scale or non-convexities in general can be reconciled with competitive equilibrium (Farrell,

[24]The Swedish economist, Bo Carlsson, knew the Farrell paper through his Ph.D. adviser Timmer, an agricultural economist and early contributor to the development of parametric frontier estimation, at Stanford.

Table 7
Pattern of cross-references

Cited papers, combinations	Citations 1986	Citations 1990	Citations 1995	Citations 2000
(1) Farrell (1957)	23	30	37	68
(2) CCR (1978)	16	20	44	81
(3) Aigner and Chu (1968)	8	4	9	8
(4) Afriat (1972)	4	10	8	5
(5) Aigner et al. (1977)	11	13	32	52
(6) Banker and CC (1984)	5	9	28	47
Intersection (1), (2)	5	11	13	26
Intersection (2), (6)	4	9	25	40
Intersection (4), (5)	2	2	2	1
Intersection (3), (5)	4	2	8	2
Intersection (3), (4), (5)	1	0	2	0
Intersection (1), (3), (4), (5)	1	0	1	0

Source: SSCI, March 2004, http://www.isinet.com.

1959) is viewed as the most important contribution (the paper has 32 citations per medio March 2004 compared with 1061 for Farrell (1957)).

The citation analysis (Table 4) reveals that Farrell (1957) became a classical paper with more than 500 citations 40 years after the publication, and Charnes et al. (1978) one year later after 19 years. The latter paper has been the leading one in generating a spectacular interest in the Farrell approach to efficiency analysis based on the programming approach in the nineties.

We have not attempted a content analysis of the citing paper to see whether the two seminal papers are quoted due to definition of efficiency measures or due to methods. It is our conjecture that the majority of the Farrell references are due to the efficiency measure definitions. But as clearly demonstrated we should not forget the development of the econometric approach in the years between the publications of the two seminal papers. Indeed, one of the econometric papers, Aigner et al. (1977), is now also a citation classic (629 citations per medio March 2004). A further conjecture is that the majority of the CCR references are due to the non-parametric method. Underlining the importance of methodological development there is also one paper generalising the non-parametric approach to variable returns to scale, Banker et al. (1984) that is now a classical paper (589 citations per medio March 2004). A final conjecture is that people referring both to Farrell and CCR are probably economists applying the non-parametric approach.

The approach of the paper has been descriptive focussing on diffusion patterns. Our criticism of OR/MS researchers within the DEA group will only be of real concern if neglect of reading Farrell leads to delay or parallel efforts. To find this out is a huge undertaking, but we have pointed out that Boles (1967, 1971) was overlooked, and that the BCC model was introduced by Afriat (1972) and applied in Färe et al. (1983) but since then both papers have been more or less overlooked. As to neoclassical production theory it is shown in Førsund (1996), Førsund and Hjalmarsson (2004a, b) that too limited knowledge of neoclassical production theory has lead to parallel and partly unnecessary efforts as to the nature of the scale elasticity. It is not possible to know how reading of a classic will add value to research, but to miss out on a classical reference is like showing a lack of proper education.

A final reflection on the nature of Farrell's contribution is in place. Already Hall and Winsten (1959, p. 85) noted:

However, his paper still suffers from a central weakness: that he does not analyse the concept of efficiency.

There have been contributions as to the nature of the Farrell efficiency measures, cf. efforts noted in Table 5, but not really contributions as to the

nature of inefficiency as such. It is the introduction of new methods for empirical applications that attracts attention.

In the Discussion (1957) Mr Colin Clark expressed:

> I think we will agree, having heard this paper, that Mr. Farrell has already reached some interesting and successful results, and has come nearer than any previous investigator to a true measure of agricultural efficiency, which figures in their turn will send the economists further down the road hunting for the social and other factors which lie behind them.
>
> (Discussion on Mr. Farrell's Paper, p. 282)[25]

However, the hunts down the road have not been too successful. The challenge to research is underlined by the summing up in Stigler (1976, p. 216):

> Waste is error within the framework of modern economic analysis, and it will not become a useful concept until we have a theory of error.

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[25]Also quoted in Burley (1994).

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