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# Empirical surveys of frontier applications: a meta-review

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## Abstract

This contribution is the first attempt to systematically review all empirical surveys that so far have been made available in the broad field of efficiency and productivity analysis using frontier estimation methodologies. We provide a systematic bibliometric review on the many empirical surveys in the field of efficiency and productivity analysis, the most relevant concepts, areas, overlaps, and potentials to explore from its introduction to the most recent surveys. We combine the United Nations' International Standard Industrial Classification (ISIC) taxonomy for the economic activity with the *Journal of Economic Literature* (JEL) classification system to classify the empirical surveys and to identify the current gaps in the literature. In addition to the most relevant/generic potential areas for applications (according to the United Nation's ISIC), this methodology provides a cluster analysis with the most relevant concepts that have been considered so far (according to the JEL codes). This overview brings an interesting guide for future work to develop the whole field.

*Keywords:* data envelopment analysis; stochastic frontier analysis; frontier estimation; empirical surveys

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## 1. Introduction

The field of efficiency and productivity analysis using frontier estimation methodologies has been developing very rapidly in the last four decades. Since the seminal articles of Charnes et al. (1978), Banker et al. (1984), and Färe et al. (1983), the literature developing both methodological and empirical contributions to the nonparametric frontier literature (often identified by the name DEA [data envelopment analysis]) has been literally booming. Equally so, since the seminal articles of Aigner et al. (1977) and Meeusen and van den Broeck (1977), stochastic frontier analysis (SFA) has almost equally flourished along both methodological and empirical lines. Further methodological developments have led to new and somewhat separate streams of literature (for an overview, see Fried et al., 2008).

Common to this broad efficiency and productivity literature using some form of frontier estimation is the enormous and booming empirical literature that has emerged. A wide diversity of sectors has been studied using cross section, time series, or panel data covering a wide variety of geographical areas (from municipalities and counties to regions, and from countries to continents). On the one hand, this efficiency and productivity literature has led to an abundance of surveys aimed at summarizing general or specialized methodological advancements (examples include Koop and Steel, 2001; Simar and Wilson, 2015; Mariz et al., 2018). On the other hand, this flood of empirical frontier applications has also led to a multitude of empirical surveys. The latter empirical surveys are the main topic of this contribution.

As a matter of fact, there are a lot of empirical surveys available in the literature focusing on specific sectors of application (see, e.g., Paradi and Zhu, 2013; Mariano et al., 2015; among others). But, to the best of our knowledge, none of the existing studies have looked at what are the most surveyed fields of empirical applications and what are instead those in which there are no or few surveys, and how this situation evolved over time. To the best of our knowledge, there is no survey on surveys in the field of frontier methods (SFA, FDH [free disposal hull], DEA, and their extensions) proposed to evaluate the many facets of the efficiency literature in the different areas of the economic activities. The main real difference from our proposal to other surveys is to use a bibliometric methodology to assess the size and importance of the applications in those areas: in addition to the number of surveys, the co-occurrence of the concepts, methods, and areas is used to define a degree of generality that allows the visualization of gaps and overlaps in the field. The topic of this paper is exactly to fill up this gap.

The basic objective of this contribution is to provide a state of the art survey of empirical surveys of frontier estimation applications as applied to different economic sectors. By lack of a better concept, we label this a meta-survey. This amounts to asking the basic question: in which sectors and fields do empirical surveys exist? And if such empirical survey exists for a sector, we want to determine how many such surveys exist for this field and how recent these surveys are? Furthermore, we look at the connections among different sectors and fields of application through co-citation analysis. This should allow us to identify the gaps in the existing sectors and fields and offer some interpretations of the currently available literatures.

To develop such a meta-survey of empirical surveys of frontier estimation applications, we encounter the following series of methodological problems. We obviously need to have a full description of all the possible economic sectors and fields, so as to be able to identify existing gaps in the literature. To identify a rather universal taxonomy of economic activity, we adopt the United Nations' International Standard Industrial Classification (ISIC) taxonomy (United Nations Statistical Division [UNSD], 2008). We allocate all of the empirical surveys we encounter to one of the available taxonomic classes. This is done manually here, but our work could also provide useful suggestions on how one could standardize this activity in the future (see also Section 7). Finally, we attribute all empirical surveys also to the *Journal of Economic Literature* (JEL) classification, which is often used to classify research papers mainly in the economics literature. We discuss in Section 7 about the importance of these classifications to standardize, improve, and facilitate further analysis and updates of this study.

The main methodological tool applied in our meta-survey is the systematic review. In addition, we employ advanced clustering and mapping techniques. Finally, a co-citation analysis is performed to investigate the evolution of the interconnections among economic sectors and fields of application.

This contribution is structured as follows. We first put the notion of research review in context to clearly delineate what we do different from other existing reviews. In the next section of methodological notes, we introduce the notion of a systematic review in some detail. In the following sections, we specify in detail the methodology used and in particular, the queries that have been run in the systematic search (Section 3), the main outcomes of the survey (Section 4), and the bibliometric and mapping exercises done on the keywords (Section 5). Section 7 offers some final comments and outlines future research.

## 2. Research reviews in context

Literature reviews are essential in the development and accumulation of scientific knowledge in each discipline and consist in a process of conducting surveys of previously published material. Literature reviews do not primarily develop new facts and findings, but focus on publications containing such primary information, whereby these publications are digested, classified, and synthesized (see Cooper and Hedges, 2009).

Various taxonomies of literature reviews are available in the literature. An interesting taxonomy is the one proposed by Cooper (1988) that is intended to be applied to literature reviews appearing in both the behavioral and physical sciences. We focus only on the two characteristics of focus and goals. His first distinction among literature reviews concerns the focus of the review. Most literature reviews center on one or more of four areas: (1) the findings of individual primary studies, (2) the methods used for carrying out the research, (3) the theories that intend to explain the phenomena under examination, and (4) the practices, programs, or treatments being used in an applied context. A second characteristic of a literature review is its goals. The most frequent goal for a review is to integrate past literature related to a common topic. Integration can involve formulating generalizations, resolving conflicts in the literature, and creating a new, common linguistic framework. For the remaining characteristics, the reader is referred to Cooper (1988) for details.

In the broad efficiency and productivity literature that is the focus of our study, there do clearly exist methodological and theoretical surveys (like Koop and Steel, 2001; Mariz et al., 2018 cited above and many others). However, our focus is on empirical surveys aimed at summarizing the findings of individual primary studies. Among these empirical surveys, it may be useful to distinguish between bibliographical and bibliometric studies: the first often contain merely a list of articles, books, and book chapters eventually complemented with non-systematic and rather personal descriptions of evolutions in the literature; the latter contain some quantitative analysis based on a variety of methods.

In the efficiency and productivity literature, bibliographical studies include the seminal efforts by Seiford (1994, 1996, 1997, 1999) and the work by Gattoufi et al. (2004a). Bibliometric studies started with the seminal work by Gattoufi et al. (2004): these authors study the growth rate of this literature, the most important journals in terms of publication outlets, and the top authors in this field. In addition, the same authors compare this field with two others in the operations research-management science (OR/MS) subdisciplines: the frontier-based efficiency and productivity literature turn out to be much more vital in terms of growth. Emrouznejad et al. (2008) review the literature in the first 30 years since the seminal article by Charnes et al. (1978). Apart from also looking at the most important publication outlets as well as the top authors, these authors also study the distribution

Table 1  
Perimeter of the systematic review

<b>Research questions</b>	Identify all existing surveys on empirical applications of frontier efficiency analysis. In how many economic sectors have these been proposed? How recent are these studies? Identify existing gaps (economic sectors not covered) and try to develop an interpretation of the results
<b>Eligibility criteria</b>	We include only reviews in international peer-reviewed journals (published or forthcoming), so we exclude books and methodological surveys.
<b>Explicit methodology</b>	Systematic review on Scopus integrated by expert knowledge.
<b>Systematic search</b>	All details about the queries run on the database are described in the paper (Table 2) and reported in Appendix (Fig. A1)
<b>Systematic presentation and synthesis</b>	The main outcomes of the meta-survey are reported in Tables 3 and 4. A mapping and clustering illustration of the main keywords is reported in Figs. 2 and 3.

of page sizes of articles and the use of keywords. Emrouznejad and Yang (2018) basically update this same study after the first 40 years.

Liu et al. (2013a) also study the growth rate of this literature and equally classify the top outlets and top researchers in the field. These same authors trace detailed citation networks and try to distinguish some of the key trajectories through the literature. Liu et al. (2013b) try to devise a classification of empirical applications using an ad hoc classification of sectors and trace the development path for the five major sectors. Lampe and Hilgers (2015) is—to the best of our knowledge—the only survey that also considers SFA contributions: this methodology makes up a relatively small fraction of the total frontier-based efficiency and productivity literature. These authors also trace top outlets in the field and distinguish research clusters based on citation analysis. Liu et al. (2016) try to delineate a series of new methodological research frontiers based on a powerful citation-based network clustering method.

Finally, Gattoufi et al. (2004b) can be mentioned for their attempt to propose a taxonomy to classify DEA articles, without considering SFA. However, to the best of our knowledge this classification has never been extensively used.

Having reviewed these existing reviews, we are now capable to position our meta-survey within this broad field of frontier-based efficiency and productivity. Our meta-survey of empirical surveys of frontier estimation applications shares with Lampe and Hilgers (2015) that we also include SFA-based articles, and it is distinct from Liu et al. (2013b) in that we do not use an ad hoc classification of sectors but instead employ the United Nations manual (2008).

### 3. Methodological notes

In this paper we follow a cautious approach of systematic review proposed by Tranfield et al. (2003), given the specific questions we wish to address. These specific questions are reported in Table 1. Table 1 summarizes the main choices we have made in our analysis pertaining to the main objective, the eligibility criteria, the explicit methodology, the systematic search, and finally the systematic presentation and synthesis.

The main research question addressed in this paper is to collect *all existing published evidence* about empirical surveys that have been realized on applications of frontier efficiency analysis with

the objective of identifying what are the sectors and fields in which there are one or more surveys and what are the *economic* sectors and fields in which there are no surveys available. In this systematic review we include only reviews in international (English) peer-reviewed journals (published or forthcoming).

However, we exclude books and methodological surveys. The exclusion of books is related to the fact that these do not provide keywords or abstracts that can be used in the following developments to analyze the semantic connections between the various empirical surveys by advanced clustering methods. Hence, books and book chapters are not included.

Nevertheless, the number of books and book chapters is quite substantial in certain sectors and areas. We provide a selection by way of example:

- Allen (1999) on ecological efficiency;
- Johnes (2007) and Nigsch and Schenker-Wicki (2015) on education;
- Pollitt (1995) on electricity;
- Cummins and Weiss (2000), Harker and Zenios (2001), Hughes and Mester (2010), Kumar and Gulati (2014), Molyneux et al. (1996), and Paradi et al. (2004) on financial services;
- Jacobs et al. (2006) and Ozcan (2008) on health;
- De Borger and Kerstens (2000) on municipalities;
- De Borger and Kerstens (2008), Forsyth (2008), Nash and Smith (2008), Oum et al. (2011), and Oum and Yu (2012) on various transportation modes.

Obviously, having to ignore books and book chapters provides potentially a substantial lacunae in our analysis.

#### 4. Systematic search

The project started in 2015 and has been progressively developed since then by meetings and consultations to specialized literature.<sup>1</sup> The last systematic search has been performed on 1 September, 2018, at 2:52 p.m. (UTC–03:00). The main results have been extracted from the system at 6 p.m. of the same day, and the subjective assessment on each abstract was made in the days following the initial collection. The search was executed on the Scopus web system, which contains the largest database of peer-reviewed scientific literature, using the search engines provided by the website. Titles, abstract, and keywords on review articles since 1978 (the year of Charnes et al. DEA seminal paper) to 2019 have been checked by the query strings produced with a combination of keywords from a starting list of 104 surveys. This expert database of surveys was selected prior by the team of authors to produce a network of co-occurring terms with high density. The densest terms were selected to compose the strings applied in the refinement procedure to track additional relevant surveys on empirical frontier assessments of various kinds. The descriptions on each of these queries are present in Table 2, and the flow diagram in Fig. A1 (see Appendix) synthesizes the stages of this process.

The density of the most prominent terms is designed by considering the keywords incidence in the empirical surveys and their interaction with other relevant keywords: the larger these metrics,

<sup>1</sup>One of the main difficulties of this kind of analyses is that over time you continue adding new references that appear, but on the other hand you have to fix a date to stop the search to finalize the elaborations.

Table 2  
Query strings used to perform Scopus systematic search

Acronym	Mention
(Q1)	(TITLE-ABS-KEY (efficiency) OR TITLE-ABS-KEY (data AND envelopment AND analysis) OR TITLE-ABS-KEY (stochastic AND frontier AND analysis) OR TITLE-ABS-KEY (benchmarking ) ) AND DOCTYPE (re)
(Q2)	(TITLE-ABS-KEY (efficiency) OR TITLE-ABS-KEY (data AND envelopment AND analysis) OR TITLE-ABS-KEY (stochastic AND frontier AND analysis) OR TITLE-ABS-KEY (benchmarking ) ) AND DOCTYPE (re) AND (EXCLUDE (SRCTYPE , “d”) OR EXCLUDE (SRCTYPE , “k”) OR EXCLUDE (SRCTYPE , “p”) OR EXCLUDE (SRCTYPE , “b”) OR EXCLUDE (SRCTYPE , “Undefined” ) ) AND (LIMIT-TO (LANGUAGE , “English”))
(Q3)	(TITLE-ABS-KEY (efficiency) OR TITLE-ABS-KEY (data AND envelopment AND analysis) OR TITLE-ABS-KEY (stochastic AND frontier AND analysis ) OR TITLE-ABS-KEY (benchmarking ) ) AND DOCTYPE (re) AND ABS (benchmarking) OR ABS (frontier) OR ABS (data AND envelopment AND analysis) AND (EXCLUDE (SRCTYPE, “d ”) OR EXCLUDE (SRCTYPE , “k ”) OR EXCLUDE (SRCTYPE , “p ”) OR EXCLUDE (SRCTYPE , “b ”) OR EXCLUDE (SRCTYPE , “Undefined ”) ) AND (LIMIT-TO (LANGUAGE , “English ”) )
(Q4)	(TITLE-ABS-KEY (efficiency) OR TITLE-ABS-KEY (data envelopment analysis) OR TITLE-ABS-KEY (stochastic frontier analysis) OR TITLE-ABS-KEY (benchmarking)) AND DOCTYPE (re) AND ABS (benchmarking) OR ABS (frontier) OR ABS (data envelopment analysis) AND (EXCLUDE (SRCTYPE,“d”) OR EXCLUDE (SRCTYPE,“k ”) OR EXCLUDE(SRCTYPE,“p ”) OR EXCLUDE (SRCTYPE,“b ”) OR EXCLUDE (SRCTYPE,“Undefined”)) AND (LIMIT-TO (LANGUAGE,“English”)) AND (LIMIT-TO (EXACTKEYWORD, “Review”) OR LIMIT-TO (EXACTKEYWORD,“Benchmarking”) OR LIMIT-TO (EXACTKEYWORD, “Data Envelopment Analysis”) OR LIMIT-TO (EXACTKEYWORD,“Efficiency”) OR LIMIT-TO (EXACTKEYWORD, “Productivity”))

the greater the potential representativeness by the keywords combinations in the queries. Figure 1 reports the most prominent terms as a density map of the relevant keywords extracted from the departing bibliography list by the first systematic search performed on 13 January 2017. Based on these indicators of query’s representativeness, the purpose is to depart from the broader set of items to end up with the narrow relevant keywords, with no imposed threshold on the number of occurrences to be detected. A total of 243 keywords’ terms emerged with at least one occurrence. From this network, 42 items are regarded as independent, in which case the item does not bring any significant contribution to design applicable queries and identify pertinent empirical surveys. Thus, the largest set of interconnected keywords consists of 201 items framed in the density map depicted in Fig. 1.

The most relevant keywords from those items are contrasted as hot spot concentrations where both the information with regard to the occurrences and their interaction among the documents are taken into consideration. The keywords “efficiency” with 26 occurrences and 106 links, “data envelopment analysis” with 19 occurrences and 84 links, “review” with 14 occurrences and 59 links, “stochastic frontier analysis” with seven occurrences and 44 links, and “benchmarking” with 19 occurrences and 84 links are some of the most dense and relevant terms identified in the keywords mining process. Other potential applicable expressions with a greater incidence and link connections are not taken into consideration for being included as search results in the results of more restricted keywords. Examples are the expressions “technical efficiency,” “efficiency measurement,” and “frontier efficiency analysis” in which search results are already included in the results when the



keywords of these surveys are used to search and find relevant surveys. These 20 surveys were not detected by the systematic search for different reasons. Some surveys (such as Salehirad and Sowlati's [2006] "Productivity and efficiency assessment of the wood industry: A review with a focus on Canada" and Sowlati's [2005] "Efficiency studies in forestry using data envelopment analysis") belong to journals that are not indexed in the SCOPUS bibliography base and for this reason were not detected by the systematic search. Other surveys in the departing list were published prior, after or in between the Scopus coverage years for the specific journal. For instance, Ashton and Hardwick (2000) "Estimating Inefficiencies in Banking: A Survey." In this study, the coverage years for the Journal of Interdisciplinary Economics comprehend the period from 2004 to 2018. The survey was published in 2000.

Other departing surveys (such as Berger and Humphrey's [1992] "Measurement and efficiency issues in commercial banking") are book chapters, handbooks, or notes that, despite their relevance, cannot be found in the SCOPUS database. In addition, it is still possible that some of the important surveys were missed during the refinements. The search strings in fact are not perfect; they need constant updates with the great amount of information and publications that have been daily added in the scientific literature.

## **5. Classification of literature**

The United Nations' International Standard Industrial Classification (ISIC) of All Economic Activities provides an international reference for the classification of productive activities that can be used for the collection, reporting and comparison of statistical data among different countries and regions worldwide. The ISIC uses a top-down methodology to aggregate categories as homogenous as possible, which identifies the section, division, group, and the class with the highest share of value added. The 21 ISIC areas of economic activities in Table 3 are used to identify, in a straightforward manner, the gaps and overlaps in the surveys of efficiency analysis applications. We have included a subdivision from the alternative structure for ISIC (United Nations, 2008, pp. 282–286) as a main area so that, for the purpose of this work, we consider 22 categories instead of 21.

There are nine ISIC categories for which no empirical survey exists. Obviously, these categories provide excellent potential opportunities for new empirical surveys provided that sufficient empirical frontier performance studies have focused on the underlying sectors. For the other ISIC categories one observes the existence of a minimum of one to a maximum of 24 empirical surveys. The three ISIC categories with the highest potential for overlap are "Agriculture, forestry and fishing" (24 studies), "Transportation and storage" (24 studies), and "Financial and insurance activities" (21 studies).

There seems to be a considerable discussion in the surveys regarding the size and ownership structure (whether public or private) as potential determinants of the performance (e.g., for airports), while considerations on the scope, geographical location, and diversification characterize agriculture studies.

In this paper we adopt both the ISIC classification and the JEL classification. Both classifications are used for two reasons. The first is to see how the fields are interconnected with each other. It would be very difficult (and unpractical) to construct the cluster visualization with only 22 nodes for the United Nation's ISIC of all economic activities. On the other hand, using 125 of the JEL codes is useful to observe how they relate with each other by means of methods, models, concepts, and



Table 3  
ISIC sectors of economic activities

ISIC main category	Number of publications
1. Agriculture, forestry, and fishing	24
2. Mining and quarrying	0
3. Manufacturing	1
4. Electricity, gas, steam, and air conditioning supply	16
5. Water supply; sewerage, waste management, and remediation activities	10
6. Construction	0
7. Wholesale and retail trade; repair of motor vehicles and motorcycles	0
8. Transportation and storage	24
9. Accommodation and food service activities	0
10. Information and communication	0
11. Financial and insurance activities	21
12. Real estate activities	1
13. Professional, scientific, and technical activities	0 <sup>a</sup>
14. Administrative and support service activities	0
15. Public administration and defense; compulsory social security	6
16. Education	3
17. Human health and social work activities	13
18. Arts, entertainment, and recreation	0
19. Other service activities	2
20. Activities of households as employers; undifferentiated goods and services producing activities of households for own use	0
21. Activities of extraterritorial organizations and bodies	0
22. Environment, sustainability, conservation and wildlife <sup>b</sup>	5

<sup>a</sup>“Professional, scientific and technical activities” area has been included in the “Education” area.

<sup>b</sup>Additional area included from the alternative structure for ISIC, Rev.4 group 949 (United Nations 2008, pp. 283–284) for the purpose of this survey.

economic activities (many fields share the same structure of analysis and approach similar concepts, despite their differences).

Second is to evaluate these different concepts. The United Nation’s ISIC of all economic activities is the main international reference for the classification of productive activities worldwide. For practical reasons, however, the ISIC classification does not provide categories for specific economic surveys, concepts, methods, regions, or decision units we want to consider in the comparison among the surveys. Besides classifying and tracing gaps and overlaps, we want to assess which methodologies (e.g., semiparametric, nonparametric, panel data, location analysis) and economic concepts (such as privatization, monopolies, asymmetric information, among others) have been discussed in the literature. For this reason we combine both classifications, in order to develop a more complete framework on the surveys for the interested audience.

Table 4 presents the information regarding these empirical reviews in terms of the main areas of application based on the ISIC classification of economic activities (United Nations, 2008) and the JEL classification on economics fields. In particular, Table 4 has each of the empirical surveys attributed into one of the ISIC sections and their associated JEL codes. For instance, Hollingsworth (2003), who surveyed 188 published papers on frontier efficiency analysis in hospitals and health

Table 4  
Empirical surveys classification

ISIC broad classification	Bibliography list	JEL code
Agriculture, forestry, and fishing	Baležentis (2014)	C14, C40, Q10
	Battese (1992)	N50, O13, Q10
	Bravo-Ureta and Pinheiro (1993)	Q10, Q12
	Bravo-Ureta et. al (2007)	Q12, D24
	Coelli, (1995)	Q10, C14, D24
	Djokoto (2015)	Q10, Q18, D24
	Djokoto and Gidiglo (2016)	Q10, Q13
	Djokoto et al. (2016)	D24, Q12
	Färe et al. (2013)	Q10, C14
	Gorton and Davidova (2004)	L25; Q12
	Iiiyasu et al. (2014a)	Q22, Q10, Q12
	Iiiyasu et al. (2014b)	Q22, D24
	Morrison et. al (2010)	L72, N57, P28, Q22
	Mareth et al. (2017)	Q02, Q12, L25, R30, Q18
	Minviel and Latruffe (2017)	C83, Q12, Q18, D24
	Ogundari (2014)	N57, O13, Q18
	Ogundari and Brümmer (2011)	N57, O13, P32, Q10
	Ogundari et al. (2012)	O13, P32, Q10, N57
	Oude Lansink and Wall (2014)	D22, Q15, Q56, Q57
	Pereira and Marques (2017)	Q15, Q10, Q25
	Salehirad and Sowlati (2006)	Q02, N52
	Thiam et al. (2001)	Q10
	Tyteca (1996)	Q57
Zhang and Choi (2014)	Q00, Q01, Q50, Q40	
Education and research <sup>a</sup>	De Witte and López-Torres (2017)	I21, I23, C14, I20
	Rhaïem (2017)	I20, I23
	Worthington (2001)	I21
Electricity, gas, steam, and air conditioning supply	Chung (2011)	Q00, Q49, N70
	Filippini and Orea (2014)	C51, D12, D24, Q40
	Haney and Pollitt (2009)	Q40, L95, M38, Q48
	Haney and Pollitt (2011)	Q40, M38, Q48
	Haney and Pollitt (2013)	Q40, M38, Q48
	Jamasb and Pollitt (2000)	Q49, L50
	Jamasb and Pollitt (2007)	Q48, L50
	Jamasb et al. (2003)	Q49, L50, D82
	Jamasb et al. (2005)	L52, L94, Q48
	Longo et al. (2016)	Q001, L94, Q51, O13, C20, C60, C67
	Martin-Gamboa et al. (2017)	Q01, Q40
	Meng et al. (2016)	Q001, L94, Q51, O13
	Li and Tao (2017)	Q01, Q40, L94, Q48
	Shang et al. (2017)	Q40
	Wang and Wu (2013)	Q40, Q41
	Zhou et al. (2008)	Q50, Q40

*Continued*

Table 4  
Continued

ISIC broad classification	Bibliography list	JEL code
Environment, sustainability, conservation, and wildlife organizations	Dyckhoff and Allen (2001)	Q00, Q57
	Ibáñez-Forés et al. (2014)	Q40, P28, L60, L61, L65, L66, Q25
	Song et al. (2012)	Q50, C67
	Sowlati (2005)	C67, C14, Q23
	Zhou et al. (2018)	Q01, Q56
Financial and insurance activities	Aiello and Bonanno (2016)	C13, C14, C80, D24, G21, L25
	Aiello and Bonanno (2018)	C13, C80, G20, G21, L25
	Altunbaş et al. (2001)	G21, D21, G23
	Ashton and Hardwick (2000)	G20, D61, G21
	Berger and Humphrey (1992)	G20, G21, G22, G23, G24, G28, G29
	Berger and Humphrey (1997)	G20, G21, G22, G23, G24, G28, G29
	Berger et al. (1993)	G20, G21, G22, G23, G24, G28, G29
	Berger (2007)	G20, G21, G22, G23, G24, G28, G29
	Berger et al. (1999)	G21, G28, G34, E58, L89
	Colwell and Davis (1992)	G20, C14, D24
	DeYoung et al. (2009)	G21, G34
	Eling and Luhnén (2010)	G22, I13, J65
	Fethi and Pasiouras (2010)	G21
	Galagedera (2003)	D92, E22, F21, G11, G24, G31, H54, O16, P45, R42, R53
	Iršová and Havránek (2010)	C13, G21, L25
	Jreisat and Paul (2010)	E50, G21
	Kaffash and Marra (2017)	G21, G22, E50, C83
	Macoris et al. (2016)	G20, G21, C67
	Paradi and Zhu (2013)	E50, G21
	von Furstenberg (2008)	G21, G20, R30, R12
Worthington (2010)	G21, G20	
Other (general) services	Becker et al. (2013)	L80, C44
	White and Bordoloi (2014)	L80 C44, C67
Human health and social work activities	Hadji et al. (2014)	I10, I11, C67, C44, C14, D24
	Hollingsworth (2003)	I10, C14
	Hollingsworth (2008)	I10, D24
	Hollingsworth et al. (1999)	I10, I13, L33, C67
	Kiadaliri et al. (2013)	I18
	Lovell (2006)	I10
	Mariano et al. (2015)	O15
	Marlin et al. (1999)	I10, I11
	O'Neill et al. (2008)	I18
	Pelone et al. (2015)	I11, I10
	Rosko and Mutter (2008)	I10
	Rosko and Mutter (2011)	I10, C67
Worthington (2004)	I10	
Manufacturing	Wu (1993)	L60, L61, L65, L66, L67, L68

*Continued*

Table 4  
Continued

ISIC broad classification	Bibliography list	JEL code
Public administration and defense	Narbón-Perpiñá and De Witte (2018a)	H70
	Narbón-Perpiñá and De Witte (2018b)	H70
	St. Aubyn (2008)	D24, K40, H59
	Voigt (2016)	K40
	Worthington and Dollery (2000)	H70
	Zanakis et al. (1995)	H53, H83
Real estate activities	Anderson et al. (2000)	L85, R30
Transportation and storage	Brons et al. (2005)	O18, C14, N70
	Catalano et al. (2019)	O18, L90, L92
	Cavaignac and Petiot (2017)	L90, L91, L92, L93, O18
	Daraio et al. (2016)	R41, R42
	De Borger et al. (2002)	R40, O18
	Dmitry (2012)	L93
	Fasone and Zapata-Aguirre (2016)	L93, D24
	Gong et al. (2012)	R49, O18, L33
	González and Trujillo (2009)	O18, R40
	Graham (2005)	L93
	Humphreys and Francis (2002)	Q48
	Jarboui et al. (2012)	C14, C67, C83, D24, L92, N70, R40
	Lai et al. (2012)	L93, L33, L25
	Liebert and Niemeier (2013)	L93
	Markovits-Somogyi (2011a)	L90, L91, L92, L93, R15
	Markovits-Somogyi (2011b)	L90, L91, L92, L93, O18, C67
	Markovits-Somogyi (2011c) <sup>a</sup>	L90, L91, L92, L93, R15, L33
	Merkel and Holmgren (2017)	L90
	Odeck and Bråthen (2012)	R49, C23, C21
	Oum et al. (1999)	L92, L50
	Panayides et al. (2009)	O18
	Shen et al. (2015)	L90, L92
	Smith (2005)	L50, L92
Suárez-Alemán et al. (2014)	L90, L99	
Water supply; sewerage, waste management, and remediation	Abbott and Cohen (2009)	L95, Q25
	Allesch and Brunner (2014)	Q53 D61 Q25 C44
	Ananda (2014)	Q25, L32, R38, C61
	Berg and Marques (2011)	L95, Q25, Q53
	Hu et al. (2016)	Q53, Q25
	Saal et al. (2013)	L95, Q25, Q001
	Thanassoulis (2000)	L50, L43, L95, Q25
	Vilanova et al. (2015).	Q25, Q53
	Walter et al. (2009)	L95, Q25, C13, C14
	Worthington (2014)	L95

<sup>a</sup>Combination of “Professional, scientific and technical activities” area with “Education” area.

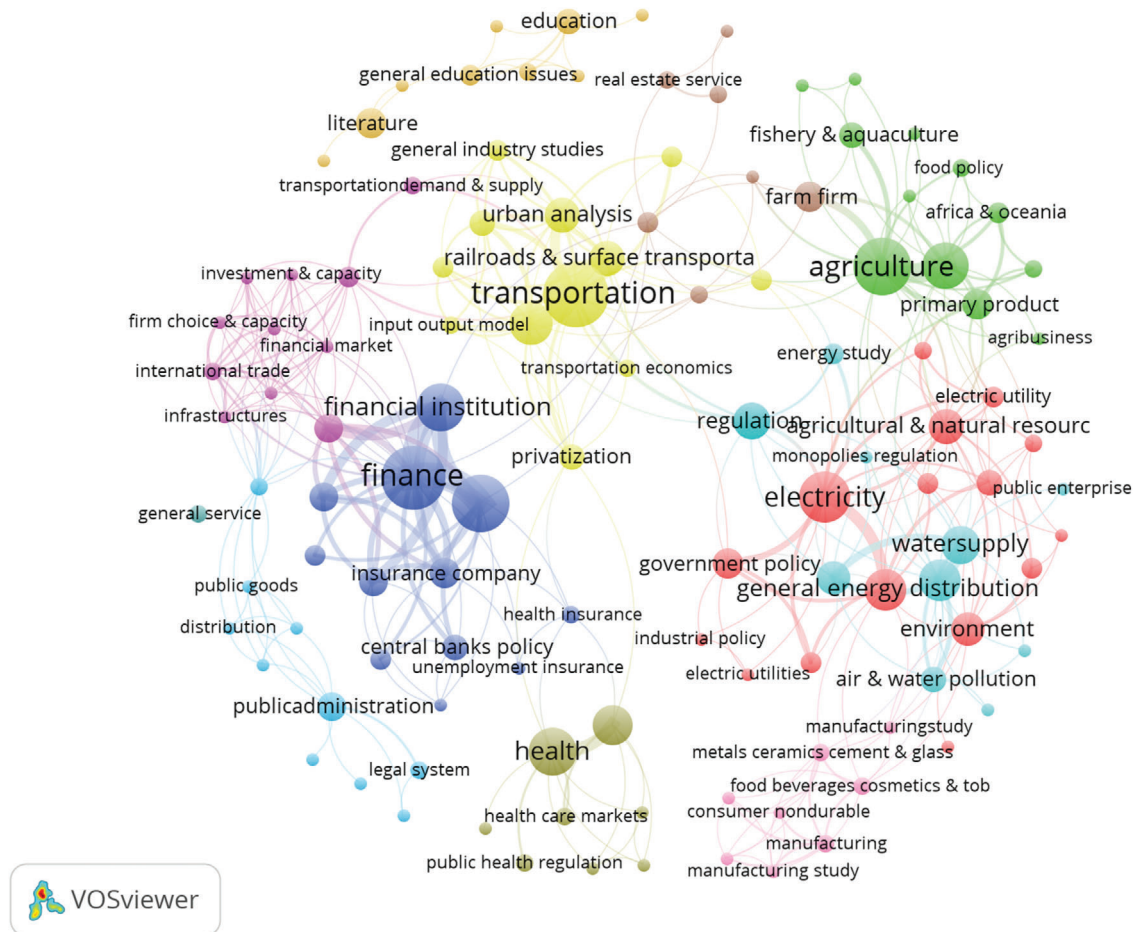


Fig. 2. Network clusters of frontier surveys on empirical application.

care units is classified in the ISIC section “Human health and social work activities” under JEL categories “General Health” (I10) and “Semiparametric and Nonparametric Methods” (C14).

## 6. Mapping the state of the art: identification of empirical gaps and overlaps

The network representation in Fig. 2 is designed with the support of the Vosviewer tool (Van Eck and Waltman, 2010). It consists of 95 interconnected nodes (JEL terms) designed by the ISIC networks of agriculture, finance, health, environment, public administration, transportation, electricity, and water supply, and 20 JEL terms that are independent (not connected with the other networks) related to the real estate, education, manufacturing, and general services areas. Thus, we have 115 nodes from the 117 economic fields (JEL codes) connected by edges composing the 12 clusters of ISIC empirical categories where at least one survey exists. The cluster visualization is constructed using a bibliometric co-occurrence matrix (Van Eck and Waltman, 2010, 2014).

The cluster visualization was constructed using the JEL codes co-occurrence in the surveys, not the references. The number of co-occurrences of two JEL codes is the number of surveys in which both JEL codes occur together. In this network representation, the ISIC areas are connected with each other through the related JEL codes in the surveys. For instance, the Agriculture, Electricity, and Environment ISIC areas present the same JEL codes in some of their surveys (e.g., Dyckhoff and Allen, 2001; Zhou et al., 2008; Song et al., 2012; Ibáñez-Forés et al., 2014; Zhang and Choi, 2014; Martín-Gamboa et al., 2017, they have the JEL codes Q00, Q01, Q40, and Q50, which are related to agricultural, natural resource, environmental, and ecological economics). Because these three areas present such association, the nodes representing their network are connected by edges and set close to each other (see Fig. 2).

Broadly speaking, the networks representing electricity, water, environment, agriculture, and regulation cluster together in space (right side of the visualization), which means they co-occur (i.e., are more related with each other) more often. From the overall set in Table 4, some JEL codes were eliminated since these relate to specific programming methodologies or because these are not relevant for the construction of the map of clusters of empirical surveys.

Table 5 brings the information underneath the network visualization relating each JEL classification code to its correspondent label in the network visualization and providing a relevance score for each JEL class. This allows us a more sophisticated way to identify important empirical gaps and overlaps. The relevance score in the last column of Table 5 measures the level of specificity or generality in the JEL codes composing the noun labels in the classification of each survey (Van Eck and Waltman, 2014).<sup>2</sup> Empirical areas have high relevance score when they co-occur with a very limited set of other JEL codes, whereas lower relevance score JEL codes designate more generic fields of application. For instance, the JEL codes labels representing the ISIC “Agriculture, forestry and fishing” category (i.e., general agriculture, family farms, agribusiness, primary products, etc.) have high incidence and co-occur with energy, with environmental studies, with food policy, fishery, aquaculture, industrial policies, water resources, natural resource, ecology, and sustainable development. This makes Agriculture to obtain a low relevance score and be a generic area of application compared to Real Estate, which besides occurs just once (in one survey) it co-occurs only with itself (i.e., with JEL codes representing real estate services, general real estate markets, spatial production analysis, or firm location).

Real Estate Services, Local Government, and Manufacturing (Metals, Cement, Glass, Ceramics, Rubber, Drugs, Food, Beverages, Cosmetics, Tobacco, Clothing, Textiles, Shoes, and Leather) are the classes with the higher relevance scores, that is, the applications regarding efficiency analysis through frontier methodologies having been weakly covered by surveys in these sectors and are limited to studies within these fields. Water Resource, Road Maintenance, Transportation Planning, General Health issues, Banking, Investment, Financial Institutions, General Agriculture, and Natural Resources have the greatest coverage. These are the classes with smallest relevance scores, that is, more generic areas of empirical efficiency analysis interacting sharply with other areas of economic activity.

The spider-chart in Fig. 3 combines this information accessed from network mapping in Table 4 (JEL classification) with the ISIC main areas for a more comfortable visualization on gaps and overlaps. The Degree of Generality is defined as the inverse of the relevance score. The scale difference

<sup>2</sup>This analysis is based on the systematic search performed on 13 January 2017.

Table 5  
Fields, labels, and relevance

JEL codes	Description	Map label	Occurrence	Relevance score
A20	General economic education and teaching of economics	Economic education and teaching	1	2.1315
C13	General estimation methods	Econometric estimation method	3	0.2569
C14	Semiparametric and nonparametric methods: general	Semiparametric and nonparametric method	15	0.1677
C20	General single equation models, single variables	Single equation models	1	0.8293
C21	Cross-sectional models, spatial models, treatment effect models, quantile regressions	Cross-sectional models	1	1.4403
C23	Panel data models, spatiotemporal models	Panel data models	1	1.034
C40	General econometric and statistical methods: special topics	General statistical methods	1	0.5671
C44	Operations research, statistical decision theory	Operations research	8	0.8086
C51	Model construction and estimation	Model construction	1	0.7161
C60	General mathematical methods, programming models, mathematical and simulation modeling	Programming models	2	0.6639
C67	Input–output models	Input and output models	16	0.2478
C80	General data collection and data estimation methodology, computer programs	Data collection and estimation	2	0.2158
C83	Survey methods	Survey method	3	0.3167
D12	Consumer economics: empirical analysis	Consumer economics	1	0.7161
D21	Firm behavior: theory	Firm behavior	1	0.462
D22	Firm behavior: empirical analysis	Empirical firm behavior	1	1.4737
D24	Production, cost, capita, capital, total factor, and multifactor productivity, capacity	Production and productivity	14	0.2132
D61	Allocative efficiency, cost–benefit analysis	Allocative efficiency and cost benefit	2	0.6135
D82	Asymmetric and private information, mechanism design	Asymmetric information	1	1.0096
D92	Intertemporal firm choice, investment, capacity, and financing	Firm choice and capacity	1	0.7018
E22	Investment, capital, intangible capital, capacity	Investment and capacity	1	0.7018
E50	General monetary policy, central banking, and the supply of money and credit	Monetary policy	4	0.444
E58	Central banks and their policies	Central banks' policy	3	0.444

*Continued*

Table 5  
Continued

JEL codes	Description	Map label	Occurrence	Relevance score
E60	General macroeconomic policy, macroeconomic aspects of public finance, and general outlook	Macroeconomic policy	1	2.1274
F21	International investment, long-term capital movements	International investment	1	0.7018
G11	Portfolio choice, investment decisions	Investment decision	1	0.7018
G20	General financial institutions and services	Financial institution	15	0.3369
G21	Banks, depository institutions, micro finance institutions, mortgages	Banks and depository institution	23	0.3554
G22	Insurance, insurance companies, actuarial studies	Insurance company	7	0.4247
G23	Nonbank financial institutions, financial instruments, institutional investors	Nonbank financial institution	5	0.4528
G24	Investment banking, venture capital, brokerage, ratings, and ratings agencies	Investment banking and ratings	5	0.4053
G28	Government policy and financial institution regulation	Bank regulation	5	0.4514
G29	Other financial institutions and services	Financial institution	4	0.4536
G31	Capital budgeting, fixed investment and inventory studies, capacity	Inventory study	1	0.7018
G34	Mergers, acquisitions, restructuring, corporate governance	Corporate governance	3	0.4462
H40	General publicly provided goods	Public goods	1	1.6822
H51	Government expenditures and health	Health government expenditure	1	1.1386
H53	Government expenditures and welfare programs	Government programs	1	2.1274
H54	Infrastructures, other public investment and capital stock	Infrastructures	1	0.7018
H59	Other national government expenditures and related policies	Government expenditure	1	1.1172
H70	General state and local government, intergovernmental relations	Local government	3	2.1274
H75	State and local government: health, education, welfare, public pensions	Local government application	1	1.488
I10	Health	General health issues	11	0.6159
I11	Analysis of health care markets	Health care markets	2	0.6172
I13	Health insurance, public and private	Health insurance	2	0.3275
I18	Government policy, regulation, public health	Public health regulation	2	1.1271
I20	General education and research institutions	General education issues	1	2.1315
I21	Analysis of education	Education analysis	2	1.3188

*Continued*



Table 5  
Continued

JEL codes	Description	Map label	Occurrence	Relevance score
I23	Higher education, research institutions	Higher education	1	1.1416
K32	Environmental, health, and safety law	Environmental and health law	1	1.1386
K40	General legal procedure, the legal system, and illegal behavior	Legal system	2	1.2989
L00	General industrial organization	Industrial organization	1	0.7332
L25	Firm performance: size, diversification, and scope	Firm performance	1	0.9563
L30	General nonprofit organizations and public enterprise	Nonprofit organizations	1	1.6822
L32	Public enterprises, public/private enterprises	Public enterprises	1	1.7579
L33	Comparison of public and private enterprises and nonprofit institutions, privatization, contracting out	Privatization	2	0.4719
L43	Legal monopolies and regulation or deregulation	Monopolies regulation	1	1.0342
L50	General regulation and industrial policy	Regulation	3	0.7925
L52	Industrial policy, sectoral planning methods	Industrial policy	1	1.1783
L60	General industry studies: manufacturing	Manufacturing study	2	1.6321
L61	Metals and metal products, cement, glass, ceramics	Metals ceramics, cement, and glass	1	1.5533
L65	Chemicals, rubber, drugs, biotechnology	Chemicals rubber, drugs, and biotechnology	1	2.0315
L66	Food, beverages, cosmetics, tobacco, wine and spirits	Food beverages, cosmetics, and tobacco	1	1.5533
L67	Other consumer nondurables: clothing, textiles, shoes, and leather goods; household goods; sports equipment	Consumer nondurable	1	2.0315
L68	Appliances, furniture, other consumer durables	Consumer durable	1	2.0315
L72	Mining, extraction, and refining: other nonrenewable resources	Mining extraction and refining	1	0.9653
L80	General industry studies: services	General service	2	1.0167
L85	Real estate services	Real estate service	1	2.6691
L89	Other industry services	Services	1	
L90	General industry studies: transportation and utilities	General transportation	4	0.7523
L91	Transportation: general	Seaports and other transportation	1	0.7426
L92	Railroads and other surface transportation	Railroads and surface transportation	8	0.598
L93	Air transportation	Air transportation	9	0.7158

*Continued*

Table 5  
Continued

JEL codes	Description	Map label	Occurrence	Relevance score
L94	Electric utilities	Electric utilities	1	0.9273
L95	Gas utilities, pipelines, water utilities	Gas and water utilities	7	0.7872
L99	Other industry studies: transportation and utilities	General industry studies	3	0.8665
M11	Production management	Production management	2	1.8483
M38	Government policy and regulation	Government regulation	3	1.0275
N50	General, international, or comparative environment and extractive industries	Extractive industry	1	1.0458
N57	Africa, Oceania	Africa and Oceania	4	0.9522
N70	General, international, or comparative transport, trade, energy, technology, and other services	International services	3	0.3519
O13	Agriculture, natural resources, energy, environment, other primary products	Primary product	5	0.973
O15	Human resources, human development, income distribution, migration	Human resource	1	1.1271
O16	Financial markets, saving and capital investment, corporate finance and governance	Financial market	1	0.8976
O18	Urban, rural, regional, and transportation analysis, housing, infrastructure	Urban analysis	9	0.7408
O30	General innovation, research and development, technological change, intellectual property rights	General innovation	1	1.2727
P28	Natural resources, energy, environment	Natural resource	1	1.2078
P32	Collectives, communes, agriculture	Communes agriculture	2	0.9615
P36	Consumer economics, health, education and training, welfare, income, wealth, and poverty	Consumer welfare economics	1	1.1386
P45	International trade, finance, investment, and aid	International trade	2	0.7018
Q00	General agricultural and natural resource economics, environmental and ecological economics	Agricultural and natural resource	8	0.5965
Q01	Sustainable development	Sustainable development	1	0.885
Q02	Commodity markets	Commodity	2	0.9466
Q10	General agriculture	General agriculture	13	0.6751
Q12	Micro analysis of farm firms, farm households, and farm input markets	Farm firm	6	0.7564
Q13	Agricultural markets and marketing, cooperatives, agribusiness	Agribusiness	1	0.8989

*Continued*

Table 5  
Continued

JEL codes	Description	Map label	Occurrence	Relevance score
Q15	Land ownership and tenure, land reform, land use, irrigation, agriculture and environment	Land use	2	1.2326
Q18	Agricultural policy, food policy	Food policy	3	0.7306
Q22	Fishery, aquaculture	Fishery and aquaculture	4	0.7197
Q23	Forestry	Forestry	1	0.5526
Q25	Water	Water resource	1	3.5322
Q40	General energy distribution	General energy distribution	6	0.7762
Q48	Government policy	Government policy	6	0.9556
Q49	Other energy studies	Energy study	3	0.9029
Q50	General environmental economics	General environmental economics	3	1.4016
Q51	Valuation of environmental effects	Environmental effects valuation	2	0.8733
Q53	Air pollution, water pollution, noise, hazardous waste, solid waste, recycling	Air and water pollution	2	1.1839
Q56	Environment and development, environment and trade, sustainability, environmental accounts and accounting, environmental equity, population growth	Environment and trade	1	1.4737
Q57	Ecological economics: ecosystem services, biodiversity conservation, bioeconomics industrial ecology	Ecological economics	3	1.2225
R12	Size and spatial distributions of regional economic activity	Activities spatial distributions	1	0.4339
R15	Econometric and input–output models, other models	Input–output models	1	0.8363
R30	General real estate markets, spatial production analysis, and firm location	General real estate markets	1	2.6691
R40	General transportation economics	General transportation economics	3	0.5564
R41	Transportation: demand, supply, congestion, travel time, safety and accidents, transportation noise	Transportation demand and supply	2	0.6367
R42	Government and private investment analysis, road maintenance, transportation planning	Transportation planning	3	0.5463
R49	Other transportation economics	Transportation economics	2	0.9807
R53	Public facility location analysis, public investment and capital stock	Public facility location analysis	2	0.7018

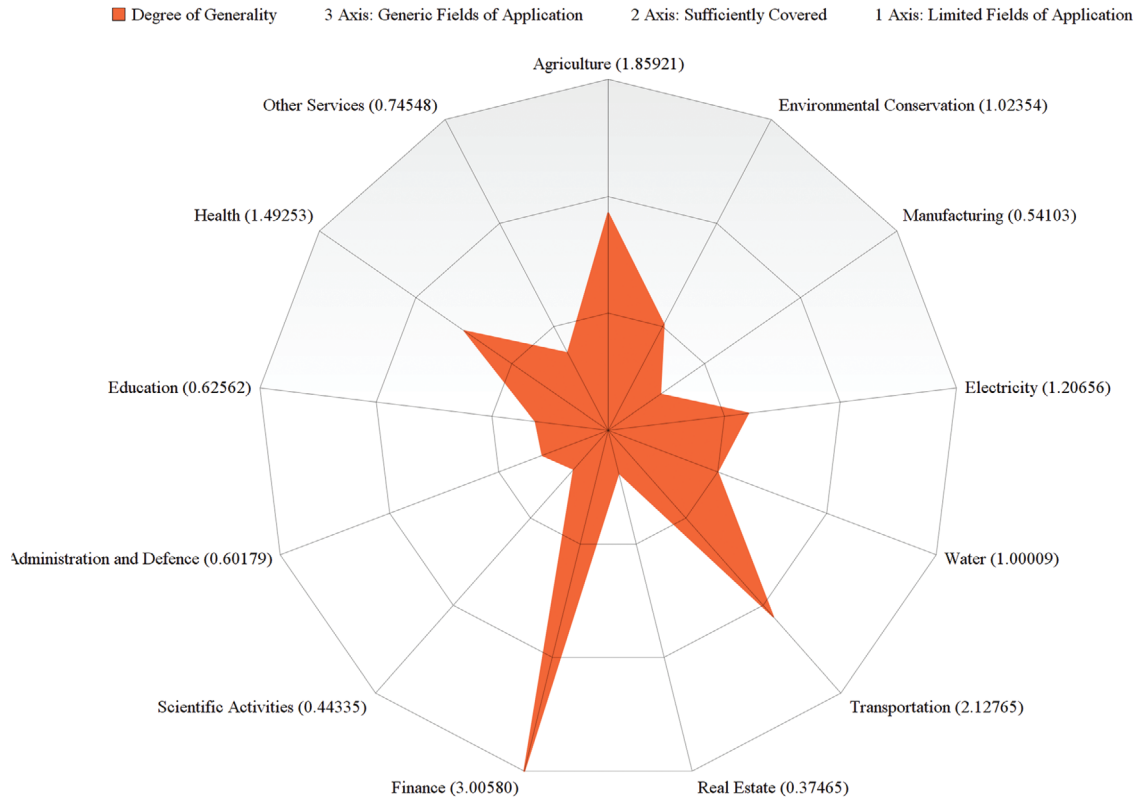


Fig. 3. Chart of gaps and overlaps (ISIC categories).

in the chart visualization becomes larger with small degrees of generality. In the proposed network it ranges between 0 and 3. The first axis in the chart is reserved for the limited fields of empirical frontier application surveys (degree of generality between 0 and 1). The service industry, manufacturing, real estate, scientific activities, education, public administration, and defense compose this category. The second axis represents the fields with sufficient surveys on applications, both in number of publications and co-occurrences with other fields (degree of generality between 1 and 2). The fields of agriculture, environmental studies, energy, health, water supply, and sanitation has been sufficiently covered by surveys of frontier application. The third axis has the more generic fields of frontier application (degree of generality between 2 and 3) because of the great number of surveys and co-occurrences with general JEL codes representing fields, concepts, and methodologies of the economic classification. Only two areas reach out this category: the financial market and transportation industry.

## 7. Concluding remarks

The key purpose of this contribution has been to provide a kind of meta-survey of empirical surveys of frontier applications applied to a wide variety of economic sectors. The basic methodology applied is a “light” version of a systematic review approach suitable for the MSs.

Starting from a prior list of 104 surveys, identified on an expert-based knowledge, the most prominent terms are selected by considering their incidence volume and their interaction with other relevant keywords (see Fig. 1 for a density map of keywords). These strings have been combined in a series of queries applied in a refinement procedure as presented in Table 2. This has led to a total of 126 final relevant empirical surveys.

We opted for a rather universal taxonomy of economic activity by adopting the ISIC of All Economic Activities as proposed in the United Nations (2008). This has led to identify in a straightforward manner gaps and overlaps in the empirical surveys in Table 3 based on the ISIC 21 main areas of economic activities. We identified nine ISIC categories for which no empirical survey exists at all: Mining and Quarrying; Construction; Wholesale, Retail Trade and Repair of Motor Vehicles; Accommodation and Food Services; Information and Communication; Administrative and Support Service Activities; Arts, Entertainment, and Recreation; Activities of Households as Employers; and Activities of Extraterritorial Organizations. These ISIC categories offer excellent opportunities for new empirical surveys. We also identified three ISIC categories with the highest potential for overlap, these are: Financial and Insurance Activities; Transportation and Storage; and Agriculture, Forestry, and Fishing. Table 4 lists each empirical survey allocated to one of the ISIC sections and the associated JEL codes.

We offer then a new covering of the different areas with the combination of the ISIC areas of economic activities with the standard codes of the JEL codes. Some contribution can be highlighted from the bibliometric perspective.

Let us conclude by summarizing the main limitations and strengths of our applied meta-review methodology. About the limitations of our approach, it is possible that some of the important surveys of frontier applications were missed during the refinements.<sup>3</sup> The search strings are not perfect; they need constant updates with the great amount of information and publications that are added daily in the scientific literature. Another limitation concerns the bibliometric methodology of co-occurrences. Some networks are characterized by a small set of publications interacting with many others. Those networks show high relevance scores, though these are poorly covered (by number of publications). Despite crucial in many circumstances, this is barely an issue in this evaluation because the areas with low generality (high relevance score) have both a few numbers of surveys and interact with only few other surveys, and the areas with low specificity (low relevance score) have a considerable number of surveys and interactions (see Table 3 and Fig. 3).

About the strengths of our proposal, some contributions can be highlighted from a bibliometric perspective. The covering evaluation provides the level of specificity or generality for the surveyed areas of frontier empirical applications. The relevance score measuring this coverage is high when the amount of published surveys in the specific field is low and they co-occur with limited (few) areas of the economic activity. Some of the less generic concepts (gaps for surveys and empirical applications), that is, with the higher relevance scores, are the efficiency analysis in the teaching of economics, real estate, public administration and police, spatial production analysis, firm location, welfare programs, intergovernmental relations, chemicals, rubber, drugs, and other consumer nondurables (see Table 5).

<sup>3</sup>Some examples of recent surveys not included in our study are Assaf and Josiassen (2016), Marchetti and Wanke (2019), Soheilrad et al. (2018), Jia (2016), and Mahmoudi et al. (2019).

When the relevance score measuring the coverage area is low, then the amount of published surveys in the specific field must be high and they must also co-occur with many areas of the economic activity. Those are the most generic (overlapping) areas and concepts. Banks, depository institutions and finance-related issues, public and private structures, general or comparative studies on transport, technology, and the concepts related to the models or methods such as estimation methods, input–output models, data collection and estimation, production, total factor and multifactor productivity, and semi-parametric and nonparametric methods are some of the most overlapping issues from the JEL classification in the analyzed surveys.

Another contribution from this analysis is the proposal of a systematic search process based on a bibliometric methodology, which results in the most relevant key terms by incidence and interaction. The combination of those keywords provides the query strings to construct and update a repository of surveys on recent advances of the efficiency and productivity analysis. In Daraio et al. (2019), an article about the software options available for efficiency and productivity analysis, we highlight the need for standards and coding to develop an Open Source Dynamic Digital Repository of software in this field. To the best of our knowledge, in this work we have provided a collection of all existing published evidence about the empirical surveys on frontier efficiency applications and approached concepts and discussions as the base for additional investigations.

## References

- Abbott, M., Cohen, B., 2009. Productivity and efficiency in the water industry. *Utilities Policy* 17, 3–4, 233–244.
- Aiello, F., Bonanno, G., 2016. Efficiency in banking: a meta-regression analysis. *International Review of Applied Economics* 30, 1, 112–149.
- Aiello, F., Bonanno, G., 2018. On the sources of heterogeneity in banking efficiency literature. *Journal of Economic Surveys* 32, 1, 194–225.
- Aigner, D., Lovell, C.A.K., Schmidt, P., 1977. Formulation and estimation of stochastic production function models. *Journal of Econometrics* 6, 1, 21–37.
- Allen, K., 1999. DEA in the ecological context—an overview. In Westermann, G. (ed.) *Data Envelopment Analysis in the Service Sector*, Gabler Edition. Wissenschaft, Wiesbaden, pp. 203–235.
- Allesch, A., Brunner, P.H., 2014. Assessment methods for solid waste management: a literature review. *Waste Management & Research* 32, 6, 461–473.
- Altunbaş, Y., Gardener, E.P., Molyneux, P., Moore, B., 2001. Efficiency in European banking. *European Economic Review* 45, 10, 1931–1955.
- Ananda, J., 2014. Evaluating the performance of urban water utilities: robust nonparametric approach. *Journal of Water Resources Planning and Management* 140, 9, 04014021.
- Anderson, R.I., Lewis, D., Springer, T.M., 2000. Operating efficiencies in real estate: a critical review of the literature. *Journal of Real Estate Literature* 8, 1, 1–18.
- Ashton, J., Hardwick, P., 2000. Estimating inefficiencies in banking: a survey. *Journal of Interdisciplinary Economics* 11, 1, 1–33.
- Assaf, A.G., Josiassen, A., 2016. Frontier analysis: a state-of-the-art review and meta-analysis. *Journal of Travel Research* 55, 5, 612–627.
- Baležentis, T., 2014. On measures of the agricultural efficiency—a review. *Transformation in Business & Economics* 13, 3, 110–131.
- Banker, R.D., Charnes, A., Cooper, W.W., 1984. Some models for estimating technical and scale inefficiencies in data envelopment analysis. *Management Science* 30, 9, 1078–1092.
- Battese, G.E., 1992. Frontier production functions and technical efficiency: a survey of empirical applications in agricultural economics. *Agricultural Economics* 7, 1, 185–208.

- Becker, J., Beverungen, D., Breuker, D., Dietrich, H.A., Rauer, H.P., 2013. Guidelines for reporting productivity studies—a review of the reproducibility of data envelopment analysis in the service sector. *International Journal of Services and Operations Management* 16, 3, 407–425.
- Berg, S., Marques, R., 2011. Quantitative studies of water and sanitation utilities: a benchmarking literature survey. *Water Policy* 13, 5, 591–606.
- Berger, A.N., 2007. International comparisons of banking efficiency. *Financial Markets, Institutions & Instruments* 16, 3, 119–144.
- Berger, A.N., Demsetz, R.S., Strahan, P.E., 1999. The consolidation of the financial services industry: causes, consequences, and implications for the future. *Journal of Banking & Finance* 23, 2–4, 135–194.
- Berger, A., Humphrey, D., 1992. Measurement and efficiency issues in commercial banking. In Griliches, Z. (ed.) *Output Measurement in the Service Sectors*. University of Chicago Press, Chicago, IL, pp. 245–279.
- Berger, A., Humphrey, D., 1997. The efficiency of financial institutions: international survey and directions for future research. *European Journal of Operational Research* 98, 2, 175–212.
- Berger, A., Hunter, W., Timme, S., 1993. The efficiency of financial institutions: a review and preview of research past, present, and future. *Journal of Banking & Finance* 17, 2–3, 221–249.
- Bravo-Ureta, B., Pinheiro, A.E., 1993. Efficiency analysis of developing country agriculture: a review of the frontier function literature. *Agricultural and Resources Economics Review* 22, 1, 88–101.
- Bravo-Ureta, B., Solís, D., Moreira López, V.H., Maripani, J.F., Thiam, A., Rivas, T., 2007. Technical efficiency in farming: a meta-regression analysis. *Journal of Productivity Analysis* 27, 1, 57–72.
- Brons, M., Nijkamp, P., Pels, E., Rietveld, P., 2005. Efficiency of urban public transit: a meta analysis. *Transportation* 32, 1, 1–21.
- Catalano, G., Daraio, C., Diana, M., Gregori, M., & Matteucci, G., 2019. Efficiency, effectiveness, and impacts assessment in the rail transport sector: a state-of-the-art critical analysis of current research. *International Transactions in Operational Research* 26, 1, 5–40.
- Cavaignac, L., Petiot, R., 2017. A quarter century of data envelopment analysis applied to the transport sector: a bibliometric analysis. *Socio-Economic Planning Sciences* 57, 84–96.
- Charnes, A., Cooper, W.W., Rhodes, E., 1978. Measuring the efficiency of decision making units. *European Journal of Operational Research* 2, 6, 429–444.
- Chung, W., 2011. Review of building energy-use performance benchmarking methodologies. *Applied Energy* 88, 5, 1470–1479.
- Coelli, T., 1995. Recent developments in frontier modelling and efficiency measurement. *Australian Journal of Agricultural Economics* 39, 3, 219–245.
- Colwell, R., Davis, E., 1992. Output and productivity in banking. *Scandinavian Journal of Economics* 94, S, 111–129.
- Cooper, H.M., 1988. Organizing knowledge syntheses: a taxonomy of literature reviews. *Knowledge in Society* 1, 1, 104–126.
- Cooper, H., Hedges, L.V., 2009. Research synthesis as a scientific process. In Cooper, H., Hedges, L.V., Valentine, J.C. (eds) *The Handbook of Research Synthesis and Meta-Analysis* (2nd edn). Russell Sage Foundation, New York, pp. 3–16.
- Cummins, D., Weiss, M., 2000. Analyzing firm performance in the insurance industry using frontier efficiency and productivity methods. In Dionne, G. (ed.) *Handbook of Insurance*. Kluwer, Boston, MA, pp. 767–829.
- Daraio, C., Diana, M., Di Costa, F., Leporelli, C., Matteucci, G., Nastasi, A., 2016. Efficiency and effectiveness in the urban public transport sector: a critical review with directions for future research. *European Journal of Operational Research* 248, 1, 1–20.
- Daraio, C., Kerstens, K.H., Nepomuceno, T.C.C., Sickles, R., 2019. Productivity and efficiency analysis software: an exploratory bibliographical survey of the options. *Journal of Economic Surveys* 33, 1, 85–100.
- de Borger, B., Kerstens, K., 2000. What is known about municipal efficiency? The Belgian case and beyond. In Blank, J.L.T. (ed.) *Public Provision and Performance: Contributions from Efficiency and Productivity Measurement*. Elsevier, Amsterdam, pp. 299–330.
- de Borger, B., Kerstens, K., 2008. The performance of bus-transit operators. In Hensher, D.A., Button, K.J. (eds) *Handbook of Transport Modelling* (2nd edn). Elsevier, Amsterdam, pp. 693–714.
- de Borger, B., Kerstens, K., Costa, Á., 2002. Public transit performance: what does one learn from frontier studies? *Transport Reviews* 22, 1, 1–38.

- de Witte, K., López-Torres, L., 2017. Efficiency in education: a review of literature and a way forward. *Journal of the Operational Research Society* 68, 4, 339–363.
- DeYoung, R., Evanoff, D.D., Molyneux, P., 2009. Mergers and acquisitions of financial institutions: a review of the post-2000 literature. *Journal of Financial Services Research* 36, 2–3, 87–110.
- Djokoto, J.G., 2015. Technical efficiency of organic agriculture: a quantitative review. *Studies in Agricultural Economics* 117, 2, 67–71.
- Djokoto, J.G., Gidiglo, K.F., 2016. Technical efficiency in agribusiness: a meta-analysis on Ghana. *Agribusiness* 32, 3, 397–415.
- Djokoto, J.G., Srofenyo, F.Y., Arthur, A.A.A., 2016. Technical inefficiency effects in agriculture—a meta-regression. *Journal of Agricultural Science* 8, 2, 109–121.
- Dmitry, P., 2012. Airport benchmarking and spatial competition: a critical review. *Transport and Telecommunication* 13, 2, 123–137.
- Dyckhoff, H., Allen, K., 2001. Measuring ecological efficiency with data envelopment analysis (DEA). *European Journal of Operational Research* 132, 2, 312–325.
- Eling, M., Luhnen, M., 2010. Frontier efficiency methodologies to measure performance in the insurance industry: overview, systematization, and recent developments. *Geneva Papers on Risk and Insurance — Issues and Practice* 35, 2, 217–265.
- Emrouznejad, A., Parker, B.R., Tavares, G., 2008. Evaluation of research in efficiency and productivity: a survey and analysis of the first 30 years of scholarly literature in DEA. *Socio-Economic Planning Sciences* 42, 3, 151–157.
- Emrouznejad, A., Yang, G-l., 2018. A survey and analysis of the first 40 years of scholarly literature in DEA: 1978–2016. *Socio-Economic Planning Sciences* 61, 4–8.
- Färe, R., Grosskopf, S. and Lovell, C.A.K., 1983. The structure of technical efficiency. *Scandinavian Journal of Economics* 85, 2, 181–190.
- Färe, R., Grosskopf, S., Pasurka, C., Martins-Filho, C., 2013. On nonparametric estimation: with a focus on agriculture. *Annual Review of Resource Economics* 5, 1, 93–110.
- Fasone, V., Zapata-Aguirre, S., 2016. Measuring business performance in the airport context: a critical review of literature. *International Journal of Productivity and Performance Management* 65, 8, 1137–1158.
- Fethi, M.D., Pasiouras, F., 2010. Assessing bank efficiency and performance with operational research and artificial intelligence techniques: a survey. *European Journal of Operational Research* 204, 2, 189–198.
- Filippini, M., Orea, L., 2014. Applications of the stochastic frontier approach in the analysis of energy issues. *Economics and Business Letters* 3, 1, 35–42.
- Forsyth, P., 2008. Models of airport performance. In Hensher, D.A., Button, K.J. (eds) *Handbook of Transport Modelling* (2nd edn). Elsevier, Amsterdam, pp. 715–727.
- Fried, H.O., Lovell, C.A.K., Schmidt, S.S., 2008. Efficiency and productivity. In Fried, H., Lovell, C.A.K., Schmidt, S. (eds) *The Measurement of Productive Efficiency and Productivity Change*. Oxford University Press, New York, pp. 3–91.
- Galagedera, D.U.A., 2003. Investment performance appraisal methods with special reference to data envelopment analysis. *Sri Lankan Journal of Management* 8, 1–2, 48–70.
- Gattoufi, S., Oral, M., Kumar, A., Reisman, A., 2004. Epistemology of data envelopment analysis and comparison with other fields of OR/MS for relevance to applications. *Socio-Economic Planning Sciences* 38, 2–3, 123–140.
- Gattoufi, S., Oral, M., Reisman, A., 2004a. Data envelopment analysis literature: a bibliography update (1951–2001). *Socio-Economic Planning Sciences* 38, 2–3, 159–229.
- Gattoufi, S., Oral, M., Reisman, A., 2004b. A taxonomy for data envelopment analysis. *Socio-Economic Planning Sciences* 38, 2–3, 141–158.
- Goddard, J.A., Molyneux, P., Wilson, J.O.S., 2001. *European Banking: Efficiency, Technology and Growth*. Wiley, New York.
- Gong, S.X.H., Cullinane, K., Firth, M., 2012. The impact of airport and seaport privatization on efficiency and performance: a review of the international evidence and implications for developing countries. *Transport Policy* 24, 37–47.
- González, M.M., Trujillo, L., 2009. Efficiency measurement in the port industry: a survey of the empirical evidence. *Journal of Transport Economics and Policy* 43, 2, 157–192.



- Gorton, M., Davidova, S., 2004. Farm productivity and efficiency in the CEE applicant countries: a synthesis of results. *Agricultural Economics* 30, 1, 1–16.
- Graham, A., 2005. Airport benchmarking: a review of the current situation. *Benchmarking: An International Journal* 12, 2, 99–111.
- Hadji, B., Meyer, R., Melikeche, S., Escalon, S., Degoulet, P., 2014. Assessing the relationships between hospital resources and activities: a systematic review. *Journal of Medical Systems* 38, 10, 127.
- Haney, A.B., Pollitt, M.G., 2009. Efficiency analysis of energy networks: an international survey of regulators. *Energy Policy* 37, 12, 5814–5830.
- Haney, A.B., Pollitt, M.G., 2011. Exploring the determinants of “best practice” benchmarking in electricity network regulation. *Energy Policy* 39, 12, 7739–7746.
- Haney, A.B., Pollitt, M.G., 2013. International benchmarking of electricity transmission by regulators: a contrast between theory and practice? *Energy Policy* 62, 267–281.
- Harker, P.T., Zenios, S.A., 2001. What drives the performance of financial institutions? In Harker, P.T., Zenios, S.A. (eds) *Performance of Financial Institutions: Efficiency, Innovation, Regulation*. Cambridge University Press, Cambridge, pp. 3–31.
- Hollingsworth, B., 2003. Non-parametric and parametric applications measuring efficiency in health care. *Health Care Management Science* 6, 4, 203–218.
- Hollingsworth, B., 2008. The measurement of efficiency and productivity of health care delivery. *Health Economics* 17, 10, 1107–1128.
- Hollingsworth, B., Dawson, P.J., Maniadakis, N., 1999. Efficiency measurement of health care: a review of non-parametric methods and applications. *Health Care Management Science* 2, 3, 161–172.
- Hu, M., Fan, B., Wang, H., Qu, B., Zhu, S., 2016. Constructing the ecological sanitation: a review on technology and methods. *Journal of Cleaner Production* 125, 1–21.
- Hughes, J.P., Mester, L.J., 2010. Efficiency in banking: theory, practice, and evidence. In Berger, A.N., Molyneux, P., Wilson, J. (eds) *The Oxford Handbook of Banking*. Oxford University Press, Oxford, pp. 463–485.
- Humphreys, I., Francis, G., 2002. Performance measurement: a review of airports. *International Journal of Transport Management* 1, 2, 79–85.
- Ibáñez-Forés, V., Bovea, M.D., Pérez-Belis, V., 2014. A holistic review of applied methodologies for assessing and selecting the optimal technological alternative from a sustainability perspective. *Journal of Cleaner Production* 70, 259–281.
- Iliyasu, A., Mohamed, Z.A., Ismail, M.M., Abdullah, A.M., 2014a. A meta-analysis of technical efficiency in aquaculture. *Journal of Applied Aquaculture* 26, 4, 329–339.
- Iliyasu, A., Mohamed, Z.A., Ismail, M.M., Abdullah, A.M., Kamarudin, S.M., Mazuki, H., 2014b. A review of production frontier research in aquaculture (2001–2011). *Aquaculture Economics & Management* 18, 3, 221–247.
- Iršová, Z., Havránek, T., 2010. Measuring bank efficiency: a meta-regression analysis. *Prague Economic Papers* 4, 307–328.
- Jacobs, R., Smith, P.C., Street, A., 2006. *Measuring Efficiency in Health Care: Analytic Techniques and Health Policy*. Cambridge University Press, Cambridge.
- Jamasb, T., Mota, R., Newbury, D., Pollitt, M., 2005. *Electricity Sector Reform in Developing Countries: A Survey of Empirical Evidence on Determinants and Performance*. World Bank, Washington (Policy Research WP 3549).
- Jamasb, T., Nillesen, P., Pollitt, M., 2003. Gaming the regulator: a survey. *Electricity Journal* 16, 10, 68–80.
- Jamasb, T., Pollitt, M., 2000. Benchmarking and regulation: international electricity experience. *Utilities Policy* 9, 3, 107–130.
- Jamasb, T., Pollitt, M., 2007. Incentive regulation of electricity distribution networks: lessons of experience from Britain. *Energy Policy* 35, 12, 6163–6187.
- Jarboui, S., Forget, P., Boujelbene, Y., 2012. Public road transport efficiency: a literature review via the classification scheme. *Public Transport* 4, 2, 101–128.
- Jia, J., 2016. Efficiency of Chinese banks: a survey and suggested directions for future research. *Chinese Economy* 49, 4, 239–256.
- Johnes, J., 2007. Efficiency measurement. In Johnes, G., Johnes, J. (eds) *International Handbook on the Economics of Education*. Edward Elgar, Cheltenham, pp. 613–742.
- Jreisat, A., Paul, S., 2010. Banking efficiency in the Middle East: a survey and new results for the Jordanian Banks. *International Journal of Applied Business and Economic Research* 8, 2, 191–209.

- Kaffash, S., Marra, M., 2017. Data envelopment analysis in financial services: a citations network analysis of banks, insurance companies and money market funds. *Annals of Operations Research* 253, 1, 307–344.
- Kiadaliri, A.A., Jafari, M., Gerdtham, U.-G., 2013. Frontier-based techniques in measuring hospital efficiency in Iran: a systematic review and meta-regression analysis. *BMC Health Services Research* 13, 312.
- Koop, G., Steel, M., 2001. Bayesian analysis of stochastic frontier models. In Baltagi, B.H. (ed.) *A Companion to Theoretical Econometrics*. Blackwell, Oxford, pp. 520–537.
- Kumar, S., Gulati, R., 2014. *Deregulation and Efficiency of Indian Banks*. Springer, New Delhi.
- Lai, P.L., Potter, A., Beynon, M., 2012. The development of benchmarking techniques in airport performance evaluation research. *Transportation Journal* 51, 3, 305–337.
- Lampe, H.W., Hilgers, D., 2015. Trajectories of efficiency measurement: a bibliometric analysis of DEA and SFA. *European Journal of Operational Research* 240, 1, 1–21.
- Li, M.J., Tao, W.Q., 2017. Review of methodologies and polices for evaluation of energy efficiency in high energy-consuming industry. *Applied Energy* 187, 203–215.
- Liebert, V., Niemeier, H.-M., 2013. A survey of empirical research on the productivity and efficiency measurement of airports. *Journal of Transport Economics and Policy* 47, 2, 157–189.
- Liu, J.S., Lu, L.Y.Y., Lu, W.-M., 2016. Research fronts in data envelopment analysis. *Omega* 58, 33–45.
- Liu, J.S., Lu, L.Y.Y., Lu, W.-M., Lin, B.J.Y., 2013a. Data envelopment analysis 1978–2010: a citation-based literature survey. *Omega* 41, 1, 3–15.
- Liu, J.S., Lu, L.Y.Y., Lu, W.-M., Lin, B.J.Y., 2013b. A survey of DEA applications. *Omega* 41, 5, 893–902.
- Longo, S., d'Antoni, B.M., Bongards, M., Chaparro, A., Cronrath, A., Fatone, F., Lema, J.M., Mauricio-Iglesias, M., Soares, A., Hospido, A., 2016. Monitoring and diagnosis of energy consumption in wastewater treatment plants. A state of the art and proposals for improvement. *Applied Energy* 179, 1251–1268.
- Lovell, C.A.K., 2006. Frontier analysis in healthcare. *International Journal of Healthcare Technology and Management* 7, 1-2, 5–14.
- Macoris, L.S., Salgado, A.P., Jr., Branco, A.M.D.F., Ciribelli, F.N., 2016. Variable portfolio proposal for banking efficiency assessment. *International Journal of Bank Marketing* 34, 7, 985–1008.
- Mahmoudi, R., Emrouznejad, A., Shetab-Boushehri, S.-N., Hejazi, S.R., 2019. The origins, development and future directions of data envelopment analysis approach in transportation systems. *Socio-Economic Planning Sciences*. <https://doi.org/10.1016/j.seps.2018.11.009>
- Marchetti, D., Wanke, P.F., 2019. Efficiency in rail transport: evaluation of the main drivers through meta-analysis with resampling. *Transportation Research* 120A, 83–100.
- Mareth, T., Thomé, A.M.T., Scavarda, L.F., Cyrino Oliveira, F.L., 2017. Technical efficiency in dairy farms: research framework, literature classification and research agenda. *International Journal of Productivity and Performance Management* 66, 3, 380–404.
- Mariano, E.B., Sobreiro, V.A., Rebelatto, D.A.N. 2015. Human development and data envelopment analysis: a structured literature review. *Omega* 54, 33–49.
- Mariz, F.B.A.R., Almeida, M.R., Aloise, D., 2018. A review of dynamic data envelopment analysis: state of the art and applications. *International Transactions in Operational Research* 25, 2, 469–505.
- Markovits-Somogyi, R., 2011a. Review and systematization of efficiency measurement methods used in the transport sector. *PROMET-Traffic & Transportation* 23, 1, 39–47.
- Markovits-Somogyi, R., 2011b. Data envelopment analysis and its key variants utilized in the transport sector. *Periodica Polytechnica Transportation Engineering* 39, 2, 63.
- Markovits-Somogyi, R., 2011c. Measuring efficiency in transport: the state of the art of applying data envelopment analysis. *Transport* 26, 1, 11–19.
- Marlin, D., Sun, M., Huonker, J.W., 1999. Strategic groups and performance in the nursing home industry: a reexamination. *Medical Care Research and Review* 56, 2, 156–176.
- Martín-Gamboa, M., Iribarren, D., García-Gusano, D., Dufour, J., 2017. A review of life-cycle approaches coupled with data envelopment analysis within multi-criteria decision analysis for sustainability assessment of energy systems. *Journal of Cleaner Production* 150, 164–174.
- Meeusen, W., van Den Broeck, J., 1977. Efficiency estimation from Cobb-Douglas production functions with composed error. *International Economic Review* 18, 2, 435–444.

- Meng, F., Su, B., Thomson, E., Zhou, D., Zhou, P., 2016. Measuring China's regional energy and carbon emission efficiency with DEA models: a survey. *Applied Energy* 183, 1–21.
- Merkel, A., Holmgren, J., 2017. Dredging the depths of knowledge: efficiency analysis in the maritime port sector. *Transport Policy* 60, 63–74.
- Minviel, J.J., Latruffe, L., 2017. Effect of public subsidies on farm technical efficiency: a meta-analysis of empirical results. *Applied Economics* 49, 2, 213–226.
- Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., The Prisma Group, 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Med* 6, 7, e1000097.
- Molyneux, P., Altunbaş, Y., Gardener, E., 1996. *Efficiency in European Banking*. Wiley, New York.
- Morrison Paul, C.J., Felthoven, R.G., de Torres, M.O., 2010. Productive performance in fisheries: modeling, measurement, and management. *Australian Journal of Agricultural and Resource Economics* 54, 3, 343–360.
- Narbón-Perpiñá, I., de Witte, K., 2018a. Local governments' efficiency: a systematic literature review—part I. *International Transactions in Operational Research* 25, 2, 431–468.
- Narbón-Perpiñá, I., de Witte, K., 2018b. Local governments' efficiency: a systematic literature review—part II. *International Transactions in Operational Research* 25, 4, 1107–1136.
- Nash, C., Smith, A., 2008. Modelling performance: rail. In Hensher, D.A., Button, K.J. (eds) *Handbook of Transport Modelling* (2nd edn). Elsevier, Amsterdam, pp. 695–691.
- Nigsch, S., Schenker-Wicki, A., 2015. Frontier efficiency analysis in higher education. In Welpel, I.M., Wollersheim, J., Ringelhan, S., Osterloh, M. (eds) *Incentives and Performance: Governance of Research Organizations*. Springer, Berlin, pp. 155–170.
- Odeck, J., Bråthen, S., 2012. A meta-analysis of DEA and SFA studies of the technical efficiency of seaports: a comparison of fixed and random-effects regression models. *Transportation Research* 46A, 10, 1574–1585.
- Ogundari, K., 2014. The paradigm of agricultural efficiency and its implication on food security in Africa: what does meta-analysis reveal? *World Development* 64, 690–702.
- Ogundari, K., Amos, T.T., Okoruwa, V.O., 2012. A review of Nigerian agricultural efficiency literature, 1999–2011: what does one learn from frontier studies? *African Development Review* 24, 1, 93–106.
- Ogundari, K., Brümmer, B., 2011. Technical efficiency of Nigerian agriculture: a meta-regression analysis. *Outlook on Agriculture* 40, 2, 171–180.
- O'Neill, L., Rauner, M., Heidenberger, K., Krau, M., 2008. A cross-national comparison and taxonomy of DEA-based hospital efficiency studies. *Socio-Economic Planning Sciences* 42, 3, 158–189.
- Oude Lansink, A., Wall, A., 2014. Frontier models for evaluating environmental efficiency: an overview. *Economics and Business Letters* 3, 1, 43–50.
- Oum, T.H., Waters, W.G. II, Yu, C., 1999. A survey of productivity and efficiency measurement in rail transport. *Journal of Transport Economics and Policy* 33, 1, 9–42.
- Oum, T.H., Yamaguchi, K., Yoshida, Y., 2011. Efficiency measurement theory and its application to airport benchmarking. In de Palma, A., Lindsey, R., Quinet, E., Vickerman, R. (eds) *A Handbook of Transport Economics*. Edward Elgar, Cheltenham, pp. 298–318.
- Oum, T.H., Yu, C., 2012. *Winning Airlines: Productivity and Cost Competitiveness of the World's Major Airlines*. Springer, Berlin.
- Ozcan, Y.A., 2008. *Health Care Benchmarking and Performance Evaluation: An Assessment using Data Envelopment Analysis (DEA)*. Springer, Berlin.
- Panayides, P.M., Maxoulis, C.N., Wang, T.-F., Ng, K.Y.A., 2009. A critical analysis of DEA applications to seaport economic efficiency measurement. *Transport Reviews* 29, 2, 183–206.
- Paradi, J.C., Vela, S., Yang, Z., 2004. Assessing bank and bank branch performance: modeling considerations and approaches. In Cooper, W.W., Seiford, L.M., Zhu, J. (eds) *Handbook on Data Envelopment Analysis*. Kluwer, Boston, MA, pp. 349–400.
- Paradi, J.C., Zhu, H., 2013. A survey on bank branch efficiency and performance research with data envelopment analysis. *Omega* 41, 1, 61–79.
- Pelone, F., Kringos, D.S., Romaniello, A., Archibugi, M., Ricciardi, C., Salsiri, W., 2015. Primary care efficiency measurement using data envelopment analysis: a systematic review. *Journal of Medical Systems* 39, 1, 156.
- Pereira, H., Marques, R.C., 2017. An analytical review of irrigation efficiency measured using deterministic and stochastic models. *Agricultural Water Management* 184, 28–35.

- Pollitt, M.G., 1995. *Ownership and Performance in Electric Utilities: The International Evidence on Privatisation and Efficiency*. Oxford University Press, Oxford.
- Rhahiem, M., 2017. Measurement and determinants of academic research efficiency: a systematic review of the evidence. *Scientometrics* 110, 2, 581–615.
- Rosko, M.D., Mutter, R.L., 2008. Stochastic frontier analysis of hospital inefficiency: a review of empirical issues and an assessment of robustness. *Medical Care Research and Review* 65, 2, 131–166.
- Rosko, M.D., Mutter, R.L., 2011. What have we learned from the application of stochastic frontier analysis to U.S. hospitals? *Medical Care Research and Review* 68, 1S, 75S–100S.
- Saal, D.S., Arocena, P., Maziotis, A., Triebs, T., 2013. Scale and scope economies and the efficient vertical and horizontal configuration of the water industry: a survey of the literature. *Review of Network Economics* 12, 1, 93–129.
- St Aubyn, M., 2008. Law and order efficiency measurement—a literature review. Working papers. Department of Economics at the School of Economics and Management (ISEG), Technical University of Lisbon, Lisbon.
- Salehirad, N., Sowlati, T., 2006. Productivity and efficiency assessment of the wood industry: a review with a focus on Canada. *Forest Products Journal* 56, 11/12, 25.
- Seiford, L., 1994. A DEA bibliography (1978–1992). In Charnes, A., Cooper, W.W., Lewin, A.Y., Seiford, L.M. (eds) *Data Envelopment Analysis: Theory, Methodology and Applications*. Kluwer, Boston, MA, pp. 437–470.
- Seiford, L., 1996. Data envelopment analysis: the evolution of the state of the art (1978–1995). *Journal of Productivity Analysis* 7, 2–3, 99–137.
- Seiford, L., 1997. A bibliography for data envelopment analysis (1978–1996). *Annals of Operations Research* 73, 393–438.
- Seiford, L., 1999. Data envelopment analysis: twenty years out. In Westermann, G. (ed.) *Data Envelopment Analysis in the Service Sector*, Gabler Edition. Wissenschaft, Wiesbaden, pp. 1–22.
- Shang, T., Zhang, K., Liu, P., Chen, Z., 2017. A review of energy performance contracting business models: status and recommendation. *Sustainable Cities and Society* 34, 203–210.
- Shen, Y., Hermans, E., Bao, Q., Brijs, T., Wets, G., Wang, W., 2015. Inter-national benchmarking of road safety: state of the art. *Transportation Research* 50C, 37–50.
- Simar, L., Wilson, P.W., 2015. Statistical approaches for non-parametric frontier models: a guided tour. *International Statistical Review* 83, 1, 77–110.
- Smith, A.S., 2005. The role of efficiency estimates in UK regulatory price reviews: the case of rail. *Utilities Policy* 13, 4, 294–301.
- Soheilrad, S., Govindan, K., Mardani, A., Zavadskas, E.K., Nilashi, M., Zakuan, N., 2018. Application of data envelopment analysis models in supply chain management: a systematic review and meta-analysis. *Annals of Operations Research* 271, 2, 915–969.
- Song, M., An, Q., Zhang, W., Wang, Z., Wu, J., 2012. Environmental efficiency evaluation based on data envelopment analysis: a review. *Renewable and Sustainable Energy Reviews* 16, 7, 4465–4469.
- Sowlati, T., 2005. Efficiency studies in forestry using data envelopment analysis. *Forest Products Journal* 55, 1, 49.
- Suárez-Alemán, A., Trujillo, L., Cullinane, K.P., 2014. Time at ports in short sea shipping: when timing is crucial. *Maritime Economics & Logistics* 16, 4, 399–417.
- Thanassoulis, E., 2000. DEA and its use in the regulation of water companies. *European Journal of Operational Research* 127, 1, 1–13.
- Thiam, A., Bravo-Ureta, B.E., Rivas, T.E., 2001. Technical efficiency in developing country agriculture: a meta-analysis. *Agricultural Economics* 25, 2-3, 235–243.
- Tranfield, D., Denyer, D., Smart, P., 2003. Towards a methodology for developing evidence-informed management knowledge by means of systematic review. *British Journal of Management* 14, 3, 207–222.
- Tyteca, D., 1996. On the measurement of the environmental performance of firms: a literature review and a productive efficiency perspective. *Journal of Environmental Management* 46, 3, 281–308.
- United Nations Statistical Division, 2008. *International Standard Industrial Classification of All Economic Activities (ISIC) (No. 4)*. United Nations Publications, Herndon.
- van Eck, N.J., Waltman, L., 2010. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* 84, 2, 523–538.
- van Eck, N.J., Waltman, L., 2014. Visualizing bibliometric networks. In Ding, Y., Rousseau, R., Wolfram, D. (eds) *Measuring Scholarly Impact*. Springer, Berlin, pp. 285–320.

- Vilanova, M.R.N., Magalhães Filho, P., Balestieri, J.A.P., 2015. Performance measurement and indicators for water supply management: review and international cases. *Renewable and Sustainable Energy Reviews* 43, 1–12.
- Voigt, S., 2016. Determinants of judicial efficiency: a survey. *European Journal of Law and Economics* 42, 2, 183–208.
- von Furstenberg, G.M., 2008. Assessing the competitiveness of international financial services in particular locations: a survey of methods and perspectives. *Open Economies Review* 19, 4, 539–556.
- Walter, M., Cullmann, A., von Hirschhausen, C., Wand, R., Zschille, M., 2009. Quo Vadis efficiency analysis of water distribution? A comparative literature review. *Utilities Policy* 17, 3–4, 225–232.
- Wang, B., Wu, C.Y., 2013. A review of influential factors and evaluation models of energy efficiency in China. *Advanced Materials Research* 734, 1662–1665.
- White, S.W., Bordoloi, S.K., 2014. A review of DEA-based resource and cost allocation models: implications for services. *International Journal of Services and Operations Management* 20, 1, 86–101.
- Wu, Y., 1993. Productive efficiency in Chinese industry. *Asian Pacific Economic Literature* 7, 2, 58–66.
- Worthington, A.C., 2001. An empirical survey of frontier efficiency measurement techniques in education. *Education Economics* 9, 3, 245–268.
- Worthington, A.C., 2004. Frontier efficiency measurement in health care: a review of empirical techniques and selected applications. *Medical Care Research and Review* 61, 2, 1–36.
- Worthington, A.C., 2010. Frontier efficiency measurement in deposit-taking financial mutuals: a review of techniques, applications, and future research directions. *Annals of Public and Cooperative Economics* 81, 1, 39–75.
- Worthington, A.C., 2014. A review of frontier approaches to efficiency and productivity measurement in urban water utilities. *Urban Water Journal* 11, 1, 55–73.
- Worthington, A.C., Dollery, B.E., 2000. An empirical survey of frontier efficiency measurement techniques in local government. *Local Government Studies* 26, 2, 23–52.
- Zanakis, S.H., Mandakovic, T., Gupta, S.K., Sahay, S., Hong, S., 1995. A review of program evaluation and fund allocation methods within the service and government sectors. *Socio-Economic Planning Sciences* 29, 1, 59–79.
- Zhang, N., Choi, Y., 2014. A note on the evolution of directional distance function and its development in energy and environmental studies 1997–2013. *Renewable and Sustainable Energy Reviews* 33, 50–59.
- Zhou, P., Ang, B.W., Poh, K.L., 2008. A survey of data envelopment analysis in energy and environmental studies. *European Journal of Operational Research* 189, 1, 1–18.
- Zhou, H., Yang, Y., Chen, Y., Zhu, J., 2018. Data envelopment analysis application in sustainability: the origins, development and future directions. *European Journal of Operational Research* 264, 1, 1–16.

## Appendix

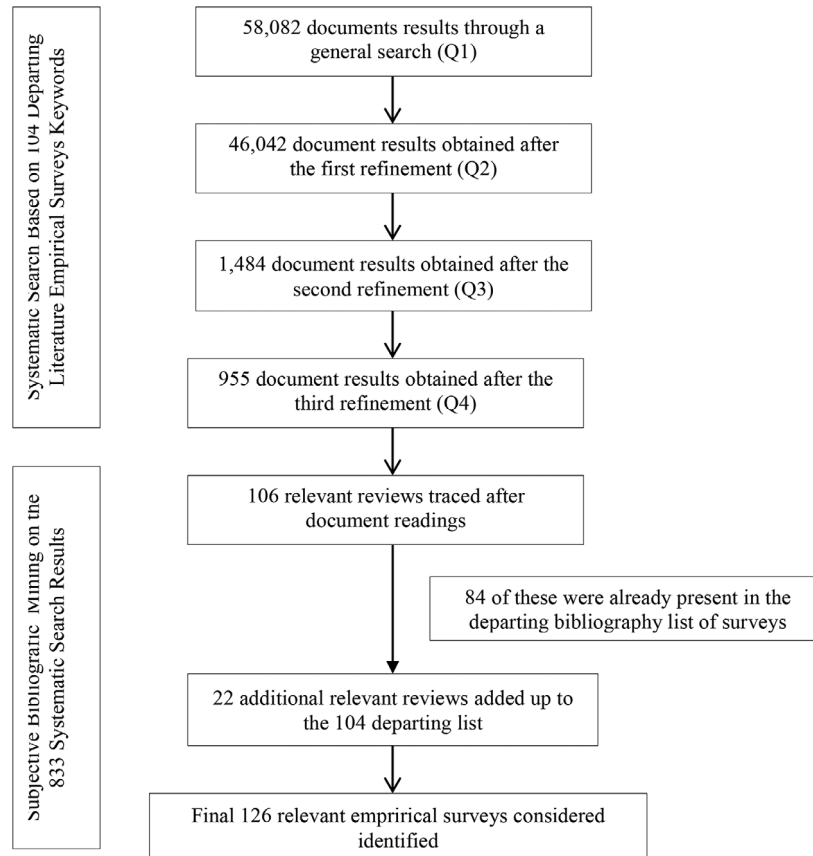


Fig. A1. Flow diagram representation of the information through the different phases of the systematic review (according to the PRISMA scheme, see Moher et al., 2009).