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An overview of data envelopment analysis application in studies on the socio-economic performance of OECD countries

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ABSTRACT

Due to large and deepening development disparities among countries, comparisons across them have gained utmost importance, both in theoretical and empirical sense. At the same time, overuse of natural resources and climate change are among the most difficult issues today's world is facing. Consequently, there is a growing research interest in investigating the performance of countries, especially in terms of environmental and energy efficiency. This paper brings a literature overview on the application of data envelopment analysis (DEA) to studies that empirically explore socio-economic efficiency of OECD (Organisation for Economic Co-operation and Development) member countries. The listed papers are categorised with regard to the relevance given to economic, environmental or energy indicators. Their basic content is summarised, along with the major findings. In this way, both measurement of countries' performance and the non-parametric approach of DEA have been given deserved attention.

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1. Introduction

During the past several decades, the global economic environment has been dramatically transformed. The challenges of reducing high unemployment and public sector debt levels, reducing socio-economic inequalities and generating sustainable balanced growth of the world economy have to be reconciled and addressed in a satisfactory manner. Consequently, a sizeable body of economic research literature has argued as to whether reducing inequality affects economic growth positively, negatively or at all. Accordingly, theoretical and empirical economic studies on the relationship between the extent of inequality and economic growth rates have yielded to conflicting results. Most of them have suggested that greater equality is beneficial to growth, while a few have claimed the opposite. Through a brief review of the theoretical and empirical literature, Cingano (2014) summarises the conditions under which greater inequality might either reduce or increase growth, highlighting that there is no consensus on the sign and strength of this relationship. However, in the literature on economic policy-making, for some time there has been a concept of the trade-off between

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equality and economic efficiency (or economic growth as one of its measures). Thus, Okun (1975) stated that a society will keep searching for better ways of drawing the boundary lines between the domain of rights and the domain of money, making progress, but never solving the problem. Claiming that the conflict between equality and economic efficiency is inescapable, he further presented an important but controversial proposition that social decisions which permit economic inequality must be justified as promoting economic efficiency. The aforementioned shows the importance of the notion of economic efficiency. It can be measured through targeted performance assessment, which is crucial in identifying the priority areas for implementation of effective measures and areas for possible improvements. Furthermore, cross-country evaluations enable us to draw an accurate picture of the situation and, thus, to identify problems and the way in which other countries deal with them and to find which countries perform better, how and why. Therefore, cross-country comparisons are of major importance for understanding the effectiveness and impact of policies and programmes adopted by individual countries, thus allowing policy-makers to learn from other countries about good practices.

With a growing number of studies using DEA as the central technique in the measurement of socio-economic efficiency of OECD countries, an overview of this field would be informative and beneficial for researchers and analysts working in or interested in this area, as well as for policy-makers. The aim of this paper is to fulfil the lack of surveys of such comprehensive literature. The paper is organised as follows. The second section gives a brief history of modern efficiency measurement and describes in short the DEA method and its basic models, together with their main extensions. An overview of DEA application in studies on the socio-economic performance of OECD countries is presented in the third and substantial section. In the fourth and final section, the main conclusions of this study are derived.

2. Data envelopment analysis: concept, history and basic models

Analysis of the socio-economic efficiency of countries, in the sense of questioning whether a particular country performs better than others in gaining more output while using the same or less amount of inputs, makes understandable the importance of evaluating socio-economic relationships. The questions of convergence, frequently posed in economics, are at the focus of a respectable range of studies on socio-economic performance of nations, with diverse objectives and methodology. The method that simultaneously fulfils the need to involve a number of various socio-economic aspects into the process of efficiency evaluation, and to obtain a single performance measure, is data envelopment analysis. The following paragraphs provide a brief history of modern efficiency measurement and a basic concept of the DEA method (Rabar, 2013, pp. 17–18).

Modern efficiency measurement has its beginnings in the middle of the twentieth century. The concept of technical efficiency, according to which a producer is technically efficient if, and only if, it is impossible to produce more of any output without producing less of some other output or using more of some input, was firstly introduced in 1951 by Koopmans. This definition is accurate, but theoretical and unsuitable for application. It is, therefore, further refined by Debreu (1951) and Shephard (1953). These two authors, respectively, introduced output- and input-oriented distance functions which, in the same manner, measure technical inefficiency as the radial distance of a producer from a frontier, the first one in an output-expanding and the second one in an input-conserving direction. Extending their work, Farrell (1957) was the first to empirically introduce how to measure cost efficiency and how to decompose it into two components – technical efficiency and allocative (price) efficiency. The first one signifies the ability to gain maximum output from given inputs and the second one the ability to employ inputs in optimal proportions, given their respective prices. These components were then aggregated to form a measure of overall economic efficiency, which was later incorporated into the linear programming (LP) framework by Charnes, Cooper and Rhodes(1978), who developed a non-parametric technique of data envelopment analysis.

The DEA approach is used for empirically determining the relative efficiency of operating entities, called decision-making units (DMUs), that are mutually comparable – consuming the same inputs and creating the same outputs. The major limitations of traditional benchmarking techniques are overcome by the following features. DEA does not assume any specific functional form linking inputs and outputs, thus avoiding problems of model misspecification. The production possibility frontier is determined empirically – by the observed values of the DMUs that are efficient (with respect to the rest of DMUs in the sample) and are all assigned an efficiency score of one (or 100%). The term 'envelopment' derives from the fact that the frontier envelops the set of observations. If a DMU does not belong to this piecewise linear or log-linear envelopment surface and, therefore, lies in its interior, then that DMU is not operating efficiently and, according to the distance from the point representing its input and output values to the corresponding reference point on the efficient frontier, receives an efficiency score of less than one (best performance), but greater than zero. The inefficiency is ascribed to input surpluses and/or output shortages and can be overcome by reaching an efficient projection point of operation on the 'best practice' frontier. This point is usually returned by DEA models for each inefficient entity, thus identifying the entities that can be used as performance benchmarks for inefficiently operating entities. Furthermore, DEA requires no *a priori* designation of input and output weights, which are instead determined by the LP model itself. This is achieved in a way that each evaluated entity receives the highest possible efficiency rating, thus circumventing the subjectivity associated with the estimation of their importance. Moreover, DEA can simultaneously handle multiple variables, each of which can be expressed in different and usually incongruous units of measurement, while still providing a single real number as a relative performance efficiency index. This index is obtained by solving the chosen DEA linear programming model that uses empirical data on inputs and outputs of all observed entities.

A number of basic and advanced DEA models that have been constructed significantly contributed to practitioners' general acceptance of this method. The models differ primarily in the assumption about returns-to-scale (constant or variable) exhibited by the production function, and in the orientation type of efficiency measurement (to input minimisation or to output maximisation). Their further distinctions are reflected in miscellaneous extensions to the basic DEA methods. Regardless of the model type, they all produce a large set of concrete, relevant and useful results. In addition to the efficiency score for each observed entity, a potential performance target is assigned for each inefficient entity, in terms of inefficiency sources and amounts, proposed improvements in each of the inputs and outputs (resulting in efficient projection onto the frontier) or reference set (defined by the closest efficient units). These results provide policy-makers with information crucial for operating more efficiently in today's dynamic business environment, where competitive rivalry is increasing exponentially.

The two most commonly applied basic DEA models are generally distinguished – CCR model, named after Charnes et al. (1978) and BCC model, named after Banker, Charnes, and Cooper (1984). These two models obtain efficiency measures under constant returns-to-scale (CRS) and variable returns-to-scale (VRS) assumptions, respectively, thus yielding two types of envelopment surfaces. The first model's efficiency score represents overall technical efficiency, which measures inefficiencies due to the input-output configuration and the size of operations. The second model results in a pure technical efficiency score which purely reflects managerial under-performance. To avoid the choice of model orientation, numerous DEA models that simultaneously estimate potential input reductions and output expansions have been developed. Thus, based on the BCC model, Charnes, Cooper, Golany, Seiford, and Stutz (1985) constructed the (input and output) translation-invariant additive model. This model was then extended by Tone (2001) into the slacks-based measure (SBM) model with unit invariant and monotone efficiency measure. Another non-oriented model that transforms data using a logarithmic structure is the multiplicative model, developed by Charnes, Cooper, Seiford, and Stutz (1982). Although these non-oriented models are more realistic in numerous real-world cases than oriented ones, they have been under-valued in the efficiency measurement literature.

In basic DEA models, DMUs are usually classified as efficient and inefficient. Thereby, the inefficient entities can be easily ranked according to their efficiency scores, while, for the efficient ones, the ranking within the DEA context can be considered post-analysis. Adler, Friedman, and Sinuany-Stern (2002) described ranking methods developed in the literature and grouped them into six basic areas, according to various criteria.

Aside from the above-mentioned, there have been a number of research thrusts, resulting in an impressive growth in the development of the advanced models and in the number of their applications to practical situations. By focusing primarily on methodological developments, Cook and Seiford (2009) reviewed a large number of models. They particularly discussed CRS, VRS and additive models, slacks-based measures, the Russell measure, alternative views such as the free disposal hull model and cross efficiency, least distance projections and invariance to data alterations. Multi-level models, such as multi-stage/serial models, including network DEA and supply chains, multi-component/parallel models and hierarchical/nested models, and multiplier restrictions, such as absolute multiplier and cone ratio restrictions, assurance regions, facet models and generating unobserved DMUs were also reviewed. The authors gave special consideration to different types of variables such as non-discretionary, non-controllable, categorical and ordinal, also including undesirable factors and flexible measures. In the same paper, data variation was also envisaged, including sensitivity analysis for problem size issues, direct and indirect data perturbations and super-efficiency, data uncertainty and probability-based models, window analysis and Malmquist models[1] as DEA approaches for investigating efficiency and productivity changes over time and stochastic data-statistical inference. Some of the models from the above partial review went somewhat beyond the usual definition of DEA. However, the usefulness and appropriateness of all these DEA-based approaches in the measurement of socio-economic performance of countries is unquestionable and proven by their increasing popularity. The main reasons behind this lie in the possibility of handling variables that are not under the direct control of policy-makers and/or their values have to remain fixed, capturing qualitative and modelling undesirable variables, incorporating flexible variables that are allowed to be on both the input and output sides of the model, providing a fair evaluation of countries that fall into natural categories, etc. Furthermore, there are acceptable solutions regarding the sensitivity of a country's efficiency to the addition of countries to or extraction of countries from the analysis, the question of a given country's maximum allowable increase in outputs or decrease in inputs that will maintain its efficiency status, the problem of modelling technical efficiency when the data for the inputs and outputs are random variables, the treatment to efficiency and productivity changes in a time series sense, etc.

Many of the above-mentioned advantageous features became prominent reasons for choosing DEA over traditional efficiency-measuring methods. However, two major obvious limitations associated with DEA method should also not be left out of consideration. First, there are the rules of thumb that provide guidance for the minimum number of entities (in relation to the total number of input and output variables) required for some discriminatory power to exist in the model, and hence for a reliable analysis. The existing considerable differences in opinions of various authors on the size of this number are summarised in Sarkis (2007). Second, the multi-criteria decision-making methodologies are generally applied to ex ante problems where data are not available, while DEA provides an ex post analysis of the past from which to draw conclusions, and on which to build (Adler et al., 2002).

Due to its aforementioned unique, desirable and powerful features, data envelopment analysis has been widely applied in many different areas such as education, healthcare, banking, service industries, engineering and science, as well as in evaluations of regional and country performances. Since 1978, when the seminal work of Charnes et al. introduced the DEA concept, up through the year 2009, around 4500 DEA-related papers, both theoretically and practically oriented, have been published in ISI Web of Science database (Liu, Lu, Lu, & Lin, 2013). In addition to this collection, around 2000 papers have been published in the same database during the period 2010 to 2014, as reported by Liu, Lu, and Lu (2016). All these papers have covered a series of decision analysis applications involving schools, hospitals, banks, hotels, airports and even countries and regions. Due to the robust characteristics and diverse practical uses in microeconomics as well as in macroeconomics, the DEA approach has been receiving deserved thorough consideration and has progressively evolved into a superior and academically accepted discipline.

3. Main findings of the empirical studies

Although the literature related to economic growth across OECD countries, based on the use of DEA method, is substantial and growing, there is a lack of a literature review in this field. Table 1 presents a brief chronological survey of the main findings on this topic. The various potential socio-economic determinants that have been used in these studies are selected based on the research scope, thus classifying this literature into three main categories (Skare & Rabar, 2016), labelled 1, 2 and 3 in Table 1. The focus of the studies in the first category is mostly on economic indicators. The most frequently used are gross domestic product (GDP), employment and capital stock. The studies in the second category underline the significance of environmental issues, combining economic indicators with ecological, usually the undesirable ones. Most commonly, these are greenhouse gas emissions to the environment, such as carbon dioxide, nitrous oxide, etc. In the studies from the third category, the emphasis is placed on the impact of energy supply and consumption. Therefore, alongside economic

Table 1. Overview of empirical literature on using DEA approaches for socio-economic performance of OECD members.

Source	No. of countries	Investigated period	Cat.	Indicators	Main findings
Färe et al. (1994)	17	1979–1988	1	• Real capital • Employment • Real GDP	Malmquist productivity indices are decomposed into two component measures – technical change and efficiency change. It is found that the United States productivity growth is slightly above average, all of which is due to technical change (innovation). The highest productivity growth and efficiency is reported in Japan, almost half due to efficiency change (catching up).
Lovell, Pastor, and Turner (1995)	19	1970–1990	2	• Real GDP per capita • Inflation rate • Unemployment rate • Trade balance • (exports/imports) • Carbon emissions per capita • Nitrogen emissions per capita	Based on a comparison of the performance of five non-European OECD countries with 14 European OECD countries, using an improved extended additive model (referred to as Global Efficiency Measure), it is demonstrated that performance rankings do change, and that the relative performance of the European countries declines when two environmental disamenities (carbon and nitrogen emissions) are added into the analysis.
Moesen and Cherchye (1998)	20	1987–1996	1	• Real GDP growth • Change in the GDP deflator • Unemployment rate • Surplus or deficit on the • current account	Using Leuven Index of Macroeconomic Performance, the suggestion of a number of studies, that the convergence criteria of the Maastricht Treaty of 1992 have induced a relative performance deterioration in the EU-nations compared to the rest of the world, is supported.
Brockett, Golany, and Li (1999)	17	1979–1988	1	• Real capital stock • Employment • Real GDP	Expanding the benefit of DEA by the use of statistical analysis based on the ranking techniques, it is shown that Greece manifested the worst and Denmark the best performance over the examined period. The United States did consistently better in its productivity efficiency than did Japan, even though its productivity growth manifested a 'slowdown' relative to Japan.
Maudos, Pastor, and Serrano (1999)	23	1975–1990	1	• Total employment • Total capital stock • Human capital stock • Real GDP	The analysis of the breakdown of change in total factor productivity into technical change and variations in efficiency, by means of the Malmquist index, shows the importance of human capital as a productive factor. Namely, taking human capital into consideration causes considerable changes in the relative positions of the United States and Japan, in terms of productivity and efficiency, all in favour of Japan.
Arcelus and Arocena (2000)	14	1970–1990	1	• Number of employees • Real gross capital stock • Real GDP	Considering a reference technology which allows variable returns to scale and satisfies strong disposability of inputs and outputs, the results indicate a high degree of catching-up among the investigated countries, although at quite different speeds, for the total industry and for the manufacturing and services sectors. However, important differences in performance among countries still remain, suggesting the possibility of further productivity improvements for many economies.

Zaim and Taskin (2000)	25	1980–1990	2	• Total capital stock • Total employment • Real GDP • CO2 emissions	Production frontier techniques are applied to construct environmental efficiency indices. The findings indicate that if the disposability for CO_2 emissions was strictly imposed as the result of an environmental regulation, the total value of output loss to the OECD countries as a whole would correspond to 3.7, 4.8 and 3.5% of the total OECD GDP for the years 1980, 1985 and 1990, respectively. Furthermore, Japan and France would carry the heaviest burden, due to the transformation of their production processes.
Cherchye (2001)	20	1992–1996	1	• Real GDP-growth rate • Unemployment rate • Inflation rate • Surplus or deficit on the current account as a percentage of GDP	The results are obtained based on three synthetic performance indicators that require differently modulated data on selected variables – Leuven Index of Macroeconomic Performance, Global Efficiency Measure (GEM) and GEM-flex. Their comparison shows small differences in countries' scores and rankings, while the calculated weights appear to have significant differences. All three measures, however, agree on Japan being the best performer.
Zofío and Prieto (2001)	14	1990,1995	2	• Total net stock of fixed capital • Total employment • Manufactured production • Industry-emitted CO_2	Hyperbolic and radial efficiency measures are used to represent efficient production processes and environmentally inefficient processes, respectively. The results show that the cost of CO_2 weak disposability congestion accounts for 5.26% and 7.57% of the OECD's total manufacturing production in 1990 and 1995, respectively. On the other hand, the cost associated with the 5% reduction regulation represents 1.96% and 0.03% of their manufacturing production.
Emrouznejad (2003)	17	1983–1988	1	• Real capital • Employment • Real GDP	The comparison of dynamic results, obtained by taking several years data in a dynamic model, and static results, obtained by Färe et al. (1994), shows that static models ignore the important factor of the capital stock. It is concluded that dynamic efficiency increases when capital stock rises, which confirms similar results obtained by Maudos et al. (1999). It is reasonable to expect that, since capital stock has effects which spread over several years.
Färe, Grosskopf, and Hernandez-Sancho (2004)	17	1990	3	• Energy consumption • Capital stock • Labour force • Real GDP • CO_2 emissions • NOx emissions • SOx emissions	An environmental performance index is constructed from distance functions, to simultaneously account for CO_2, SOx and NOx. Then the observed-countries sample is broken into groups with below and above median performance. No significant difference is found across the two groups of countries in terms of per capita GDP. The countries with the best environmental indicators – France and Sweden – have the highest dependency on nuclear power.
Arcelus and Arocena (2005)	14	1970–1990	2	• Employment • Real gross capital stock • Real GDP • CO_2 emissions from fuel combustion	Four strategies (No-GDP-Growth, Maximum-GDP-Growth, Mixed-Growth and Good-Output-Only) are employed to investigate the feasibility of achieving productivity growth and pollution reduction agreed by Kyoto Protocol. The inefficient countries for the No-GDP-Growth strategy do not require technical change to lower their CO_2 emission levels without reducing GDP. For the others, technical change is required, even if the level of compliance is quite high in all cases.

(*Continued*)

Table 1. (*Continued*).

Source	No. of countries	Investigated period	Cat.	Indicators	Main findings
Barla and Perelman (2005)	12	1980–1992	2	• Total employment • Gross capital stock (excluding residential structures) • Real GDP • SO_2 emissions • R&D expenditures in the business enterprise sector as a percentage of GDP • Rate of capital formation • Sum exports and imports as a percentage of total GDP	An output based Malmquist productivity index is estimated using distance functions derived from successive frontiers. It is decomposed in technical and efficiency change. Analysing the impact of SO_2 on productivity growth, technical efficiency and technological progress, the results suggest two countervailing effects. On one hand, SO_2 cutbacks adversely affect efficiency, but, on the other hand, they stimulate technical change.
Zhou, Ang, and Poh (2006)	30	1998–2002	3	• Total primary energy supply • Population • GDP in PPP • CO_2 emissions	Two slacks-based efficiency measures are developed. The first one is treated as a composite index for modelling economic–environmental performance, while the second one is used to estimate the impacts of environmental regulations. During 1998–2000, none of the studied countries has proved to be efficient in both economic and environmental performance. It is also observed that zero opportunity costs due to environmental regulations occur in a few countries.
Zhou, Poh, and Ang (2007)	26	1995–1997	3	• Labour force • Primary energy consumption • GDP • CO_2 emissions • SOx emissions • NOx emissions • CO emissions	A non-radial approach, which consists of a non-radial DEA-based model for multilateral environmental performance comparisons and a non-radial Malmquist environmental performance index for modelling the change of environmental performance over time, is presented. The results show that the environmental performance of OECD countries as a whole has been improved from 1995 to 1997, which mainly came from the technological improvement.
Camarero, Picazo-Tadeo, and Tamarit (2008)	22	1971–2002	2	• Real government and private net capital stock (excluding residential capital) • Total employment • Real GDP • CO_2 emissions	Multivariate tests are used to assess the degree of convergence in environmental performance which is measured using two indicators previously computed based on DEA input distance function. The results show that the poorest environmental performances correspond to Portugal, Greece, the USA and Australia. The group of countries as a whole, as well as the majority of countries considered separately, are catching-up with the benchmark country, i.e. Switzerland.

Zhou and Ang (2008)	21	1997–2001	3	• Capital stock in PPP • Labour force • Coal • Oil • Gas • Other energy • GDP in PPP • CO_2 emissions	Three indices are developed for measuring economy-wide energy efficiency performance. The first one attempts to proportionally reduce the energy inputs to the frontier of the best practice. The other two, based on non-radial and slack-based models, account for the energy mix effects. The results indicate that, without increasing the amounts of non-energy inputs and CO_2 emissions or decreasing GDP, Canada and Japan have the greatest potential to reduce their energy consumption.
Halkos and Tzeremes (2009)	17	1980–2002	2	• Total capital stock • Total employment • Sulphur emissions per capita • Real GDP per capita	Using DEA window analysis and generalised method of moments estimators, the analysis with the application of dynamic panel data reveals the absence of a Kuznets type relationship between environmental efficiency and income. Allowing for dynamic effects, the adjustment to the target ratio is instantaneous. Increased economic activity does not always ensure environmental protection and, thus, the path of growth is important in addition to the growth itself.
Afonso and St. Aubyn (2013)	19	1970–2000	1	• Human capital per worker • Public physical capital per worker • Private physical capital per worker • GDP in PPS per worker • Governance effectiveness	Based on semi-parametric analysis, computing DEA-based Malmquist productivity indices and on stochastic frontier analysis, the findings point out that private capital is important for growth. Public and human capital also contribute positively, but less significantly. The government effectiveness indicator explains inefficiency suggesting, as expected, that better governance helps countries to achieve a better performance.
Camarero, Castillo, Picazo-Tadeo, and Tamarit (2013)	22	1980–2005	2	• Real GDP • CO_2 emissions • NOx emissions • SOx emissions	In the first stage, DEA is employed to assess overall eco-efficiency and pressure-specific eco-efficiency. In the second stage, an econometric approach is used to test for the existence of convergence groups. The results indicate that, with the exception of NOx emissions, eco-efficiency has improved over the period. Switzerland is the most eco-efficient country, while European Mediterranean countries are among the worst performers. However, all countries tend to form clubs of convergence among them.
Lu, Chiu, Shyu, and Lee (2013)	32	2005–2007	2	• Industry • Population • GDP • Fossil-fuel CO_2 emissions	The models employed to incorporate both undesirable and non-proportional variables are the undesirable DEA model, Hybrid Efficiency model and SBM model. The findings indicate that the countries' efficiency rankings when controlling CO_2 emissions present more volatility. Almost all European countries are the most efficient. Japan is the only Asian country with its efficiency score close to 1 in this period. All OECD countries are required to reduce CO_2 emissions by 6.66%–7.49% in the next several years.

(*Continued*)

Table 1. (*Continued*).

Source	No. of countries	Investigated period	Cat.	Indicators	Main findings
Simsek (2014)	23	1995–2009	3	• Labour • Real capital stock • Oil+natural gas consumption • Hydropower+nuclear consumption • Coal consumption • Real GDP • CO_2 emissions	Using the non-radial and non-oriented Bad Output model under CRS, that utilises input and output slacks directly and deals with desirable and undesirable outputs independently, the results show that Ireland, Japan, Norway, Switzerland, the United States and the United Kingdom were found efficient in each year. Italy and Mexico were found efficient in the beginning, while Sweden and Poland were efficient at the end of the investigated period.
Apergis, Aye, Barros, Gupta, and Wanke (2015)	20	1985–2011	3	• Number of employees • Renewable energy consumption • Non-renewable energy consumption • Real productive capital stock • Real GDP • CO_2 emissions	The results of an SBM model with undesirable or bad outputs are combined with GLMM-MCMC methods in order to produce a model for energy performance with effective predictive ability. It is shown that efficiency levels are high and are reducing over time. The analysis of the effect of contextual variables (economic blocks and capital-labour ratio) on the efficiency level showed that higher efficiency levels are found in EU countries, followed by NAFTA and G7. Moreover, capital-intensive countries are more energy efficient than labour-intensive countries.
Rashidi, Shabani, and Saen (2015)	25	2007	3	• Labour force • Precipitation average • Coal consumption • Petroleum consumption • Real GDP • CO_2 emissions	SBM and RAM models have been extended to incorporate non-discretionary, non-energy and undesirable factors into eco-efficiency assessment. The results point to France, Germany, Luxemburg, Norway, Sweden and the United Kingdom as the eco-efficient countries. Italy and South Korea have the lowest and highest potential for energy saving (ESP), respectively. Iceland and Poland have the lowest and highest potential for undesirable output abatement (UOAP), respectively. Spearman correlation test indicates a direct and positive relationship between ESP and UOAP.
Rashidi and Saen (2015)	19	2012	3	• Labour force • Precipitation average • Energy use • GDP in PPP, per unit of energy use • CO_2 emissions from fuel combustion	A DEA-based model that divides inputs into energy and non-energy and outputs into desirable and undesirable is developed along with a bounded adjusted measure based on green indicators to calculate eco-efficiency. The results recognise Australia, Finland, Ireland, New Zealand and Switzerland as eco-efficient countries. Spearman correlation coefficient between energy consumption and undesirable outputs turned out to be high and positive.

Woo, Chung, Chun, Seo, and Hong (2015)	31	2004–2011	3	• Labour • Capital • Renewable energy supply • GDP • Carbon emissions	The Malmquist productivity index is applied to estimate the average efficiency change over the study period. The results reveal geographical differences in environmental efficiency across the countries. While countries in America have the highest average environmental efficiency, those in Europe have the largest standard deviation. It is also found that dynamic efficiency is influenced by the global financial crisis triggered in the United States and that both catch-up and frontier shift strategies are implemented to improve environmental efficiency.
Zhou et al. (2016)	29	2000–2011	2	• Real capital stock • Labour force • Real GDP • CO_2 emissions • CH_4 emissions • N_2O emissions	Both radial and non-radial DEA models are applied to calculate the environmental efficiency and productivity under the CRS environmental DEA technology. Regardless of the model used, the environmental efficiency appears to be relatively stable during the sample period, while EPI shows mostly a declining trend, mainly driven by the degeneracy of environmental production technology. Among the most environmentally efficient are Japan, Luxembourg, Norway, Sweden and Switzerland.
Skare and Rabar (2016)	30	2002–2011	2	• Inflation rate • Unemployment rate • Real per capita GDP • Exports/imports cover ratio • Scientific and technical journal articles • Public health expenditure • Seats held by women in national parliaments • CO_2 emissions	Using an output-oriented window analysis model under VRS, the relative efficiency of the countries is measured in two steps – first employing four economic indicators and then adding four new indicators that cover social, institutional and environmental dimensions. It is found that performance rankings change, in some cases very significantly and that the overall relative performance of the countries increases when the set of economic indicators is extended.

Notes: CH4 – Methane; CO – Carbon Monoxide; CO2 – Carbon Dioxide; G7 – Group of Seven; GLMM – Generalized Linear Mixed Model; MCMC – Markov Chain Monte Carlo; N2O – Nitrous Oxide; NAFTA – North American Free Trade Agreement; NOx – Nitrogen Oxide; PPP – Purchasing Power Parity; PPS – Purchasing Power Standard; RAM – Range Adjusted Measure; R&D – Research and Development; SO2 – Sulphur Dioxide; SOx – Sulphur Oxide
Source: Authors' survey

and environmental ones, energy indicators, such as gas, power, coal and oil consumption, are usually employed. Although researchers' interest and engagement in formulating and applying analytical and modelling techniques in energy and environmental studies goes much further back in time, it has rapidly intensified over the past 15–20 years. Consequently, a significant portion of the studies listed in Table 1, particularly of more recent ones, tackle environmental and energy issues in performance measurement. Comprehensive reviews of the empirical applications of DEA techniques in this type of studies are given by Zhou et al. (2008a), and more recently by Song, An, Zhang, Wang, and Wu (2012). Another two studies by Zhou, Ang, and Poh (2008b) and Zhou, Poh, and Ang (2016) focused on the theoretical foundation and several models for DEA-based measurement of environmental efficiency and productivity (i.e., environmental DEA technology). The last paper also presents a case study on measuring the environmental performance of OECD countries.

The number of countries being the subject of the analyses reviewed in this paper varies for several reasons, depending not only on the authors' preferences and research efforts, but on the availability of data and on the number of OECD members in the observed period. Although the OECD countries have been the subject of numerous studies in which they were compared both mutually and to non-member countries, this survey is narrowed down to their mutual comparisons.

For the purpose of macroeconomic examination, data envelopment analysis was first used by Färe, Grosskopf, Norris, and Zhang (1994). An interesting feature of this study, which makes it extremely important for our research, is that it addressed precisely the OECD countries. Although all the studies from Table 1 use DEA-inspired approaches to evaluate the efficiency and productivity of OECD countries, range of employed models, their extensions and combinations is quite extensive. Moreover, the relative performance measurement was supported and enriched using a wide range of ideas like using differently based strategies for designing various performance indices and tests to validate those indices and to assess the degree of convergence, decomposing productivity growth into changes in efficiency and changes in technology, dividing the set of countries into sub-groups (e.g., European and non-European countries, countries with below and above median performance), comparing socio-economic efficiency estimated with and without the inclusion of environmental factors, combining DEA with other statistical and non-statistical methods, dividing the observed period into sub-periods, summarising performance by merging separate dimensions into a single synthetic measure, determining lower and upper bounds for inputs and outputs, dividing inputs into both energy and non-energy and outputs into both desirable (good) and undesirable (bad) outputs, constructing environmental efficiency as a ratio of good efficiency performance (using a good output) to a bad efficiency measure (using a bad output), etc. A progressive shift of researchers' focus from economic efficiency in the 1990s to environmental efficiency in the 2000s, and consequently to energy efficiency in the 2010s is evident. Hence, the theme of environmental and energy issues took precedence in the new millennium and became dominant in the papers dealing with efficiency measurement using DEA.

4. Concluding remarks

The empirical application of data envelopment analysis in the macroeconomic performance evaluation of OECD countries is here certainly not completely covered. Certain pertinent articles may have been omitted because they are of mostly theoretical character, are out of reach, have a narrow scope (focusing on single aspects of socio-economic development, such as healthcare, education, agriculture, public spending, etc.) or analyse similar but older datasets as already selected articles and/or are less often cited.

A multitude of studies using different DEA-based approaches have been presented in this paper, all with the common goal to assist researchers and practitioners, interested in using DEA, in choosing the most suitable tools for cross-country comparisons of socio-economic inequalities. Although each approach may be useful for specific issues of interest, none of them can be prescribed as the best solution. Nevertheless, they all provide a stimulus for further research that might result in an advancement of this field.

Note

1. Although the Malmquist productivity index is defined based on the concept of distance function, it can also be directly represented by DEA efficiency measures (Zhou, Ang, & Poh, 2008a).

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