Data Envelopment Analysis and the concept of sustainability: A review and analysis of the literature

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Abstract

Sustainable development and sustainability have been the targets of policy making on every level and the focus of multi-national agreements. However, both notions are vaguely defined and no concrete methodological guidance is offered on how to achieve them. One methodology that is increasingly being used to measure sustainability is Data Envelopment Analysis. The purpose of the current paper is to review the literature from 2017 until 2020 and investigate how researchers have used Data Envelopment Analysis to measure sustainability. Building also from the conclusions of previous reviews, results indicate that the social dimension of sustainability is still underrepresented. Furthermore, proxy indices are used as a substitute for sustainability. Despite their important merits, such measures do not fully capture the multi-dimensional structure of sustainability and sustainable development. Finally, the review illustrates that the majority of applications concerns Asian nations or Chinese regions, while the study on European areas and/or nations appears to be lagging considerably.

Keywords: Data Envelopment Analysis; Sustainability; Literature Review; Sustainable Development; Composite Indicators; Eco-efficiency;

Highlights

- The traditional three-dimensional structure of sustainability is still dominant
- The social dimension of sustainability is underrepresented, despite continuous efforts to incorporate it
- Recent efforts focus on including new dimensions in sustainability like technology
- The study of sustainability has shifted towards urban environments
- The lack of a unified definition of sustainability persists in current research

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Abbreviation list

DEA: Data Envelopment Analysis

DMU: Decision Making Unit

PM10: fraction of particles with an aerodynamic diameter smaller than 10μm

BoD: Benefit-of-the-Doubt

VRS DEA: Variable Returns to Scale DEA

SORM DEA: Semi-Oriented Radial Measure DEA

RAM DEA: Range Adjusted Measure DEA

CRS DEA: Constant Returns to Scale DEA

HDI: Human Development Index

GNI: Gross National Income

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1. Introduction

Sustainable development in a broad sense means “the ability to meet the needs of the present without compromising the ability of future generations to meet their own needs” [1]. Kates et al. [2] indicated that sustainable development means the imposition of limits; these limits concern the effect of social organization and technology on natural resources and the ability of the biosphere to absorb those effects. Apart from limitations, what the definition of sustainable development implies is that a sustainable system should be able to promote fairness in distributions of resources [3]. As a result, any policy aimed at achieving such a state should be able to address all these dimensions that are explicitly and implicitly incorporated in its definition and interpretations.

Another issue that emerges is the one of how to measure sustainable development; on this subject, the notion of sustainability has been employed. It is a measure of endurance of natural systems [4] and has been extensively used to measure the extent to which the state of sustainable development has been achieved.

Similar to sustainable development, sustainability should be a multi-dimensional concept [5], integrating into one concept multiple, different and even non-quantitative dimensions. The task of assessment becomes more difficult by several questions such as:

- How can different (and even contradictory) indicators be combined (in the most appropriate manner) to assess sustainable performance?
- How can qualitative notions be incorporated and assessed in a quantitative analysis in an appropriate manner?
- Which of these qualitative and/or quantitative notions/variables should be used and why?

Such questions are not only interesting from a research perspective; they have real-life implications. Employing effective methods that address these questions can assist policy makers in reaching appropriate and sound decisions [6]. Hence, this type of complexity is perhaps the reason why methods that rely on cost-benefit analysis may not be able to fully capture the multi-dimensionality of the problem [7]. A different approach to measure sustainable performance of public (or private) organizations is the Data Envelopment Analysis (DEA) method.

The foundations of DEA can be traced in the works of [8–10]. The method was originally developed as a non-parametric, mathematical programming approach for the performance evaluation in situations involving multiple criteria and where price information is not available [11–13]. Further advantages of DEA include:

- It does not require the identification of any type of relation between inputs and outputs [14].
- It does not require any specific statistical distributions for the data of input and output variables.
- It can provide information on how to improve the performance of a non-efficient entity [6].

These advantages indicate why DEA was originally intended as a tool in a microeconomic context. Nonetheless, it has evolved to be considered as an acceptable solution for aggregating economic, environmental and social indicators with different units, thus proving suitable for use in a macro-economic [15] and sustainability context [16].

In the context of sustainability, Zhou et al. [4] performed an extensive literature review on the use of DEA and sustainability covering the years 1996 to 2016. Among the most important patterns that the authors detected in the literature are: (a) Data Envelopment Analysis has seen an increase in its use to assess sustainable development, (b) early adopters of the methodology tend to use the classic DEA models, but as their familiarity increases so does the use of more advanced variations of the method, (c) there is trend to combine DEA with other methodologies such as Life Cycle Assessment or Tobit regression analysis with the purpose of mitigating the intrinsic disadvantages and/or limitations of the methods, and finally (d) a stream of research in DEA literature for assessing sustainability that is gaining traction is the construction of composite indicators as they are easy to communicate and they can measure multi-dimensional concepts that may not share common units of measurement [17].

However, the authors also identify several gaps in the literature: The main focus of the applications concerns the study of economic and environmental measures, while the integration of the social dimension is lagging. Moreover, there is the need for a context analysis of sustainability, mainly which variables should be included that explain best the economic, social and environmental dimensions [4].

Another limitation that was not explicitly mentioned by the authors is that when the sustainability of countries or regions is assessed with DEA, the main focus is on Asia and Chinese regions. Furthermore, Moutinho et al. [18,19] identified that the methodology is sensitive to the choice of inputs and outputs, while data considerations may limit the available options. More social indicators need to be employed, but Moutinho et al. concluded that the limitation in the number of inputs and outputs that can be used in DEA, means that the inclusion of social variables (such as for example level of education or public spending on research and development) may come at the expense of economic or environmental variables, hence not capturing the complex structure of sustainability. In conclusion, it seems that the assessment of sustainability of countries can be limited by DEA’s methodological considerations [20].

Consequently, the main objective of the current paper is to build on the work of Zhou et al. [4] and perform a literature review on the use of DEA for the measurement of sustainability for the years 2017-2020. This literature review has a twofold purpose: First to investigate whether the gaps identified by Zhou et al. have been subsequently addressed and second investigate whether the limitations identified in the definition and the methodological framework have affected how sustainability has been measured.

The rest of the paper is organized as follows: in section 2, a historical context of the definitions of sustainable development and sustainability is provided. In section 3, the review of the literature on how Data Envelopment Analysis has dealt with sustainability is described. The lessons that have been learned from the literature are presented in section 4, while conclusions are discussed in section 5.

2. Sustainable development and Sustainability

The term of sustainable development was cemented in the public discourse in the 1980s with the Brundtland report [1]. The report was the culmination of an effort to identify the fact that all human activities had damaged the natural integrity and had caused unbalances to ecosystems that could seriously threaten the security of the human societies [21].

The report brought to the limelight of public debate the notion that the objectives of policy makers and governments cannot be solely to promote social development while facilitating economic prosperity [22]**,** but there needs to be a constant reminder in the decision-making process that conflicts can exist between economic growth and the environment [5]**.**

Hence, to achieve sustainable development governmental policies should have economic, social and environmental dimensions. Their consequences should contribute neither to overexploitation of the natural resources nor to widen the gap in distribution of social services [3]. Finally, sustainable development should always reconcile technological development and efficiency [23], while considering the cultural context and the values system in which it is applied [24].

Despite of the immense complexity associated with the concept of sustainable development -even from its beginning- efforts to achieve that state have become common practice in all levels of public policy, from government laws [3] to regional and private decision-making [25]. The reason behind that effort is best captured by the implications if sustainable development is not achieved: the ability of the natural environment to provide critical resources will be severely diminished [26] followed by dire consequences for human societies.

Thus, the achievement of sustainable development is an enormous, complex and ongoing effort, but the first step should always be to address the widely recognized need of how best to measure it [27].

The notion that has been used to measure the extent to which sustainable development has been achieved is the one of *sustainability*. It originates from the field of ecology and in its most basic form it signals the ability of a natural system to retain its essential properties and naturally replenish its population. Hence, sustainability is a measure of endurance of natural systems [4], while in terms of human systems and processes, sustainability focuses on the ability to live without environmental degradation [23,28].

Despite their importance, both sustainable development and sustainability are characterized by a plethora of definitions and meanings for people and organizations [23,29]. In general, however, all the definitions fall under two categories: there is the three-dimension approach (integration of economic, social and environmental dimensions) and the dualistic topology that emphasizes the relationship between human and nature [23]. Lately, an even more contested term has entered the arguments of the opposing categories, with some claiming that the road to sustainable development can be achieved through *technology and innovation* while the rest claiming that this road could only lead to further environmental degradation [29].

Consequently, to continue to be an uncontested governmental activity [21], sustainable development needs to be defined in such a way that it does not exclude any views; whether one perceives sustainability as a three-dimensional construct or as a measure of balance between humans and nature, there is the need to develop a measure or index that incorporates both (or even more) perceptions.

The lack of a unified definition notwithstanding, policy makers understood the importance of trying to achieve sustainable development and a series of international treaties and policy frameworks have been reached. The most important examples of recent years are the Sustainable Development Goals of the European Union that attempt to synchronize the effort across European countries [7] and the United Nations Conference of the Parties 2015 Agreement (or else known as the COP-21/Paris Climate Agreement), the focus of which has been to underline the connection between sustainable patterns of consumption and the fight against climate change [30].

What these attempts do not seem to offer however, is methodological guidance and a unified framework on how to measure sustainability in practice and therefore achieve sustainable development [5]. The use of such an appropriate framework and/or guidance could immensely help policy makers reaching effective decisions related to sustainable policies [6], especially since decision-making is increasingly characterized by multi-dimensional complexity.

Composite indicators emerged as a tool for the proper measurement of sustainability [21]. A composite indicator can be considered as a mathematical construction that can measure multidimensional concepts, derived from individual indicators that usually have no common units of measurement [4]. Their advantages include the fact that they can be easily communicated and act as justification tools for policy makers, while - if properly constructed - they can lead to meaningful comparisons, policy monitoring and benchmarking [31].

These indicators have been considered essential for regional sustainability measurement [32], but in the beginning they mainly focused on the environmental aspect of sustainable development [33], covering the effects of economic activities to the environment. The criticism over this focus, has lead the research towards integrating more aspects of the sustainability structure such as the social dimension [34–36], innovation as a force for socioeconomic change [29], and the capacity of a country to produce a steady stream of sustainable technological products [24].

Apart from the criticism on what these indices should include and measure, there have also been voices of concern of how they are constructed. The main objection is that they are usually developed by using a framework of weighted linear aggregation. Linear aggregation however implies compensability among the parameters (or sub-indicators) that construct the overall indicator; disadvantages of one sub-indicator could be offset by a sufficiently large advantage of another sub-indicator [5]. In the case of sustainability for example this could mean that the loss of potable water or the diminished levels of clean air could be substituted by economic growth [17].

Such an assumption is not realistic and even goes against the very notion of sustainability. For that reason, a robust methodological framework is necessary to mitigate the methodological limitations and assist in constructing effective and appropriate sustainability indices.

Furthermore, the linear aggregation function demands the determination of weights from the analyst/policy-maker that builds the function. However, the problem with this type of weighting is that the resulting indicator will represent the values of the analyst/policy-maker, which may differ even within the same society/environment etc. [11].

In conclusion, the studying of sustainable development and sustainability led to the identification of the following gaps: First, the lack of a unified definition on what sustainable development is, resulted in different and even conflicting interpretations, which may have a negative effect on the communication of why sustainable development is necessary. Second, the lack of a unified methodological framework for measuring sustainability led to the employment of methods that may not be suitable to capture its multi-dimensional nature, which may have resulted in policies that are not sufficient and effective. Finally, these two gaps are interrelated: misguided assumptions about what sustainable development is accompanied by misguided methodological assumptions on how to measure it, lead to wrong estimations, hence the individual consequences of each one is amplified, increasing the overall complexity of the endeavor.

The next section is focused on how Data Envelopment Analysis has attempted to mitigate the methodological limitations of measuring sustainability, while in parallel offering examples within DEA of how the problem of different definitions still persists affecting the results.

3. DEA and Sustainability

As it was mentioned in the introduction, Data Envelopment Analysis emerged as a suitable method to measure sustainability. It is a non-parametric method that is used for the assessment of the *technical efficiency of Decision Making Units (DMUs)* relative to one another [7,37], where technical efficiency can be defined as a measure of how well a DMU can transform inputs into outputs.

The definition of efficiency for DEA originates in engineering and is defined as the ratio of the sum of its weighted outputs over the sum of its weighted inputs.

$$technical\ efficiency = \frac{\sum w_{output} * y}{\sum w_{input} * x}, where\ x = input\ level\ and\ y = output\ level \quad (1)$$

The method was established in the seminal papers of Charnes, Cooper and Rhodes [12] and Banker, Charnes and Cooper [13]. In its most basic form, it is assumed that there are N DMUs that use *m* inputs to produce *s* outputs. The notation includes the variables of x_{ij} (i=1…m, j=1…N) the level of the i^{th} input of DMU j, and y_{rj} (r= 1…s, j = 1…N) the level of r^{th} output of DMU j.

Then the calculation for the *technical efficiency for the input-oriented model* can be found by solving the LP:

$$min\ \Theta_0 - e\left(\sum_{i=1}^{m} S_i^- + \sum_{r=1}^{s} S_r^+\right) \tag{2}$$

$$subject\ to\ constraints:$$

$$\sum_{j=1}^{N} \lambda_j * x_{ij} = \Theta_0 * x_{ij_o} - S_i^-, i = 1 \dots m \tag{3}$$

$$\sum_{j=1}^{N} \lambda_j * y_{rj} = y_{rj_o} + S_r^+, r = 1 \dots s \tag{4}$$

$$\lambda_j \geq 0, j = 1 \dots N, S_r^+, S_i^- \geq 0 \tag{5}$$

The technical efficiency of the above problem for DMUj_o is the variable Θ_0 and it takes values between 0 and 1 (or 0 and 100%). The mathematical program represented with equations (2)-(5) is solved separately for each DMU and there are three options for the results after the solution:

1. DMUj_o is Pareto-efficient if and only if $\Theta_0 = 1$ at the optimal solution and $S_r^+, S_i^- = 0$ for all inputs and outputs
2. If the value of one of the slack variables S_r^+, S_i^- is positive at the optimal solution, the corresponding input (or output) of DMUj_o can be further improved
3. If none of the above applies, then DMUj_o has technical efficiency ${\Theta_0}^*$. In the particular case, the technical efficiency at the optimal solution $\Theta_0 = a\ (< 1)$ reflects the maximum radial contraction of the input levels, without worsening the output levels, in order for DMUj_o to be considered efficient.

This simple model and the notion of efficiency has proven to be appropriate for the measurement of sustainability. Zhou et al. [4] performed an extensive literature review of how Data Envelopment Analysis has been used in the context of sustainable development and sustainability. Their work covers research efforts until 2017, and the authors consider their work an extension of the review by Dakpo, Jeanneaux and Latruffe [38]. Their focus is not only the environmental dimension of sustainability, but they attempt to include and search for the social factors that can contribute to sustainable development.

For the current paper, a search was performed in bibliographic databases (Scopus and Google Scholar) for the years after 2016 to investigate the extent to which the method has been used for sustainability (using as keywords the terms “composite indicators” and “data envelopment analysis” or “DEA”). From the initial sample of articles, a further screening was performed by reading the abstract (and where necessary the main text) to check for measurement of sustainability (or similar notions). Finally, several articles from the original review are included in the final sample because they were used to draw alternate interpretations of the results. Tables 1, 2 and below summarize the new search, grouped per region of application.

Table 1 Summary of the new research on the literature- Applications in Europe

Work	Input	Intermediate	Output	Index	DEA variation	Combination with other method	Area of Application
[18]	Labor productivity, capital productivity, the weight of fossil energy and the share of renewable energy in GDP	-	GDP/GHG	Efficiency	Classic DEA	Quantile regression	EU countries
[39]	consumption of electricity, consumption of heat, consumption of fuel, consumption of sawn wood and particle boards, consumption of fiberboard, consumption of sheets of float glass, consumption of paper and cardboard, consumption of cement, consumption of basic chemicals and plastics, consumption of metallurgical products, water consumption, wastewater discharged in waters, emissions of air pollutants, waste production	-	GDP, gross value added	Eco-efficiency	Classic DEA	-	Polish regions
[42]	AROPE rate, unemployment rate, LCA result, Public school vacancies, number of crimes, inhabitants with higher education	-	Net disposable income	Efficiency	Classic DEA	Material Flow Analysis+ Life Cycle Assessment	Spanish cities
[19]	GDP, population density, labor productivity, total resource productivity, patent applications per 10000 inhabitants	-	GDP per capita, CO_2emissions	Eco-efficiency	Classic DEA	Malmquist index	German and English cities
[43]	Greenhouse gases, Gross final energy consumption, renewable energy consumption	-	GDP, population	Efficiency	Classic DEA	Zero Sum Gains DEA	EU countries
[45]	mathematical programming scores and scores from the energy trilemma	-	energy consumption, GHG generations, share of renewable energy in gross final energy consumption	Efficiency	Classic DEA	Mathematical Programming	EU countries
[47]	infrastructure, efficiency of the legal system, tourists, high school qualifications, unauthorized buildings	-	Environmental index, GDP per capita	Eco-efficiency	Classic DEA	Malmquist index	Italian regions
[49]	Percentage of people with low income, Carbon emissions, Traffic flow, House Price, Anxiety	-	Happiness, Life Satisfaction, Income of tax Payers	Efficiency	Non radial DEA	Temporal analysis	London boroughs

[52]	Gross Fixed Capital in PPS, Total Labor Force	GDP per capita in PPS	Share of renewable energy in gross final energy consumption, Greenhouse gas emissions (in CO2 equivalent), Overall life satisfaction, Satisfaction with living environment, Satisfaction with financial situation, Intramural R&D expenditure for all sectors of the economy	Sustainability index	Multi-stage DEA	-	EU countries
[53]	Fixed Capital in Purchasing Power Standards (PPS), Total Labor Force,	GDP per capita in PPS	Share of renewable energy in gross final energy consumption, Greenhouse gas emissions (in CO2 equivalent), Overall life satisfaction, Satisfaction with living environment, Satisfaction with financial situation, Intramural R&D expenditure for all sectors of the economy, Mean equivalized net income, ability to face unexpected financial expenses as percentage of the population	4 sustainability indices using combinations of inputs and outputs	Multi-stage DEA applied 4 times		EU countries

Table 2 Summary of the new research on the literature- Applications in Asia

Work	**Input**	**Intermediate**	**Output**	**Index**	**DEA variation**	**Combination with other method**	**Area of Application**
[40]	Capital, Labor, Energy	-	Gross Regional Product, CO_2 emissions, SO_2 emissions, soot, wastewater, Chemical Oxygen Demand, NO	Efficiency under natural and managerial disposability	Intermediate DEA	-	Chinese regions
[41]	Capital, Labor, Energy	-	Gross Regional Product, CO_2 emissions, SO_2 emissions, soot, waste water, Chemical Oxygen Demand, NO emissions	Efficiency under natural and managerial disposability	Intermediate DEA	-	Chinese regions
[22]	population, investment in energy industry	coal consumption, oil consumption, electricity consumption, natural gas consumption	CO_2 emissions, GDP	Efficiency	Two-stage DEA	-	Chinese regions
[44]	electricity consumption, total primary energy consumption	-	GDP, GDP per capita, total CO_2 emissions, CO_2/total primary energy	Efficiency and natural and managerial disposability	Intermediate DEA	-	Asian countries
[46]	Employment, Total Energy Consumption, Fixed capital input	-	Total discharge of industrial wastewater, Discharge of industrial waste gas, amount of industrial solid waste	Efficiency	Ray slack-based DEA	-	Chinese regions
[32]	Total renewable energy potential, network length, total installed power of renewable energy, transformer capacity	-	Gross energy generation from renewable energy, number of consumers, total exports, GDP per capita, HDI, Total energy production, Population, area	Super efficiency	Super efficiency DEA	Tobit regression analysis	Turkish regions
[22]	Capital, labor, build-up land, water, energy	-	Solid waste, household refuse, SO_2 emissions, soot, industrial dust, wastewater, GDP	Eco-efficiency	Classic DEA	-	Chinese regions
[48]	Capital, Labor, Energy	-	Gross regional product (GRP), CO_2emissions, SO_2 emissions, soot and dust, wastewater, COD, Ammonia nitrogen	Efficiency	Intermediate DEA		Chinese regions

[50]	Capital, Labor, Energy, RFE %	GDP	Wastewater, waste gas, Solid waste, SHC, SBE, SSSE	Efficiency	Parallel DEA models	-	Chinese regions

Table 3 Summary of the new research on the literature- Applications in various countries

Work	Input	Intermediate	Output	Index	DEA variation	Combination with other method	Area of Application
[3]	total material consumption, labor unemployment	-	GDP per capita, CO_2 emissions, employment protection index	Efficiency	SORM DEA	Inverse SORM DEA	OECD countries
[30]	Labor, capital	-	GDP, ecological reserve deficit	Aggregation of efficiency and anti-efficiency	RAM DEA	-	Various countries
[51]	Imports of goods and services in current US$, total annual freshwater withdrawals in percentage of internal resources, public expenditure per capita in current US$, duration of compulsory education	-	exports of goods and services in current US$, GNI per capita in current US$, total life expectancy at birth in years, total employment, proportion of seats held by women in national parliaments in percentage, CO2 emissions, total refugees leaving the country	Efficiency	Classic DEA	-	Various countries

The tables above indicates papers that were published until 2020. The first aspect that can be noticed is that apart from the indicators that were identified as inputs and outputs by Zhou et al. [4], an effort has been made to diversify their types with the aim of including social sub-indicators. Furthermore, their variety has increased with authors trying to diversify the types of pollutant emissions, waste, consumption etc. Interestingly, of all the papers that were studied only five diversify completely from the norm.

Gonzalez-Garcia et al. [42] who use as inputs several social indicators that were not used before like level of higher education, crimes etc. and as output the net disposable income to study the efficiency of Spanish cities with regards to sustainability. Furthermore, Carboni and Russu [47] include the quality of the legal system along with notions of corruption and quality of life to investigate the eco-efficiency of Italian regions.

However, only in 2019 notions like “happiness”, “proportion of seats held by women in national parliaments in percentage” and “total refugees leaving the country” have started to be included explicitly as equally important inputs and outputs in analyses [49,51].

The inclusion of diverse social indicators continues in the work of Tsaples et al. [52] who include notions such as “overall life satisfaction” and “satisfaction with the living environment” in their calculation of sustainability. Furthermore, Tsaples and Papathanasiou [53] further continue this trend with variables such as the “ability to face unexpected financial expenses as percentage of the population”.

Despite the inclusion of more societal dimensions, the literature is lagging in including technology and innovation in the measurement of sustainability. In the work by Santana et al. [24], the authors use as input the gross domestic expenditure on Research and Development along with the total number of applications, as outputs they use GDP per capita, means of schooling years, life expectance, CO_2 emissions to measure the efficiency of sustainable development of BRICS and G7 countries. Finally, Tsaples et al. [52] and Tsaples and Papathanasiou [53] include the variable of “Intramural R&D expenditure for all sectors of the economy” in their calculations.

Consequently, in the debate of how to define and measure sustainable development, the research on DEA illustrates that the concept of the three-dimensional sustainability appears to be predominant. It must however be noted that in that way, other views and definitions are usually excluded from the analysis. Only recently, individual efforts have started to look how sustainability could be defined in an alternate way.

Regarding the actual notion of sustainability, Figure 1 below illustrates the type of index that has been employed.

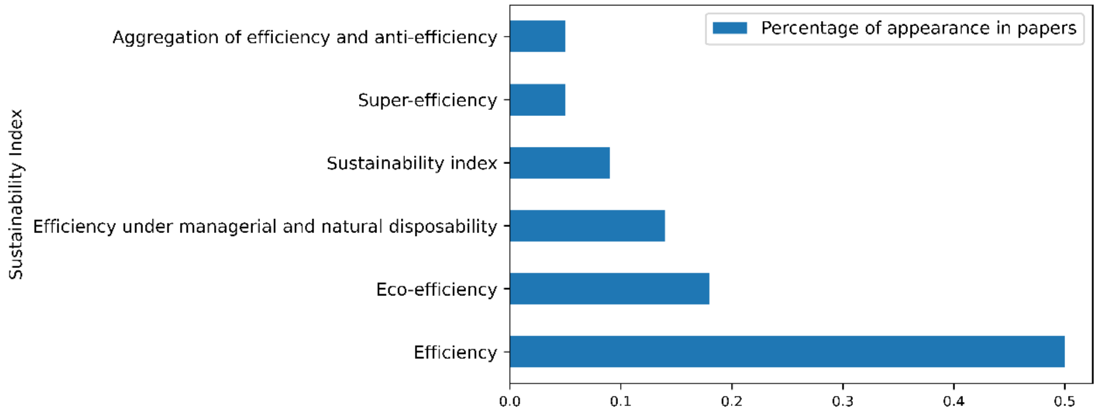

Figure 1 Frequency of appearance of sustainability index

As it can be observed, the majority of the papers use Efficiency (or some variation) as a proxy for sustainability and only in two papers there is an explicit mention of calculating a sustainability indicator. Furthermore, the second most-used term is that of eco-efficiency.

Eco-efficiency is one of the most widely used indicators that is related to the more encompassing notion of sustainability [11]. The aim of an eco-efficient system is the maximization of the production while keeping the environmental consequences to a minimum [18,54]. OECD [55] defined it more formally as "the efficiency with which ecological resources are used to meet human needs".

Its concept can be traced in the decade of 1970s when it was linked to the efforts to achieve environmental efficiency [47,56];. According to Huppes and Ishikawa [57], the notion of eco-efficiency can be measured in real life with 4 ways:

- As the ratio of economic output to environmental pollution (named as environmental productivity).
- As the ratio of environmental pollution to economic activity (named as environmental intensity).
- As the ratio of improvement cost to environmental improvement (named as environmental improvement cost).
- As the ratio of environmental improvement to improvement cost (named as environmental cost effectiveness).

Similar to the discussion on which inputs and outputs should be used with DEA to measure sustainability, the above notions of economic output, environmental pollution etc. are perceived differently by different authors and different combinations of inputs and outputs are used to measure eco-efficiency.

The notion of eco-efficiency is considered critical since it provides a pathway to the design of policies that could reduce environmental pressure [58]. Furthermore, the ratio of economic value over environmental damage (or its inverse) is considered intuitive and clear, thus making eco-efficiency a measure of sustainability that is easy to communicate [11].

For those reasons, eco-efficiency has been extensively used with DEA as a measure of sustainability of regions and countries [59].

Masternak-Janus and Rybaczewska-Błażejowska [39] used a classic DEA model to measure eco-efficiency of Polish regions, while in Moutinho et al. [19] the authors did the same for German and English cities. Finally, a stream of research utilized the notion of eco-efficiency to measure sustainable development of various regions. This stream includes the works of Carboni and Russu [47] for Italy and Lin and Chiu [22] for Chinese regions.

Despite its popularity, eco-efficiency has attracted a lot of criticism. Ehrenfeld [60] sees eco-efficiency as a symptomatic solution where technological innovation is solving the problems that were created by technological innovation. Furthermore, attempting to achieve adequate levels of eco-efficiency does not guarantee a state of sustainable development [11]. A recurring criticism that was observed in all the literature, is which inputs and outputs should be used in the DEA model with the aim of measuring eco-efficiency.

As a result, the lack of a unified definition has an impact of how sustainability is perceived and how it should be measured. In the DEA literature, efficiency is used as equivalent to sustainability, while other notions like eco-efficiency are regarded as sufficient proxies. Furthermore, the diverse definitions have an effect on which inputs and outputs should be used to measure sustainability. In the DEA literature, the typical three-dimensional construct is prevalent, but recently efforts have been made to include technological aspects. Finally, only one recent paper attempted to integrate different definitions of sustainability within the same measurement.

Apart from the effects of different definitions of sustainability, differences are also observed in the methodology used even within the same DEA framework. Figure 2 below illustrates the frequency of the method that has been used in the literature.

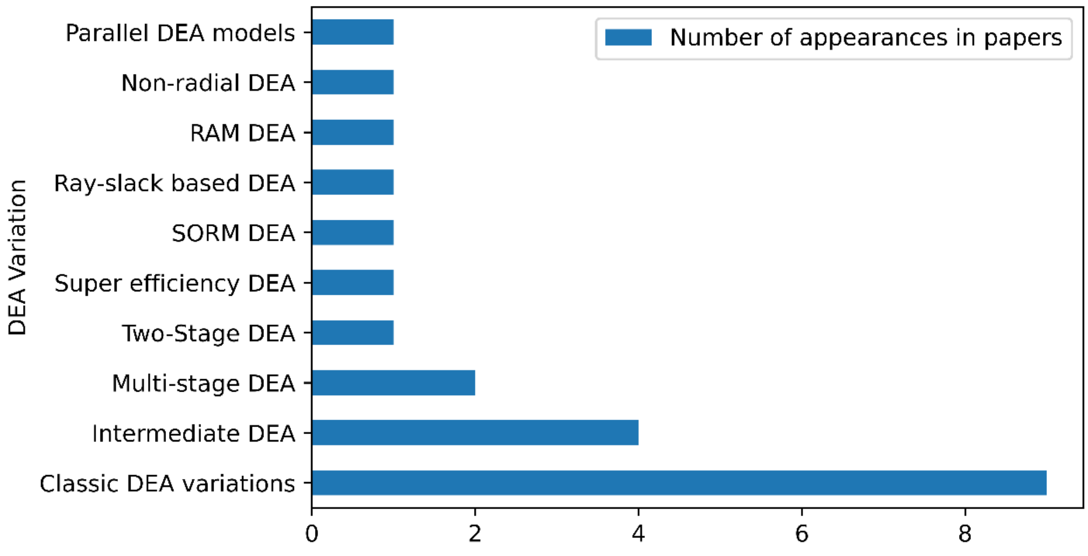

Figure 2 Frequency for DEA variations in the papers under study

Thus far, it appears that classic variations of DEA are the preferred option for researchers, with non-radial and multi-stage approaches gaining traction in the last years.

Moreover, a trend is observed where authors enrich the results generated by DEA with another method to gain another layer of knowledge. For example, a combination of a classic CRS DEA model with another method is the one proposed by Cucchiella et al. [43]. After analyzing the DEA model, the authors perform a second analysis to identify the input values that make the system under study globally efficient.

A similar idea but with a different approach was executed by [3]. The authors combined a DEA model with its inverse; its purpose was to determine the most desirable inputs and outputs that keep the levels of efficiency unchanged [61].

Another stream of work observed in the literature is the use of the Intermediate DEA. The method was proposed by Sueyoshi et al [41]. and a typical example of its use is the work on [44]. The authors measure efficiency but they do so under the concepts of natural and managerial disposability.

The examples that were described thus far use the typical, one-stage version of DEA. However, in recent years, researchers understood that the robustness of a model increases (where by robustness it is meant to increase the validity of the results by mitigating some of the limitations of DEA) if the region/country under study is not considered a black box; for this reason, a network-version of DEA could be used. Furthermore, in any DEA analysis, the number of inputs and outputs depends on the number of DMUs under study for the results to be meaningful i.e. the number of DMUs, must be no less than three times of the total number of inputs and outputs (for example if one uses 2 inputs and 2 outputs to measure sustainability then the number of DMUs or regions under study should not be less than 12) [62].

As a result, increasing the number of intermediate stages increases the discriminatory power of the DEA model and the analysis. For example, Zhao et al. [50] used parallel settings of DEA to explicitly model the three dimensions of sustainability and their potential interactions. In a similar direction, the work by Tsaples et al. [52] and Tsaples and Papathanasiou [53] use multi-stage DEA models to calculate the different sub-indicators that sustainability entails and integrate them in a final sustainability index.

Consequently, even within the DEA framework it appears that there are differences on the variation that is being used to measure sustainability. As a result, the lack of a unified methodological framework from the birth of the notion of sustainable development persists to date.

Finally, by examining the area of application, it is revealed that for the last years the scope of research is tailored towards urban environments with a focus on Chinese regions. The measurement of sustainability of European countries is steadily increasing, but it appears that the papers that investigate the sustainability among the EU countries is still lower than those measuring sustainability of Chinese regions. One possible explanation could be that the rapid economic development that was observed in China the previous years, made the research community to reflect on what the impact of this development could be in the environment. Figure 3 below illustrates the frequency of appearance for the various areas of application.

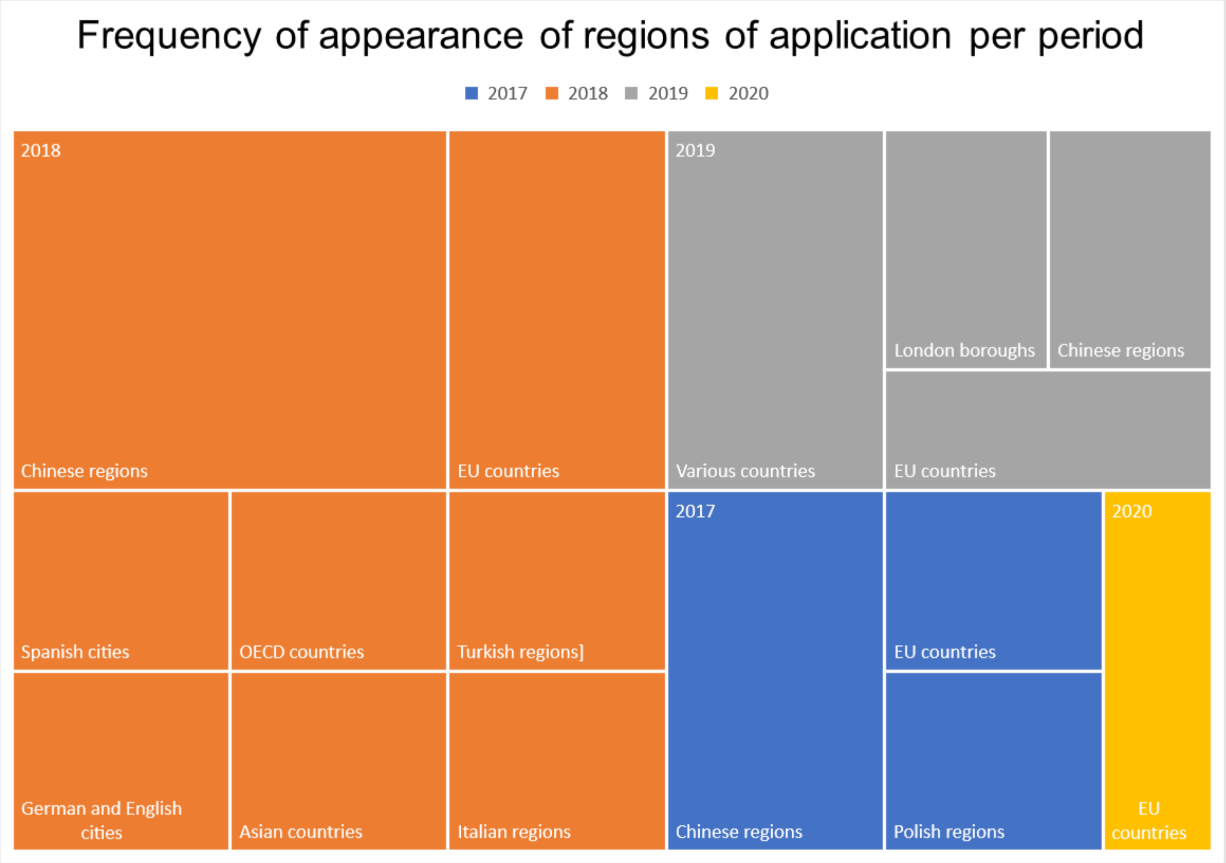

Figure 3 Frequency of appearance for the various regions of application of DEA in sustainability measurement per year

4. Lessons Learned from the Literature

The studying of the literature on Data Envelopment Analysis and Sustainability has highlighted that the ambiguity of the definition of sustainable development has permeated to the research. The three-dimensional structure of sustainability appears to be the preferred option, however there are approaches where there is an effort to integrate different dimensions, like technology and innovation, in the measurement of sustainability.

Moreover, even sustainability as a measurement of sustainable development appears to have different definitions. In the DEA literature, efficiency is used as equivalent to sustainability, while other notions like eco-efficiency are regarded as appropriate proxies. These diverse definitions have an effect on which inputs, outputs and data should be used to measure sustainability, thus impacting the final results.

In addition to the lack of a common definition of sustainability, differences are observed on the variation of DEA that is being used. All these differences result in different measurements of sustainability, which may cloud the robustness of the research efforts and ultimately affect the policy making that depends on those measurements.

Finally, by examining the area of application, it is revealed that for the last years the scope of research is tailored towards urban environments with a focus on Chinese regions. One possible explanation could be that the rapid economic development that was observed in China the previous years, forced policy makers and the research community to reflect on the impact of this development.

5. Conclusions

The purpose of the current paper was to perform a literature review on how Data Envelopment Analysis has been used in the context of sustainability . The purpose of the review was to extend the literature review performed by Zhou et al. [4] and investigate whether the lack of unified definition and methodological framework for the measurement of sustainable development has affected the research.

To do so, bibliographic databases were searched for research efforts concerning the years from 2017 until 2020. Several interesting insights are revealed in the literature. First, the vague definition of sustainability has led to different approaches on how to measure it. However, in the DEA literature the authors heavily use the 3-dimensional structure (economic, social and environmental), with individual efforts attempting to incorporate different dimensions such as technology and innovation.

Moreover, even when the 3-dimensional structure of sustainability is used, differences are observed on the combinations of inputs and outputs of the DEA model. This is to be expected since the social dimension, for example, might have a different meaning for different people. Nonetheless, each of these approaches, by using one combination of parameters excludes the other perceptions from the analysis.

Another issue that was also mentioned in the review by Zhou et al. [4] is that the social dimension of sustainability has been underrepresented in the studies so far. In fact a lot of environmental and energy studies use the same combinations of inputs and outputs as those that explicitly measure sustainability. Despite the recent approaches that seek to remedy the issue, there is still a lot of effort needed to fully capture the multi-dimensional notion of sustainability in a coherent and mathematically sound way.

Moreover, in the last few years the research on sustainability has shifted towards urban environments and within country regions. A large portion of the research activity concerned Chinese regions. One possible explanation could be that the research community is focused on investigating the possible visible and not visible consequences that the country’s economic development could have on the environment and the society. Finally, from the papers that were reviewed, those that focus on the comparison of the EU countries with regards to sustainability appear to be lagging in numbers. Nonetheless, it is deemed important to address the specific gap especially since the Sustainable Development Goals are part of the European Policy Framework.

All these gaps result in different measurements of sustainability, which may have a negative impact on the robustness of the research efforts. Equally important, this fact could have negative implications in policy making. First, decisions based on those measurements may be rendered ineffective because the measurements cannot really capture the full scope of sustainability. Moreover, these decisions could produce undesired consequences in areas of public life that were not addressed in the analysis. Finally, these differences in measurements have an effect on communicating policy efforts to the general public. As a result, citizens may be less inclined to abide by policies if these appear to be based on contested measurements.

Consequently, it is the belief of the authors that in order to mitigate those limitations, the research efforts could be directed (but not limited) to the following avenues: First, take a top-down approach and provide a unified definition of sustainable development and sustainability thus, forcing everyone to measure the same notion. The other avenue could follow an opposite, bottom-up approach, where scientists propose a unified methodological and/or computational framework that attempts to mitigate the limitations of individual methods and integrates different and diverse definitions of sustainability into the same measurement. The authors of the current paper hope that this review can be a useful source of research efforts on sustainability and Data Envelopment Analysis.

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