Journal of Sustainable Development; Vol. 16, No. 3; 2023
ISSN 1913-9063 E-ISSN 1913-9071
Published by Canadian Center of Science and Education

Sustainable Efficiency of Sugarcane Mills in the State of São Paulo: A Data Envelopment Analysis

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Received: February 20, 2023 Accepted: April 6, 2023 Online Published: April 14, 2023

doi:10.5539/jsd.v16n3p63 URL: https://doi.org/10.5539/jsd.v16n3p63

Abstract

The pursuit of greater competitiveness and efficiency today goes hand in hand with concerns directly linked to sustainable development. The traditional sugar-energy sector, with a strong influence on the economy since colonial Brazilian periods, not only played a pioneering role in replacing fossil fuel with renewable resources but is also characterized by substantial production-related differences. The Brazil is currently the largest global producer of sugarcane, and the state of São Paulo, in southeastern Brazil, leads this production. The objective of this research was to analyze the sustainable efficiency of sugarcane mills in the state of São Paulo, through Data Envelopment Analysis (DEA). For this, the work was based on the Triple Bottom Line, considering environmental, economic and social approaches to the performance of the mills. Regarding the main results, it was possible to notice that the production scale factor favored large mills in some points of analysis, while at other times, small mills were highlighted.

Keywords: sustainable efficiency, sugarcane mills, Brazilian production, Data Envelopment Analysis

1. Introduction

Societies and production systems have undergone remarkable transformations in recent decades. The quest for greater competitiveness and efficiency is now closely allied to concerns directly tied to sustainable national development.

The literature contains a wide range of research works on the production chain in general, and its inherent factors, which currently converge to the best use of available resources.

In this regard, it should be noted that, in terms of supply chain efficiency, the position of the Brazilian economy shows significant heterogeneity (Steingraber & Gonçalves, 2013). Possible culprits for this condition are low investment in research and development (R&D), obstacles entrepreneurs and companies face in obtaining credit, tax complexity, and political instability in recent years.

In view of this trend in the production system and the growing focus on sustainability, Brazil's Federal Government launched the National Environmental Education Program (ProNEA) in 2004. Within the educational sphere, the purpose of the program has been to ensure the balanced integration of the multiple dimensions of sustainability (environmental, social, economic, political, ethical and cultural) in Brazil's economic development. However, in spite of public policies aimed at accessing information about improvements in the production system, there are still large gaps.

One of these relevant gaps today pertains to sugar and ethanol production management. In response to growing global concerns for the sustainable and efficient use of production chains – aiming to prevent permanent losses for future generations – research on the sustainable production efficiency of the sugar and ethanol industry, which pioneered the use of renewable resources in place of fossil fuels, has reached a bottleneck.

Sugarcane is a very efficient crop with a faster cycle than other commercial crops, which can be grown using sustainable techniques (Birru, 2016). The structural and chemical composition of sugarcane makes it attractive, given its potential for industrial transformation into valuable products such as fuel ethanol and bioelectricity generated through the combustion of sugarcane bagasse (Birru, 2016).

Sugarcane production potential is also emphasized by others authors. A wide variety of products can be obtained in the sugar alcohol industry, such as ethanol, electricity, sugar and high-pressure steam generated by burning the sugarcane bagasse produced at the mill (Brasil, 2021). These authors describe the concept of Renewable Energy Efficiency to explain the level of sustainable production a mill can produce – a combination of efficient production management and a horizon of possibilities for sustainable products derived from sugarcane processing.

Since colonial times, Brazil has shown a propensity for planting sugarcane. According to the Ministry of Agriculture, Livestock and Food Supply (Brasil, 2021), Brazilian sugarcane production reached a total of 654.5 million tons in the 2020/21 crop year, making it the largest global producer. The state of São Paulo, which leads production in the country, accounted for 54.1% of the quantity produced in that crop year (São Paulo, 2021).

The country has been investing resources in more sustainable production techniques, including the use of sugarcane harvesting machines (to prevent pre-harvest cane burning, which facilitated manual harvesting), biological pest control, the use of vinasse (a by-product of sugarcane processing) as biogas, energy and fertilizer, and systems that reduce carbon dioxide emissions. It should be noted that such efforts are important and must be strengthened and expanded to increase the sustainability of this production chain in the country.

1.1 Sugar Mill Efficiency

This section provides a brief literature review of relevant studies on sugar mill efficiency, especially in India and Brazil, two of the world's largest producers. The idea is not to explore all the studies, but instead just a few considered relevant and more contemporary.

Cano and Tupy (2005) analyzed the production efficiency of the sugar and ethanol industry in the state of São Paulo, Brazil, especially after the 1990s, a period in which companies in the sector turned their attention to efficient and competitive management. These authors' research was based on data extracted from the Sugarcane Yearbook (Procana, 2003) of 2002, consisting of production variables and production factors from 63 mills that produced both sugar and ethanol in the 2001/2002 crop year. The model chosen for estimating the boundaries of efficiency was DEA.

The input variables were the quantity of sugarcane used by the mill, and labor. The output variables were the quantity of ethanol, and the quantity of sugar produced by the mill.

The authors found an average business efficiency of 96.1%, considering variable returns to scale (VRS). From the standpoint of constant returns to scale (CRS), the average efficiency was 94.5%. Cano and Tupy (2005) point out that 22.2% of the 63 analyzed mills had a maximum score from both standpoints (VRS and CRS), while 19% showed a maximum score only in VRS, indicating that they are efficient in their use of inputs, but have problems on the production scale.

In relative terms (efficient enterprises/total enterprises), the macroregion of Presidente Prudente presented the best result, since about 60% if its enterprises were considered efficient. The macroregion of Araçatuba (SP) showed the worst result, with 78% of the mills showing some type of inefficiency, followed by that of Piracicaba (SP).

Singh and Agarwal (2006) examined the change of total factor productivity (TFP) in India's sugar industry, encompassing private, public, and cooperative sugar mills. The input variables the authors used were: installed capacity, number of employees, planted area, and energy and fuel consumption. The outputs were sugar production and molasses production. TFP growth was estimated by applying the Malmquist index, based on an SBM-DEA model, on panel data from 36 sugar mills in the period of 1996-97 to 2002-03.

The mentioned study indicated that the sector's average TFP varied positively by 1.6% per year, throughout the investigated period. In this case, the TFP variation resulted more from technological change than from changes in technical efficiency.

For the authors, the sectoral estimate of TFP indicates that the greatest growth occurred in the private sector and then in the cooperative sector. It was also possible to observe that the sugarcane mills in the west had a greater growth in TFP, when compared to the other two regions. Other results also indicate that larger sugarcane mills had a greater increase in productivity when compared to smaller ones.

The study by Salgado et al. (2009) involved an analysis of the relationship between operational efficiency and size of sugar and ethanol plants in the northeast of the state of São Paulo. Three strata were constructed (large, medium and small size), following the categories established by the Brazilian Sugarcane Industry Association (União da Indústria de Cana-de-Sugar, 2012). The sugarcane crushing capacity of large mills is more than 2.5 million tons per crop year, while that of medium mills is 1 - 2.5 million tons per crop/year, and that of small mills is less than 1 million tons per crop/year.

After stratification, 26 sugar and ethanol mills (statistically representative of the target population) were randomly chosen and the DEA technique was applied to create an operational efficiency-based ranking framework for the 2007/2008 crop year. The following variables were analyzed – input variables: (i) planted area, (ii) number of employees, (iii) consumption of fertilizers, (iv) processed cane, and output variables: (v) ethanol production and (vii) sugar production.

The study classified mills as efficient and inefficient. The groups of mills (small, medium and large) showed an average efficiency of 81.9%, 80.9% and 89.7%, respectively. The results suggested that there are small efficient mills and large inefficient ones. Hence, despite their higher average efficiency, not all the mills in the group of large mills are considered efficient, and conversely, despite their lower average efficiency, not all the small mills are considered inefficient.

The research by Kumar and Arora (2012), as well as that by Singh and Agarwal (2006), analyze technical and scale efficiencies in India, in intertemporal and interstate terms, in two steps. The temporal delimitation of the research covers 31 years, from 1974 to 2005, and due to changes in macroeconomic policies, is divided into (i) the pre-reform period (1974 to 1991) and (ii) the post-reform period (1992 to 2005).

DEA was used in the first step to obtain efficiency scores for the top 12 sugar producing states. The model that was used included the following inputs: labor, raw material, fuel and capital. The output used was total production.

The results indicate that the Overall Technical Efficiency (OTE) of India's sugar industry ranged from 43.7% to 73.8%, with an average of 64.5%, and that the average level of the Overall Technical Inefficiency (OTIE) was 35.5%. Moreover, with respect to the latter criterion, it was found that Indian mills could increase their productivity by an average of 35.55% if they adopted best practices, without increasing the quantity of inputs. This finding clearly indicates seriously inefficient resource allocation in the Indian sugar and ethanol sector.

The aforementioned authors point out that there are differences in scores between the periods before and after India's macroeconomic reform. During the pre-reform period, the annual operational efficiency of the sector exceeded 70%. After the transition in 1991 to the post-reform period, the OTE decreased from 74% to the level of 52.8%.

In the second step, panel data were subjected to truncated regression to evaluate the main factors that explain the variations observed in efficiency levels. In this context, skilled labor and profitability were the main determinants of the technical efficiency of the Indian sugar industry.

Lastly, Pereira and Silveira (2016) analyzed total factor productivity (TFP) and its components at 17 mills in Brazil's South-Central region in the period of 2001-2008. They used DEA and the Malmquist Index, breaking them down into indices that pinpoint variations in technical efficiency and technological changes. In their analysis, they used the quantity of crushed sugarcane and number of employees as input variables, and sugar and ethanol production as the output variable.

During the time frame of their research, the group under analysis showed an 84% increase in ethanol production and a 43% increase in sugar production. This justifies the authors' research, since it demonstrates the growing demand for ethanol in domestic and foreign markets, which is reflected in the construction of Greenfield Projects.

The DEA-based Malmquist productivity index showed a negative average annual variation of 0.2% and a decline over the years of the survey. A possible explanation for this is that, in 2003/2004, the efficient boundary of the component of technical change shifted to a value above 1, while that of the component of technical efficiency showed negative growth. In other words, mills in 2003/2004 did not reach the boundary, resulting in a final average TFP below 1. In 2006/2007, there was a further decline in TFP.

Pereira and Silveira (2016) also state that another possible influencing factor for the drop in 2003/2004 may be the good level reached by the sample in 2003, resulting from a combined increase of 13.2% in crushed sugarcane and 13% in final production. This good performance caused the TFP index to decline in the subsequent year, since sugarcane crushing increased by less than 5%, and ethanol production decreased, which can be explained by variations in the price of the commodity in that crop year.

The aforementioned studies share a relatively common characteristic: they portray aspects of technical efficiency and scale of the mills, be they Brazilian or Indian. This type of research usually provides significant information about the context in which the mills operate, from the economic, and in some cases, social standpoint. There is still a paucity of studies that cover the third pillar of sustainability, i.e., the environmental pillar. The next section discuss several studies about the issue of sustainability in the reality of Brazilian mills will be presented.

1.2 The Issue of Sustainability in Sugar and Ethanol Production in Brazil

In 2009, Gonçalves (2009) conducted an important study aimed at determining the magnitude and characteristics of problems pertaining to sugarcane cultivation in Brazil, based on available census data. The author states that some sectors of Brazilian government and sugarcane producers are seeking to incorporate practices and techniques that reduce environmental impacts and ameliorate the social aspects of the activity. However, the sector's rapid growth in both planted area and sugar mill construction calls such practices and techniques into question.

Demand for ethanol has driven sugarcane production, be it due to domestic and/or international demand (flex-fuel vehicles), or to the product's growing acceptance as a "perfect substitute" for gasoline. Furthermore, sugarcane-based fuel has proven effective to combat global warming and climate change. Global biofuel production, which had amounted to 187 thousand barrels (mostly ethanol and biodiesel) in 2000, reached 1.8 million barrels by 2019 (British Petroleum Company, 2021).

In this context, Brazil is considered a world reference, since it accounts for almost 50% of global fuel ethanol production. However, although this good productivity goes hand in hand with better sugarcane cultivation techniques (e.g., elimination of the practice of pre-harvest burning), this expansion has raised some concerns. Among the most frequent ones are: (i) competition for land; (ii) water security; (iii) encouragement of deforestation to expand agriculture; (iv) large-scale use of pesticides; (v) vulnerability of agriculture to climate change; and (vi) agricultural waste and effluents, etc. (Gonçalves, 2009).

Agriculture has grown significantly throughout Brazil, but it is still concentrated mostly in the southeastern region. The state of São Paulo, the main producer of sugarcane, showed a 217% growth rate in the period of 2008 to 2021 (Companhia Nacional de Abastecimento, 2021), concentrating most of the country's production.

Although some studies released by the Brazilian government refute concerns about the socioeconomic and environmental effects resulting from the expansion of sugarcane production, such an increase in scale of production is highly aggressive to the environment, concentrating land use and causing social problems. According to Gonçalves (2009), the state of São Paulo has been blamed for the exclusion of other agricultural activities, the degradation and quasi-extinction of native vegetation, and deforestation of permanent preservation areas and legal nature reserves.

During his research, Gonçalves (2009) drew attention to two factors in sugarcane production: pre-harvest sugarcane burning and vinasse. The former was under debate in every sugarcane producing state of the country, particularly in São Paulo, where the Agro-Environmental Protocol was signed in 2007, aimed at ending pre-harvest fires in a mechanizable areas by 2014 and, by 2017, in non-mechanizable. The signing of this protocol represented an important advance for the state of São Paulo.

The second factor mentioned by Gonçalves (2009) refers to one of the most voluminous wastes generated in the ethanol production process, namely, vinasse – a residual liquid. This byproduct consists mainly of water and solid salts, with a pH level varying from 4.0 to 4.5, and its polluting power is approximately 100-fold higher than that of domestic sewage.

Today, vinasse is mainly used as a highly effective organic fertilizer. However, it can be used for other purposes, which involve its concentration through evaporation, drying for animal feed, aerobic fermentation by microorganisms to produce single-cell proteins, anaerobic fermentation using methanogenic bacteria to produce methane (biogas), etc.

Gonçalves (2009) points out that, notwithstanding the efforts of Brazil's government and of mills and rural producers to mitigate the social and environmental impacts, the tendency for expansion of the sector has given rise to serious concerns about the social and environmental problems it generates. The sector's main deficiency, according by the author, does not involve technology but pertains to the political and institutional nature of legislation and to scant oversight.

Lastly, the research by Macedo et al. (2010) underscores the importance of social and environmental issues in Brazilian mills, with respect to society's growing demand for information about the impacts caused by business activities on workers, the community and the environment. Using DEA, the authors sought to determine the relationship between social and environmental benefits and investment capacity in mills, postulating that the most efficient plants are those with the lowest investment capacity and the greatest benefits achieved. Their analysis involved data from 19 mills for the years 2004, 2005 and 2006.

For this analysis, the mill's net revenue was used as a proxy for the availability of resources to invest in the socio-environmental area, and was classified as input. The output variables were: internal social indicators (measures the total resources invested in employee well-being), external social indicators (the sum of all resources invested by companies in benefit to society), and environmental investments (investments in the environment, be it inside or outside the mill).

The results of the survey indicate that, in 2004, only 15.8% of the analyzed mills were efficient, but that sugar mill efficiency had increased to 21% in efficient in 2005 and 2006. Overall, the best socio-environmental performance was presented by Agrovale (the main benchmark), and the poorest by the São José Estiva sugar mill. Moreover, socio-environmental performance and size (measured by revenue) were found to be correlated, with the largest companies showing better performance.

1.3 Objective

The main objective of this study was to investigate the efficiency of mills in the state of São Paulo in the period of 2007 to 2016, from the economic, social, environmental and sustainability standpoints, using a more complex data envelopment model and generating models complete and robust efficiency models.

In view of the data and brief theoretical compilation presented herein, this research is justified since, as mentioned earlier, there is still a paucity of studies in the literature about sugar and ethanol mill efficiency which include variables that jointly consider aspects of sustainability (social, environmental and economic).

2. Materials and Methods

To achieve the research objective, several steps and strategies were previously defined, which make up the research method. The technique used here was DEA, which underpins all the steps described in this section.

The initial proposal of temporal delimitation of this research involves the period of 2007 to 2016, the most recent period for which standardized data are available.

2.1 Initial Specifications

The sample of this research was defined based on the identification of 15 sugar and ethanol mills in the state of São Paulo (Figure 1) that have been in operation throughout the years of this analysis and that meet the criterion of membership in the Brazilian Sugarcane Industry Association.

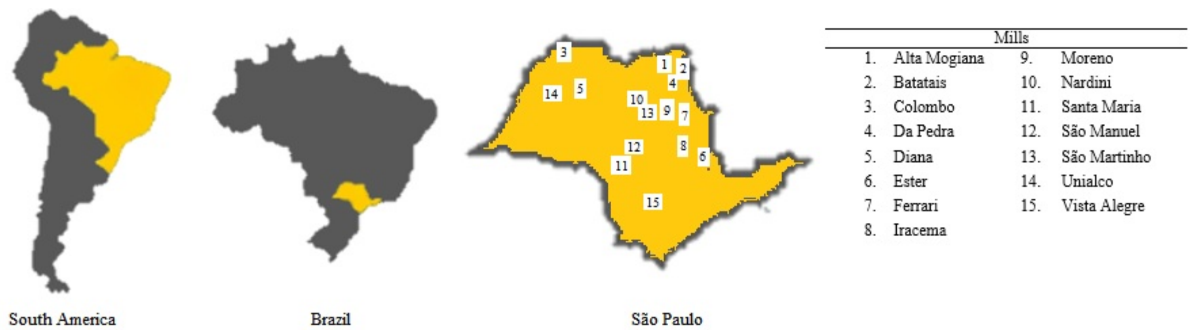

Figure 1. State of São Paulo, Brazil – location

In this work, each sugar and alcohol mill in each year of the investigation was treated as one mill. Thus, in the period of 2007 to 2016, Mill "X", for example, generated 10 virtual mills, same applying to all the others. Thus, the total number of investigated mills corresponds to 150. Table 1 presents the list of mills that were analyzed, as well as their characteristics.

Table 1. Investigated sugarcane mills

Mills	Size/Profile
São Martinho, Alto Mogiana, Colombo	Large/Sugar
Da Pedra	Large/Ethanol
Iracema, Batatais, Nardini, São Manuel, Moreno	Medium/Sugar
Ferrari, Ester, Diana, Santa Maria, Unialco	Small/Sugar
Vista Alegre	Small/Ethanol

Brazilian sugar and ethanol mills are classified as (a) large, (b) medium, or (c) small, according to the size of the operation. Large mills are those that crush more than 4 million tons of sugarcane per year, medium size mills crush between 2.5 and 4 million/year; and small ones crush less than 2.5 million tons a year.

In addition to classification by size, these mills also have strategic profiles according to their core product, which may be sugar or ethanol. Thus, based on the conversion estimate that 1 ton of crushed sugarcane is converted into (i) 118 kg of sugar (Agência Embrapa de Informação Tecnológica, 2006) or (ii) 90 liters of ethanol (Nova Cana, 2012), one can determine the proportion of sugarcane destined for each of the two products.

An analysis of the average percentage of crushed sugarcane destined to each product per mill, within the time interval of this survey, enables one to determine the average profile of the analyzed mill. To this end, a simple majority method is used to determine that, if the average conversion of sugarcane to ethanol is exceeds 50%, this mill has an ethanol profile (and vice versa).

The research was carried out using four efficiency models. The first three models considered the three pillars of sustainability (economic, environmental and social) individually. The fourth model united the three previous models into a single one, that of sustainability.

All the models shared the same input variables, which, to some extent, reflected traditional factors of production. A large part of previous research has mostly used the following variables as inputs: (i) number of employees: administrative, agricultural and industrial; and (ii) planted area (hectares). These data are available in the Sugarcane Yearbooks (Procana, several years).

It is the output variables that that differentiate the models. The literature presents the following output variables as possibilities for the economic model: ethanol production (m^3) and sugar production (tons). These data are available in the Sugarcane Yearbooks (Procana, several years). Thus, the economic efficiency model was elaborated (Equation 1):

$$\text{Ethanol production} + \text{Sugar production} = \text{Employees} + \text{Planted area} \tag{1}$$

For the environmental model, the literature indicates one variable as a possibility: CO_2 emissions. The CANASAT Project (Instituto Nacional de Pesquisas Espaciais, 2018), a remote sensing system, monitors sugarcane cultivation using satellite images to map and quantify the total harvested area, by municipality, breaking it down into unburned harvested area and burned harvested area. After confirming that the entire harvested area in a municipality belongs to the only mill established therein, the volume of CO_2 emitted by each analyzed mill was calculated using the method proposed by Figueiredo and Scala (2011).

Figueiredo and Scala (2011) reported that emissions from pre-harvest burning correspond to 3.104 kg of $CO_{2eq}ha^{-1}y^{-1}$, while emissions caused by harvesting raw sugarcane amount to 1.62 kg of $CO_{2eq}ha^{-1}y^{-1}$, considering the balance of emissions caused by agricultural activities. This finding enabled an estimation of the amount of CO_{2eq} emissions from the sugarcane growing areas of the mills under analysis, both with and without the use of pre-harvest burning, per mill per year. Equation 2 represents this variable:

$$ECO2^i_j = (Aq^i_j \times 3.104) + (Ac^i_j \times 1.620) \tag{2}$$

Where $ECO2^i_j$ is the amount of CO_{2eq} emissions produced by mill j during its sugarcane harvesting process in year i, and Aq^i_j corresponds to the area of sugarcane harvested by mill j, in hectares, after pre-harvest burning, in year i.

It should also be noted that the calculated variable is classified as an undesirable variable, since it is expected that CO_{2eq} emissions are of the type "the lower the better". The method of monotonically decreasing transformation proposed by Seiford and Zhu (2002) was therefore used, whereby undesirable output values are transformed into the inverse of their value. Thus, the variable of CO_{2eq} emissions will be minimized rather than maximized.

Another point worth mentioning is that data from the CANASAT project (Instituto Nacional de Pesquisas Espaciais, 2018) were available for the environmental and sustainable models up to the period of 2013. Therefore, these models were created for the period of 2007 to 2013. Thus, the environmental model was elaborated (Equation 3):

$$CO_2 = \text{Employees} + \text{Planted area} \tag{3}$$

For the social model, based on an adaptation of the work of Zambianco (2018), the proposal was to use the variable of average salary. These data were obtained from the Annual Social Information Report (RAIS) published by the Ministry of Economy (Brasil, 2019).

This variable was the only one measured in monetary units, and considering that all the mills were analyzed jointly in different years, average nominal salaries had to be transformed into average real salaries. The index used here was the National Consumer Price Index – INPC, published by the Brazilian Institute of Geography and Statistics – IBGE. The values used were adjusted to constant prices, using the year 2007 as the base date. Thus, the social model was elaborated (Equation 4):

$$\text{Average salary} = \text{Employees} + \text{Planted area} \tag{4}$$

Finally, the sustainable model uses the same input variables as the previous models and all the output variables: ethanol production, sugar production, CO_2 emissions and average salary. Thus, the sustainable model was elaborated (Equation 5):

$$\text{Ethanol production} + \text{Sugar production} + CO_2 + \text{Average Salary} = \text{Employees} + \text{Planted area} \tag{5}$$

2.2 Data Acceptance

The specialized literature on DEA describes several methods for the validation of variables, and hence, of the proposed efficiency models. In this research, we used Principal Component Analysis applied to DEA (PCA-DEA). The PCA-DEA method proposed by Adler and Golany (2001) seeks to reduce dataset size by combining the original data.

The PCA-DEA technique is widely used in international research, and compared to other methods, it presents robust and accurate results (Adler and Yazhemsky, 2010). Nataraja and Johnson (2011), in their research, examined several methods of selection of variables, and their results are in line with those of Adler and Yazhemsky (2010).

Two points are relevant in defining the permanence or impermanence of variables in proposed PCA-DEA models, namely: the commonalities and eigenvalues.

The commonalities indicate the proportion of the variance explained by the principal components. There are as many commonalities as there are variables in the model, and values may vary from 0 to 1, with 0 indicating when the factors do not explain any variance of the variable and 1 indicating when the factors explain it entirely. Values below 0.5 suggest the exclusion of the variable. Eigenvalues indicate the accumulated percentage of the variance that the factors are able to explain.

2.3 Scale Return

To define the model that best represents the production technology, several choices must be made regarding its orientation and type of return to scale.

For this research, the input-oriented model was not considered adequate, as we did not intend to reduce the resources of the analyzed mills (employees and area). The goal was to increase the outputs, based on the observed levels of inputs. Therefore, the output-oriented DEA model was chosen.

In relation to the selected model, CRS or VRS, it is important to calculate the efficiency scores considering both models. In this context, Banker et al. (1996) suggest that the Kolmogorov-Smirnov (KS) test be applied in order to choose between one of the two models, since model selection is important and, if done incorrectly, can generate inconsistent results. The statistics for this test are given by (Equation 6):

$$TSM = \max\{F(\theta DEA\ CRS), F(\theta DEA\ VRS)\} \tag{6}$$

Where F ($\theta_{DEA\ CRS}$) and F ($\theta_{DEA\ VRS}$) are the cumulative inefficiency distributions of the DEA-CRS and DEA-VRS models. In the test procedure, the TSM statistic is compared with the critical value of D obtained. If $T_{SM} < D$ critical, H_0 is accepted; if TSM > D Critical, H_0 is rejected and H_1 is accepted. Here, H_0 determines the acceptance of the CRS model and H_1 indicates the acceptance of the VRS model.

The KS test was performed and the VRS model was selected. In the next sections, this procedure is presented. The proposed model, output-oriented VRS is presented in detail in the Appendix.

3. Results and Discussion

This section describes the results obtained from the validation of the proposed models, returns to scale, and from the DEA.

3.1 Acceptance of the Models

With regard to the commonalities of the economic, social and sustainable models, as indicated in Table 2, all the variables can be maintained, since values below 0.5 suggest that common factors explain the variance of the variable. The results obtained in the environmental model appear to be acceptable, considering that the number of employees explains little about the variance of the other components.

Table 2. Commonalities

	Initial	Sustainable	Economic	Social	Environmental
Planted area	1.0	0.9	0.8	0.8	0.9
Employees	1.0	0.6	0.6	0.7	0.2
Sugar production	1.0	0.9	0.6	-	-
Ethanol production	1.0	0.6	0.7	-	-
CO_2	1.0	0.7	-	-	0.9
Salary	1.0	0.5	-	0.8	-

Table 3 presents the eigenvalues, the percentage of variance that the factors are able to explain, and the cumulative percentage of this variance. Overall, the economic model has two components greater than 1, explaining 63.9% of the total variability. On the other hand, the social model, with two retained components, can explain 75.7% of the total variability; while the sustainable model, also with two retained values, explains 59.6% of the total variability; and the environmental model explains 97.3% of the total variability. All the models initially proposed were validated based on these results.

Table 3. Total variance explained (eigenvalues)

Models	Economic			Social		
Comp.	Initial eigenvalues			Initial eigenvalues		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	1.4	36.1	36.1	1.2	39.2	39.2
2	1.1	27.8	63.9	1.1	36.5	75.7
3	0.8	19.6	83.5	0.7	24.3	100.0
4	0.7	16.5	100.0			
Models	**Sustainable**			**Environmental**		
Comp.	**Initial eigenvalues**			**Initial eigenvalues**		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	2.06	34.3	34.3	2.0	64.7	64.7
2	1.52	25.3	59.6	1.1	32.6	97.3
3	0.99	16.5	76.1	0.0	2.7	100.0
4	0.73	12.3	88.4			
5	0.65	10.9	99.3			
6	0.04	0.7	100.0			

3.2 Returns to scale

All the models were subjected to scale testing. The critical value for the economic and social models is the same, taking into account that the number of observations includes the entire temporal delimitation of the research. For the environmental and sustainable models, the number of observations is smaller, since data on CO_2 emissions is available only up to 2013.

For the economic model, the hypothesis of variable returns to scale (VRS) was accepted based on the aggregate data (2007-2016) and the statistical value (0.17) compared to the critical value (n=150, α=5%; D critical = 0.11). For the social model, the hypothesis of VRS was also accepted based on the same critical values and a statistical value of 0.18.

The social and sustainable models have a set of 105 observations. For the social model, the hypothesis of VRS was accepted based on the data from 2007 to 2013 and the statistical value (0.22) compared to the critical value (n=105, α=5%; D critical = 0.13). Lastly, the sustainable model, also with a set of 105 observations, has a statistic of 0.19 and when compared to the critical value (n=105, α=5%; D critical = 0.13), it also supports the hypothesis of variable returns to scale.

3.3 Data Envelopment Analysis

This section presents and discusses the results of the application of DEA to data from 15 sugar and ethanol mills. The analyses are based on maximizing the input/output ratio, where output varies according to the perspective analyzed, while input remains unchanged, as mentioned earlier herein.

3.3.1 Economic approach

The analysis of the economic approach is based on maximizing the ratio of outputs – sugar production (tons) and ethanol (cubic meters) to inputs – planted area, in hectares, and number of employees, for the crop year in question. Table 4 presents the results of the economic model, with the mills aggregated by size and profile, and some cases being analyzed individually.

Table 4. Economic efficiency of the mills

Size	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**Average**
Large	83.9%	81.4%	86.7%	82.1%	87.9%	80.1%	81.5%	83.5%	87.7%	86.2%	84.1%
Medium	51.2%	50.9%	62.0%	68.0%	61.3%	50.7%	60.8%	57.8%	65.7%	68.2%	59.7%
Small	24.8%	35.5%	36.6%	30.4%	36.2%	32.2%	42.2%	46.8%	39.2%	46.3%	37.0%
Profile	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**Average**
Ethanol	50.4%	58.3%	61.2%	49.3%	57.6%	49.9%	53.7%	54.9%	61.5%	57.0%	55.4%
Sugar	49.2%	52.0%	58.0%	57.9%	58.5%	51.3%	59.7%	61.1%	60.9%	65.3%	57.4%

Statical measures – by mills				
Maximum	Minimum	Average	Median	Standard deviation
100.0%	3.9%	57.1%	56.8%	26.3%

The mills showed an overall average efficiency of 57.1%, with a standard deviation of 26.3%. In addition, the analysis by size revealed a trend towards greater efficiency and homogeneity as a function of size, demonstrating that the economic performance of the analyzed mills is marked by economies of scale. However, the profile analysis did not indicate any trend, since the two possible core products showed a similar efficiency. The benchmark mill in this analysis was the large São Martinho S.A. mill, with its sugar profile, which showed an average efficiency of 96.3% (for the years analyzed), confirming the trend towards economies of scale discussed earlier in the economic analysis of the mills.

Table 5 presents the average values, ffr the period 2007 to 2016, of sugar (in tons) and ethanol (in cubic meters) produced per area (in hectares) and the efficiency for the different sizes and profiles of mills.

Table 5. Input/output ratio and efficiency indicators of the mills

Size	Sugar/area	Ethanol/area	Economic efficiency
Large	32.3	17.5	84.1%
Medium	18.4	10.5	59.7%
-Small	13.6	8.4	37.0%
Profile	**Sugar/area**	**Ethanol/area**	**Economic efficiency**
Sugar	20.5	10.9	57.4%
Ethanol	18.1	15.7	55.4%

The input variable of "planted area" was selected for the analysis, since it has the highest commonality in the economic model (see Table 2).

As can be seen, there is an association between productivity indicators and economic efficiency, when mills are analyzed by size. Large mills, which have the best performance in the production of sugar and ethanol by area, are also the most efficient. On the other hand, small mills, which have the worst performance in terms of production per area (sugar and ethanol), are also the least efficient.

At this point, it should be kept in mind that the economic model used here, which considers the inputs of "planted area" and "employees", can explain 63.9% of the variability in sugar and ethanol production of mills (see Table 3). It should be noted that the data in Table 5 do not include the indicators of "sugar/employee" and "ethanol/employee", or other variables that could also contribute to the efficiency of the mills.

3.3.2 Social Approach

In the social model, the basis of the investigation of maximizing the input/output ratio was maintained, while changing only the reference value of the output for the average salary of the sugarcane field worker. Therefore, we sought to optimize the ratio of average salary to planted hectare.

Table 6 presents the results of the social model, with the mills aggregated by size and profile, and some cases being analyzed individually. The average overall efficiency of the mills was 61.5%, with a standard deviation of 20.2%.

Table 6. Social efficiency of the mills

Size	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Average
Large	49.9%	52.1%	57.2%	59.0	58.4%	72.4%	77.6%	79.0%	71.1%	74.9%	65.2%
Medium	39.0%	39.7%	50.8%	52.0%	53.0%	53.3%	63.0%	56.6%	61.0%	63.0%	53.1%
Small	48.2%	54.5%	55.9%	57.7%	66.8%	76.3%	73.9%	75.5%	75.1%	76.9%	66.1%
Profile	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**Average**
Ethanol	58.2%	62.9%	71.5%	77.1%	75.7%	86.3%	89.3%	90.6%	92.7%	95.5%	78.0%
Sugar	43.7%	46.8%	52.0%	52.9%	57.5%	64.7%	68.5%	67.0%	65.7%	68.1%	58.7%

Statical measures – by mills				
Maximum	Minimum	Average	Median	Standard deviation
100.0%	20.3%	61.5%	61.2%	20.2%

Breaking it down by size, one can see that small and large mills had the higher average results, with 66.1% and 65.2%, respectively, while medium size mills had an average social efficiency of 53.1%. However, when the analysis is based on profile, it is clear that the social performance of mills with an ethanol profile was better, as well as more homogeneous among all the mills.

Even so, the small Santa Maria Mill, with its sugar profile, ranked as one of the reference mills in this analysis. With an average efficiency of 89.6% and a standard deviation of 7.9%, the mill paid, on average for the entire period, R$0.36/planted hectare, demonstrating that even small mills can be socially efficient.

In conclusion, Table 7 presents the average values of salary per area and efficiency for the different sizes and profiles of mills, between 2007 and 2016. This table explains the relationship between the average remuneration paid per worker for each hectare planted and the mill's social efficiency indicator.

As in the economic model, the input variable of "planted area" was selected for the analysis, which is presented next for corresponding to the highest commonality in the social model, as shown in Table 2.

Table 7. Input/output ratio of the mills and efficiency indicators

Size	**Salary/area**	**Social efficiency**
Large	0.09	65.2%
Medium	0.06	53.1%
Small	0.13	66.1%
Profile	**Salary/area**	**Social efficiency**
Sugar	0.09	58.7%
Ethanol	0.13	80.0%

The data in Table 7 demonstrate that small-scale mills with an ethanol profile, in addition to providing better remuneration per planted area, are also more efficient in the social approach. It is also important to point out that the values presented are the results of averages, which means that there may be some mills with a good salary/area ratio and that are of other sizes or profile.

The Santa Maria (sugar profile) and Da Pedra (ethanol profile), small and large mill, respectively, are the ones with the best performance in terms of remuneration per hectare (R$0.36 and R$0.17, respectively) and are in the group of the most efficient mills. The two mills with the lowest performance in terms of salary/area, both with a sugar profile (Batatais and São Manuel mills, with average remuneration of R$0.01 and R$0.02 per hectare, respectively), are the least efficient (33.7% and 39%, respectively), both being medium-sized.

The social model used here, considering the inputs of "planted area" and "employees," can explain 75.7% of the variability of the salaries of the mills, as indicated in Table 3.

3.3.3 Environmental Approach

This analysis seeks to identify the mills with the best environmental performance in terms of carbon dioxide emissions, aggregated by size and profile.

According to this approach, the lower the amount of CO_2 emitted per planted area, in hectares, the higher the environmental efficiency of the analyzed mill. In fact, it should be noted that, after a mathematical manipulation of the data, the higher the amount of CO_2/area the lower is its emission per planted area (in hectares), resulting in greater environmental efficiency. Table 8 describes the overall result of the model.

The average environmental efficiency was 54.8%, with a standard deviation of 30%. In the size analysis, small mills showed higher efficiency indices than large and medium ones, but the standard deviations were highly heterogeneous, preventing the identification of a size-related trend. However, the profile analysis revealed a trend for ethanol mills to show higher average efficiency, with lower standard deviations – demonstrating homogeneity and efficiency.

Table 8. Environmental efficiency of the mills

Size	2007	2008	2009	2010	2011	2012	2013	Average
Large	53.5%	55.5%	56.6%	60.8%	56.2%	60.1%	62.5%	57.9%
Medium	43.4%	42.3%	45.2%	48.8%	44.6%	41.8%	50.3%	45.2%
Small	60.6%	61.9%	62.2%	62.3%	56.9%	58.1%	62.7%	60.7%
Profile	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**Average**
Ethanol	65.7%	61.0%	63.0%	66.0%	61.7%	62.3%	69.0%	64.1%
Sugar	51.0%	52.5%	53.8%	56.1%	51.2%	51.8%	56.9%	53.3%

Statical measures – by mills				
Maximum	Minimum	Average	Median	Standard deviation
100.0%	3.4%	54.8%	57.7%	30.0%

In general, the most efficient mills were those that emitted less CO_2/area, although another variable (employees) was also used to calculate environmental efficiency. In all the years investigated, the ethanol profile mills were more efficient and emitted less CO_2 than many sugar profile mills. In the case of analysis by size, the grouping of small mills had the highest average efficiency in almost all the years analyzed and, on average, lower CO_2 emissions.

Once again, the Santa Maria mill of the J. Pilon group stood out. This mill showed an average environmental efficiency of 96.3% and was the one with the lowest CO_2 emissions in 2013. Its average recorded emissions were $3.8E^{-8}$ in the years under analysis – compared to an average of $8.2E^{-9}$ by all the mills and of $1.2E^{-8}$ by the small mills. This is further evidence that small mills can achieve high levels of environmental efficiency, as well as social efficiency, without the need for economies of scale or operational magnitude.

Large mills, once again, failed to use the largest production scale to obtain environmental gains and are in the worst group of CO_2 emissions. The São Martinho mill, of large size and sugar profile, obtained 71.8% efficiency and was the seventh largest emitter of CO_2 in the investigated sample. The Batatais mill, of medium size and sugar profile, was the largest emitter of CO_2 in the sample and the one with the lowest environmental efficiency index among the plants investigated.

Table 9 shows the relationship between CO_2 emissions and the environmental efficiency indicator. The higher the value of the CO_2/area indicator the lower the amount of CO_2 emitted per mill per planted hectare, according to Seiford and Zhu (2002) monotonic decreasing transformation used in the treatment of emissions data. Hence, the mill's environmental efficiency should also be greater, since it means that it emits less CO_2 per area planted with sugarcane, thus maximizing its environmental efficiency per hectare.

Table 9. Input/output ratio of the mills and efficiency indicators

Size	CO_2/area	Environmental efficiency
Large	$4.88E^{-9}$	57.9%
Medium	$6.55E^{-9}$	45.2%
Small	$1.19E^{-8}$	60.7%
Profile	**CO_2/area**	**Environmental efficiency**
Sugar	$8.46E^{-9}$	53.3%
Ethanol	$6.70E^{-9}$	64.1%

As with previous models, the input variable of "planted area" was selected for the analysis discussed below, due to its highest commonality in the environmental model (described in Table 2).

The four mills with the best performance in terms of CO_2 emissions per hectare belong to the group of the most efficient mills, three of which are small mills (Santa Maria, Ferrari and Ester) and one medium size (Nardini). The five mill with the worst performance in the CO_2/area ratio are located in the group with the lowest efficiency, one of which is large (Alto Mogiana), three are medium-sized (Moreno, São Manuel and Batatais) and one is small (Unialco).

The environmental model used here, from the standpoint of the inputs "planted area" and "employees," can explain 97.3% of the variability in CO_2 emissions by the mills, as indicated in Table 3.

3.3.4 Sustainable Approach

In this analysis, the aim is to apply all the outputs listed previously, while maintaining the inputs specified earlier. The main objective is to delimit sustainable mills jointly from the economic, social and environmental perspectives. This analysis involved data only from 2007 to 2013, because data on CO_2 emissions from the mills and municipalities in question in later periods were unavailable. Table 10 presents the results of the sustainable model, with the mills aggregated by size and profile, and some cases being analyzed individually.

The average overall efficiency of the mills was 60.7%, with a standard deviation of 20%. The analysis based on size indicated that large mills exhibited a more sustainable performance, while that of the medium and small mills was homogeneous. The analysis by profile, in turn, revealed that the performance of mills with an ethanol profile tended to be more sustainable than that of mills with a sugar profile, albeit less homogeneous.

It is important to emphasize the performance of the Da Pedra and Santa Maria mills from the standpoint of sustainability. The average sustainable efficiency of Da Pedra – a large mill with an ethanol profile – was 94.9%, with a maximum efficiency of 100% in 2013; this mill was the most sustainable one in the sample. One of the reasons for this is that this mill is active in the Greener Ethanol Protocol and is certified by Bonsucro EU, which ensures internationally required sustainability standards, and that it also joined the RenovaBio Program.

Table 10. Sustainable efficiency of the mills

Size	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**Average**
Large	65.1%	66.8%	75.5%	72.6%	74.7%	77.2%	82.1%	73.4%
Medium	44.5%	48.0%	56.9%	66.6%	61.6%	56.3%	64.6%	56.9%
Small	45.5%	48.1%	53.3%	51.5%	59.3%	66.0%	63.8%	55.3%
Profile	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**Average**
Sugar	48.8%	51.8%	59.7%	61.2%	62.8%	64.2%	66.8%	59.3%
Ethanol	60.9%	61.0%	65.3%	68.7%	73.0%	76.1%	83.0%	69.7%

Statical measures – by mills				
Maximum	Minimum	Average	Median	Standard deviation
100.0%	27.7%	60.7%	62.8%	20.0%

Equally important, the Santa Maria mill also proved to be highly sustainable, with an efficiency of 96.5% in 2013, in which year it was the most efficient mill, both socially and environmentally. Once again, this proves that economies of scale and operational magnitude are not required for a mill to be efficient, according to the approaches proposed in this work. Thus, it was found that the mills that ranked best in the economic, social and environmental approaches, by causality, achieved the highest rates of sustainable efficiency among all the mills analyzed in this study.

Lastly, Table 11 summarizes the results of the indicators used in the analysis of sustainability, and their respective sustainable efficiency indicators, with the mills aggregated by size and profile.

Table 11. Input/output ratio and efficiency indicators of the mills

Size	Sugar/area	Ethanol/area	Salary/area	CO_2/area	Efficiency
Large	32.3	17.5	0.09	4.88E^{-09}	73.4%
Medium	18.4	10.5	0.06	6.55E^{-09}	56.9%
Small	13.6	8.4	0.13	1.19E^{-08}	55.4%
Profile	**Sugar/area**	**Ethanol/area**	**Salary/area**	**CO_2/area**	**Efficiency**
Sugar	20.5	10.9	0.09	8.46E^{-09}	59.3%
Ethanol	18.1	15.7	0.13	6.70E^{-09}	69.7%

The purpose of the sustainable model is to explain the logic that a mill will be sustainable if it has good economic, social and environmental performance. The Da Pedra mill, of large size and ethanol profile, showed good productivity indicators (sugar/area: 31.8; ethanol/area: 26.5), CO_2 emissions (9.0E^{-9}) and remuneration per area (R\$ 0.17 per m^2) and, consequently, obtained the best efficiency score in the sample (94.9%). The medium-sized Nardini mill with a sugar profile had the best productivity indicators (sugar/area: 49.3; ethanol/area: 26.6), an indicator of remuneration per area above the sample average (R\$ 0 .13 per m^2) and the second best indicator of CO_2 emission (2.3E^{-8}) in the sample and obtained 73.6% of average efficiency.

Three other mills, São Manuel, Batatais and Unialco (the first two being medium-sized and the third small), all with a sugar profile, showed poor indicators for: sugar productivity (5.9; 5.8; 4,1, respectively), ethanol productivity (3.8; 3.0; 1.8, respectively), CO_2 (3.8E^{-10}; 2.3E^{-10}; 3.2E^{-10}, respectively) and salary per area (R\$ 0.02 per m^2; R\$ 0.01 per m^2; R\$ 0.02 per m^2, respectively) and, consequently, obtained low efficiency rates (38.2%; 36%; 37.4%, respectively).

To achieve sustainable efficiency requires a mill to present good economic, social and environmental indicators. This requirement makes the task of obtaining a good efficiency indicator more complex.

Based on the inputs of "planted area" and "employees," the sustainable model can explain 59.6% of the variability in ethanol and sugar production, CO_2 emissions and salaries of the mills (see Table 3).

4. Conclusions

The growing concern for the three pillars of sustainability has transformed the capitalist system in order to emphasize the importance of competitiveness, efficiency and sustainability for its survival and ascendancy. In this regard, there has been a significant increase in the number of research works and analyses of the application of the pillars of sustainability to the production chain and decision-making process, based on measures of productive performance.

Therefore, this study focused on an analysis of the efficiency of fifteen sugar and ethanol mills in the state of São Paulo, from economic, social, environmental and sustainable standpoints.

The results obtained by classifying the mills according to size and profile are consistent with the reality of the sugar and alcohol sector in the state of São Paulo, Brazil. The large mills showed greater efficiency and homogeneity from the economic and sustainable standpoints, indicating the presence of economies of scale and best sustainable practices according to size. Small mills showed superior social and environmental performance, with intermediate standard deviations. However, the medium-size mills failed to exhibit efficiency in the analyses, and showed irregular standard deviations in all the models.

The analysis by profile indicated that the mills with an ethanol profile showed better social, environmental and sustainable performance. The social and environmental approaches of these mills were more homogeneous, indicating a trend towards better performance in terms of the efficiency and consistency of these approaches. The mills with a sugar profile, however, were more efficient from the economic standpoint, as well as more homogeneous, suggesting greater efficiency and uniformity of their core product.

The result of the sustainable model should be discussed in detail. The observed trend was that the mills with the best economic, social and environmental indicators not only proved to be more homogeneous in the period under study but were also those that exhibited the highest sustainable efficiency scores. This trend is confirmed by the aforementioned cases of Da Pedra and Santa Maria mills, both with excellent results in the approaches analyzed herein.

In this context, this work is innovative in that it creates a sustainable model applicable to the sugarcane agribusiness, something that has not been carried out in any other national or international survey for a significant period: 2007 to 2016. Therefore, we sought to fill this gap in the literature, emphasizing a significant number of mills and periods, in addition to considering approaches relevant to the current stage of capitalism.

Acknowledgements

We thank the São Paulo Research Foundation (FAPESP) for funding this research (process number 2018/16399-3), and the Federal University of São Carlos (UFSCar) and the Graduate Program in Economics, at São Paulo State University (UNESP), for financial support for the publication of this manuscript. We also thank to the anonymous reviewers of the manuscript.

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Appendix

VRS model description:

$$Maximize\ \sum_{i=1}^{n} v_i x_{ki} + v_k$$

Subject to:

$$\sum_{r=1}^{m} u_r y_{rk} = 1$$

$$\sum_{r=1}^{m} u_r y_{jr} - \sum_{i=1}^{n} v_i x_{jr} - v_k \geq 0$$

$$u_r, v_i \geq 0$$

Considering: y = *outputs*; x = *inputs* / u, v = weights / r = 1,..., m.; i = 1,..., n; j=1,...,n.