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Article

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The CO₂ emission Gini index and the environmental efficiency: An analysis for 60 leading world economies

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Abstract

The aim of this study was to analyze the CO₂ emission Gini index and the environmental efficiency for 60 leading world economies, in 2010. We consider the technological heterogeneity dividing the sample into similar groups, and estimating environmental efficiency indicators into metafrontier and group frontiers. Despite the fact that pollution concentration is more prominent in developed countries, the results showed that this group is more efficient. On the other hand, lower-income group, and medium-technology countries present the worst indicators. We could conclude that the inefficiency observed in developed countries group was attributed to mismanagement, while in the developing countries group the inefficiency could be related to technological differences.

JEL classification: C61; O57; Q54

Keywords: Environmental efficiency; Metafrontier; Pollutants; Gini index

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1. Introduction

The ever-growing attention to the environment is not only related to social concern regarding the exhaustion of natural resources, but also to the capacity of the planet to absorb the pollutants generated by human being. According to studies conducted by the [World Bank \(2015\)](#), between 1960 and 1990, environmental indicators deteriorated greatly due temperature increase via the Greenhouse effect (GHG). The carbon dioxide (CO₂) emission through fossil fuel has been responsible for approximately 56.6%.

The United States of America (USA) are at the top when it comes to the pollution ranking, being responsible for about 30% of the world emission between 1970 and 2010. Then, with 13%, comes China, followed by Japan (5.97%) and the United Kingdom (3.69%). It is possible to see that around 70% of CO₂ emission is derived from ten countries (also including India, Russia, France, Canada, Italy and Poland). Another important factor is that, out of the ten greatest emitters, seven are also on the list of countries with the largest GDP – the USA, Japan, France, the United Kingdom,

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Italy, China, and Canada – indicating a dependence relation between production and pollution emission (World Bank, 2015).

To create effective environmental policies regarding this issue, several researches have been made in order to analyze the relationship between productive process and CO₂ emission (Grossman and Krueger, 1991; Panayotou, 1993; Selden and Song, 1994; Iwata and Okada, 2014). The main pieces of evidence suggested that there is a relation following an inverted U format, a behavior that is similar to Kuznets's (1955) assumption, regarding the economic growth effect on income inequality. The Environmental Kuznets Curve (EKC), as it was known after Grossman and Krueger (1991), suggests that the environmental degradation rate could increase during early development, due to the income expansion necessity at this moment. Nevertheless, it grows progressively less until maximum peak, where it reverses the behavior. This path was attributed to consumer satiation, the socioeconomic indicators evolution, the increasing environmental restrictions, and the social environmental consciousness.

Despite the fact that EKC has been widely used, we can see that its functional form takes undesirable output (pollution) as a function of the desirable output (production). Nevertheless, Färe et al. (1996) demonstrate that productive process could generate two outputs: the desirable and the undesirable output. Furthermore, as remarked by Zhou et al. (2010), EKC function could not distinguish good production practices from other intensive pollution methods. This analysis could be useful because it provides information about resource allocation, including the natural ones.

Several studies have been conducted in order to relate desirable and undesirable outputs as products through frontier models (Zhang and Choi, 2013). According to Chiu et al. (2012), these models could generate environmental efficiency indicators, which show the best relationship between production and pollutant emission. This indicator could determine how close a unit, as a country, is from efficiency frontier, as well as how much pollutant's reduction is necessary for it to be efficient. Therefore, we could analyze the trade-off between production and environmental conservation by using the production theory (Kuosmanen and Kortelainen, 2005).

Conceptually, we should consider only homogeneous units to apply the production theory on environmental efficiency analysis. However, this restriction cannot always be obeyed, because it could exist heterogeneity among countries caused by socioeconomic variables and technological differences. We could not presume that lower-income countries are over the same technological frontier as development countries (Chiu et al., 2012). For this reason, O'donnell et al. (2008) suggested dividing the sample into k subgroups, following technological criteria previously established, and to attribute a part of the environmental inefficiency to technological gap between frontiers and another part to mismanagement. This methodology was named metafrontier analysis. Nevertheless, there is not a compelling criterion in the literature about how to group countries according to technological level. In addition, we could apply some technological proxies to construct groups, as high technological products exportation, and research and development expenditures. These variables could be crucial to formulate groups in the same technological levels. However, these criteria were not applied yet.

Therefore, this study aims to analyze the environmental efficiency of the largest world economies, controlling the heterogeneity amongst countries, estimating production frontier with desirable and undesirable products. This approach allows the identification of countries that are on metafrontier and on group frontiers. Cluster analysis was used to group the countries into similar frontiers. In addition, the CO₂ emission Gini index was calculated in order to give empirical support to the environmental efficiency indicators, showing the pollutant concentration degree.

This paper is organized as follows: In Section 2 it is introduced the environmental efficiency theoretical model used in this paper. The analytic framework is presented in Section 3, showing the metafrontier and group frontiers models. The analysis results are shown in Section 4. Finally, in Section 5 this paper's conclusion is summarized.

2. The production technology for desirable and undesirable products

The production of goods that improve social welfare could be associated with other products that society does not wish for, such as pollution. Because these goods are produced jointly in the production process, the country faces the trade-off between productive expansion and environmental conservation (Coase, 1960; Zhang and Choi, 2013). Formally, a desirable output could be denoted as $y \in \mathfrak{R}_+^M$; an undesirable output, as $b \in \mathfrak{R}_+^I$; and the inputs, as $x \in \mathfrak{R}_+^N$. The desirable and undesirable sets are compact and closed, *i.e.*, finite amounts of input produce finite

amounts of goods (Färe et al., 2005). That said, the general production technology is described according to the following expression (1a).

$$P(x) = \{(x,y,b) : x \text{ can produce } (y,b)\} . \quad (1a)$$

The input vector produces desirable (y) and undesirable (b) outputs. The $P(x)$ set can be extended to hold a larger amount of outputs as follows:

$$y = (y_1, \dots, y_M) \in \mathfrak{R}_+^M \quad \text{and} \quad b = (b_1, \dots, b_J) \in \mathfrak{R}_+^J . \quad (1b)$$

According to Färe et al. (2005), the technology proposed by Eq. (1a) is consistent with the traditional neoclassical model, except undesirable output specification. To include the externality in the traditional model, some assumptions must be considered. First, the authors suggest including pollutant emissions as output into production function because productive process can generate desirable and undesirable outputs together. This condition is named as “null jointness” and we can express it as follows:

$$\text{If } (y, b) \in P(x) \text{ and } b = 0, \text{ then } y = 0. \quad (2)$$

Therefore, undesirable goods set will only be null if, and only if, the desirable goods set is null. This implies that if any desirable good is produced, an undesirable good should also be produced. We can say that the desirable good production can generate a negative externality, which involves social inefficiency (Pigou, 1920). However, measures to reduce or eliminate the externality could be more harmful than the externality itself, since the restriction of an undesirable good, such as pollutant emission, usually implies a reduction of a desirable good, such as economic growth (Coase, 1960). The referred condition means it could be possible to reduce pollutant emission, if the society is willing to give up a piece of the production. According to Färe et al. (2005), it implies that desirable and undesirable goods are “weakly disposable”. Formally:

$$\text{if } (y,b) \in P(x) \text{ and } 0 \leq \theta \leq 1, \text{ then } (\theta y, \theta b) \in P(x), \quad (3)$$

where θ is a proportionality parameter. Färe et al. (2005) defend that reductions in undesirable goods are always possible if desirable products are reduced as well. According to Chung et al. (1997), the condition (3) implies that $b \neq 0$ is inevitable, since the only way to mitigate externalities is leaving the desirable output production. On the other hand, it can be assumed that the goods are “strongly disposable”, *i.e.*:

$$\text{if } (y,b) \in P(x) \text{ and } (y', b) \leq (y,b), \text{ then } (y',b) \in P(x). \quad (4)$$

Therefore, if desirable and undesirable goods sets are feasible, then any vector with an inferior amount of goods shall also be feasible (Färe et al., 2005). It is important to note that a production technology satisfies the condition expressed in Eq. (4), it also satisfies the condition in Eq. (3). However, the reverse is not always verified.¹ It is crucial to report that if a good is not desirable, such as the pollutant emission, the strong monotonicity axiom, that is, “if $x \geq y$ and $x \neq y$ then $x > y$ ”, according to Varian (1992), it is not satisfied, since the agent affected by externality needs smaller amounts of the good given.²

Accordingly, the directional distance function could be used to accommodate the microeconomic assumptions of technologies with desirable and undesirable goods (Chung et al., 1997; Färe et al., 2005; Zhang and Choi, 2013). To demonstrate it, $g = (g_y, -g_b)$ will be a direction vector, and $g \in \mathfrak{R}^M \times \mathfrak{R}^J$. Then, the direction distance function can be defined as:

$$\bar{D}_0(x, y, b; g_y, -g_b) = \max \{ \beta : (y + \beta g_y, b - \beta g_b) \in P(x) \} . \quad (5)$$

The function (5) seeks to increase the desirable goods and to reduce the undesirable ones at the same time. The direction vector is $g = (g_y, -g_b)$. The directional vector is to be added to the observed vector (y, b) , and the observation must be dimensioned through g until $(y, b) + \beta g$ is limited by $P(x)$. This function offers translation property, according to the expression (6):

$$\bar{D}_0(x, y + \alpha g_y, b - \alpha g_b; g_y, -g_b) = \bar{D}_0(x, y, b; g_y, -g_b) - \alpha, \alpha \in \mathfrak{R}. \quad (6)$$

¹ See Färe et al. (2005).

² Varian (1992) suggests to redefine it as an “absence of emissions”, therefore satisfying the axiom.

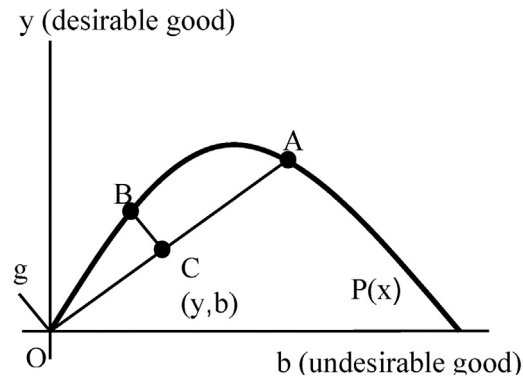


Fig. 1. Distance functions.

Source: Chung et al. (1997)

According to Färe et al. (2005), the property described above is analogical to the homogeneity of Shephard’s (1970) distance function, in which:

$$\bar{D}_0(x, y, b) = \min \{ \theta : (y/\theta, b/\theta) \in P(x) \}. \tag{7}$$

If the direction vector is chosen, i.e., $g_y = y$ e $g_b = b$, then,

$$\bar{D}_0(x, y, b; g_y, -g_b) = \frac{1}{D_0(x, y, b)} - 1. \tag{8}$$

The direction distance function is also a performance measurement. Overall, if:

$$\bar{D}_0(x, y, b; g_y, -g_b) = 0, \tag{9}$$

then the agent is efficient regarding to direction $(g_y, -g_b)$. If $\bar{D}_0(x, y, b; g_y, -g_b) > 0$ there will be a gap between the production of the agent and the frontier, making it inefficient.

3. Analytical framework

3.1. The environmental Gini index

Inequality measures have been used into economy since seminal study conducted by Gini (1912), which proposed an income inequality index. This indicator uses an equity distribution with an extension ranging from [0,1]. The closer to 1, the higher the level of inequality, and the closer to 0, the higher the level of equity. This study presents an alternative application of Gini index to measure the CO₂ emission concentration. We calculate it through expression (10):

$$G = |1 - \sum_{k=1}^{n-1} (GDP_{k+1} - GDP_k)(CO2_{k+1} + CO2_k)|, \tag{10}$$

where G is the Gini coefficient; GDP is the cumulative proportion of the “income” variable; CO₂ is the accumulated proportion of the “pollution” variable, ranging from class k=1 to the class k=n-1, assuming direct relationship between income and pollution emission. Accordingly, a high degree of equality is expected, since literature has shown that countries with higher-than-average product tend to emit more pollutants.

3.2. The environmental efficiency measure

According to Chiu et al. (2012), environmental efficiency measures are based on the efficiency indicators constructed by distance functions. We can define environmental efficiency as the best possible result when desirable and undesirable outputs are considered (Chiu et al., 2012; Kuosmanen and Kortelainen, 2005). Chung et al. (1997) were the first to

incorporate the effects of undesirable goods into distance functions to estimate the environmental efficiency. Fig. 1 illustrates the distance functions with desirable and undesirable goods.

The desirable good is represented by y ; b is the undesirable good; and $P(x)$ is the production possibility set. All points on this frontier are efficient. Then, if we project the decision-making unit (DMU) “C” at point “A” by factor AO/OC , we could consider it efficient. However, if pollution was regulated, the society would not wish to make it efficient at point “A”, since the amount of emitted pollutant would also increase. It is possible to achieve the efficient level in which the amount of undesirable output is lower, as the point “B”. We could define the environmental efficiency by estimating the frontier from the best environmental practices. Moreover, a greatest vantage is that we do not need information about inputs and output prices, and of a specific functional form for the production function.

3.3. The environmental technical efficiency and production frontiers

The method used in this study to estimate the environmental technical efficiency is based on Data Envelopment Analysis (DEA). This technique is a non-parametric tool that estimates the technical efficiency of homogeneous DMUs through mathematical programming. The technique considers an input (x) vector, desirable goods (y) and undesirable goods (b) sets. A country could be considered environmentally efficient if it maximizes y , emitting the least possible of b . Additionally, for environmentally inefficient countries, this method allows tracing paths converging to the frontier.

Charnes et al. (1978) showed that DEA models assume constant returns to scale (CRS model), that is, an increase in input produces a proportional increase in undesirable and desirable goods. Nevertheless, literature has shown the need for flexibility, given the existence of changes in the pollutant emission pattern that relate to economic development stages (Grossman and Krueger, 1991). This change can be introduced by variable returns to scale models (VRS model — Banker et al., 1984). Fig. 2 illustrates the behavior of CRS and VRS models.

In the CRS model, input variations can produce variations of the same magnitude on the $P(x)$ set. As for VRS, it is possible to see that this situation only occurs at point B, where the CRS line intersects the VRS line. The country in that point can be considered purely efficient in an environmental sense, since it is over the frontiers on both models (pure technical efficiency). However, the models differ at other points, since CRS considers the countries that are in points A and C inefficient. At point A, although the country is technically efficient in the VRS model, its scale is growing, making it possible to expand its current production level. As for point C, even if it is efficient in the VRS model, the country is producing less, which suggests that a reduction of its production is necessary. Therefore, the inefficiency of countries on A and C is not technical, but rather an inefficiency of scale, as they can become purely efficient by adopting measures to project to point B. For that reason, the VRS model allows the separation of technical efficiency and scale efficiency, completing the possible analyses of the CRS model.

In the presence of undesirable goods, the DEA-VRS model that maximizes y and minimizes b , keeping constant the x set, can be represented by the expression (11):

$$\begin{aligned}
 & \text{MAX}_{\phi, \lambda} \phi \\
 & \text{s.a.} \\
 & -\phi y_0 + \sum y_i \lambda_i \geq 0 \\
 & -\phi/b_0 + \sum (1/b_i) \lambda_i \geq 0 \\
 & x_{0p} - \sum x_{ip} \lambda_{ip} \geq 0 \\
 & \sum_{i=1}^n \lambda_i = 1 \\
 & \lambda_i \geq 0, \forall i,
 \end{aligned} \tag{11}$$

where y_0 is the desirable “Gross Domestic Product (GDP)” for country “0”; b_0 is the undesirable “CO₂ emission” product for country “0”; x_{ip} is a vector (1xp) of inputs, including the “labor”, “gross fixed capital formation” and “energy consumption” of the i -th country. The linear programming problem (LPP) presented in Eq. (11) is solved once for each country and, as a result, presents the λ and ϕ values. In this respect, we can define $\theta = 1/\phi$ as efficiency score for i -th country, and λ as the values that project it towards the frontier.

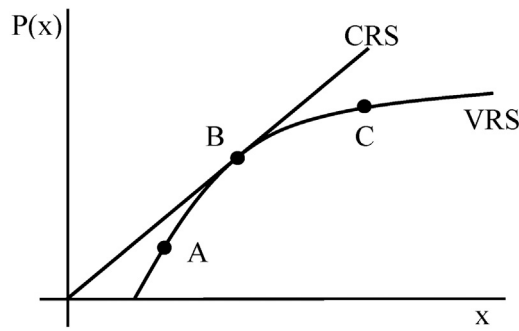


Fig. 2. CRS and VRS models.

Source: Elaborated by the authors

3.4. The environmental technical efficiency estimation on the metafrontier and frontier subgroups

The environmental efficiency measures based on DEA assume that countries have the same production technology. However, this is not a realistic assumption in this study, since the geographical, political and socioeconomic differences may influence the production process and thus account for a biased indicator (Chiu et al., 2012). O’donnell et al. (2008) suggest splitting the sample of countries in k subgroups from pre-established criteria, in which countries of similar technologies are compared. The environmental technical efficiency measure obtained in the subgroups (ETAG) is less than or equal to the measure of efficiency obtained when a total group is considered (environmental technical efficiency metafrontier — ETAM). As pointed out by Chiu et al. (2012), the ETAM/ETAG division presents a meta-technology ratio (MTR):

$$0 < MTR = \frac{ETAM}{ETAG} \leq 1, \tag{12}$$

which provides a technological heterogeneity measure as it becomes more distant from 1, a situation in which the environmental efficiency of the group differs systematically from the efficiency on the metafrontier. The MTR expressed in Eq. (12) indicates that a DMU in the specific frontier of the subgroup can only be distinguishable from the others because of the technological heterogeneity between the two frontiers. Therefore, the source of inefficiency in the metafrontier cannot be identified. Thus, the inefficiency of a DMU in global frontier must be decomposed by the inefficiency caused by the technological gap (TGI) and managerial inefficiency of the country (GMI) observed into subgroup frontiers. TGI is the inefficiency of DMU originated from the gap between the metafrontier and the subgroup frontier. Chiu et al. (2012) define the inefficiency caused by technological gap through the following expression (13):

$$TGI = (ETAG)(1 - MTR). \tag{13}$$

GMI is the inefficiency of the DMU originated from the excessive inputs used in the production, from the undesirable goods produced and from the deficit in the desirable goods production due to the improper management by the country. This inefficiency can be represented by the following expression (14).

$$GMI = 1 - ETAG. \tag{14}$$

In this sense, the environmental inefficiency over the metafrontier can be expressed as follows:

$$ITM = TGI + GMI. \tag{15}$$

The environmental inefficiency of DMU is the sum of the inefficiencies caused by the technological gap and by inadequate management. Fig. 3 illustrates this situation. Three groups that produce desirable and undesirable goods. Group 1 consists of the DMUs M and M' , Group 2, by the DMUs N and N' , and Group 3, by DMUs A , P and P' . The environmentally efficient group frontiers are represented by connecting the points $M-M'$, $N-N'$ and $P-P'$, respectively. The metafrontier, as denoted by $M-N'$, involves all frontiers of the subgroups.

The DMU A 's efficiency in the metafrontier and in the frontier subgroup can be represented by $ETAM(A) = OF/OD$ and $ETAG(A) = OE/OD$, respectively. Thus, $MTR(A) = OF/OE$. The inefficiency caused by the technological gap and the mismanagement of resources is defined by $TGI(A) = ETAG(A)(1 - MTR(A)) = FE/OD$ and $GMI(A) = (1 - ETAG(A)) = ED/OD$. The environmental inefficiency can be defined as $ITAM(A) = TGI(A) + GMI(A) = FD/OD$.

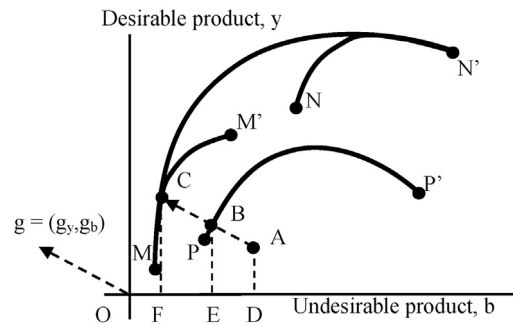


Fig. 3. The metafrontier and group frontiers.

Source: Chiu et al. (2012)

To split the sample, we used the cluster analysis, specifically the Ward's hierarchical method, which made it possible to aggregate countries into homogeneous subgroups. This technique uses standardized Euclidean distance between the variables and defines subgroups from the variability among them. We use the proportion of research and development expenditures, GDP per capita and the high technological products exportation as technologic proxies, in order to define the subgroup frontiers.

3.5. The variables description and the data source

This study analyzed the CO₂ emission Gini index and the environmental efficiency of 60 countries in 2010. This sample represents about 84.95% of world GDP and 71.87% of CO₂ emission. The data were obtained from the [World Bank \(2015\)](#) database. For the group formation, we used high technological products exportation per capita (US\$), research and development expenditures (GDP percentage), and GDP per capita. Regarding the environmental efficiency indicator, we used the total labor force (LAB), gross fixed capital formation (CAP) and energy consumption (ENE) as inputs, and as desirable and undesirable products, GDP and CO₂ emission ([Chung et al., 2007](#); [Zhou et al., 2010](#); [Chiu et al., 2012](#)).

4. Results

4.1. The CO₂ emission Gini index and group frontiers

This study utilized Ward's hierarchical procedure to define four subgroups of countries: high technology and income (HH, 17 countries), high technology and middle income (HM, 9 countries), low technology and middle income (LM, 18 countries) and low technology and low income (LL, 16 countries). [Table 1](#) presents descriptive statistics of the variables that were part of the cluster analysis and those that were the subject of the efficiency analysis.

[Table 1](#) shows that the average expenditure on R&D, exports of high-tech products and GDP *per capita* were higher in the HH group, characterizing them as high-tech and high-income countries. We can also highlight its average in the variable "gross fixed capital formation" and "energy consumption". The LM group, considered to be under development, could be considered labor-intensive, since its average was excessively superior to others. Besides, it issued more pollutants than the HH group (developed group). This result is not surprising, since China, a member of the group, took over the position of most polluting country in 2010, surpassing the USA. In addition to China, Russia, Mexico and Brazil also stand out. The countries that are part of the HM group, mostly countries from Europe and the Middle East, were fewer labor-intensive and had the second highest average income. In turn, the LL group could be considered poor and less developed, given the low indicators for income, R&D expenditure and high-tech products exportation. [Table 2](#) shows the subdivision of countries.

The grouping by cluster analysis could be realistic, since the subgroups are consistent with the current global economic environment (see [Table 2](#)). The HH group, composed by countries such as the USA, Japan and Germany, is highly developed. The HM group, although it present lower income when compared to HH, has good technology indicators (especially Israel, which invested in 2010 4.43% of its GDP on R&D). The LM group was composed

by developing economies (*e.g.* Brazil, China and Mexico), characterized by middle income and low technological standards. Finally, the LL group represents the countries that are technologically and economically in a less favorable situation, such as Ethiopia, Mozambique and El Salvador.

In addition, we calculated the Gini coefficient proposed by the expression (10), subdividing countries into four groups (USA – 30.3% of GDP and 22.4% of emission – Japan, China and Germany – 25, 5% of GDP and 42% of emission – the UK, France, Italy, Canada, Spain, Brazil, South Korea and Mexico – 26.3% of GDP

Table 1
Average of variables per grouping.

N	Group	PED	EXP	PIBpc	CO ₂	ENE	CAP	LAB
17	HH	2.33	1483.16	39,602.01	596,148	258,652	357,657	24.738
9	HM	1.84	1087.24	18,633.81	125,970	55,204	76,006	7.432
18	LM	0.82	388.73	7454.76	677,206	230,627	155,110	61.655
16	LL	0.36	17.24	2082.75	52,949	24,865	10,411	11.429

Source: Research findings.

PED = Average expenditure in R&D (GDP percentage).

EXP = Average *per capita* export of high-tech products (unity *per capita*).

PIBpc = Average *per capita* GDP (unity *per capita*).

CO₂ = Amount emitted (ton of petroleum).

ENE = Energy consumption (kWh).

CAP = Average gross fixed capital formation (millions).

LAB = Average number of labor workers (millions).

Table 2
Subdivision of the 60 countries.

OBS	Countries	Subgroup	OBS	Countries	Subgroup
1	Australia	HH	31	Croatia	LM
2	Hong Kong	HH	32	Latvia	LM
3	Canada	HH	33	Panama	LM
4	Finland	HH	34	Poland	LM
5	United Kingdom	HH	35	Romania	LM
6	Italy	HH	36	Russia	LM
7	Japan	HH	37	Turkey	LM
8	Norway	HH	38	Uruguay	LM
9	United States	HH	39	Costa Rica	LM
10	Austria	HH	40	Estonia	LM
11	Germany	HH	41	Lithuania	LM
12	Denmark	HH	42	Mexico	LM
13	France	HH	43	Hungary	LM
14	Sweden	HH	44	Malaysia	LM
15	Belgium	HH	45	Armenia	LL
16	Ireland	HH	46	Azerbaijan	LL
17	Holland	HH	47	Bulgaria	LL
18	Cyprus	HM	48	Belarus	LL
19	Spain	HM	49	Colombia	LL
20	Portugal	HM	50	Egypt	LL
21	Israel	HM	51	Ethiopia	LL
22	Slovakia	HM	52	Guatemala	LL
23	Slovenia	HM	53	Kyrgyzstan	LL
24	Czech Republic	HM	54	Sri Lanka	LL
25	South Korea	HM	55	Morocco	LL
26	Malta	HM	56	Moldavia	LL
27	Argentina	LM	57	Mozambique	LL
28	Brazil	LM	58	Nepal	LL
29	Chile	LM	59	El Salvador	LL
30	China	LM	60	Ukraine	LL

Source: Research findings.

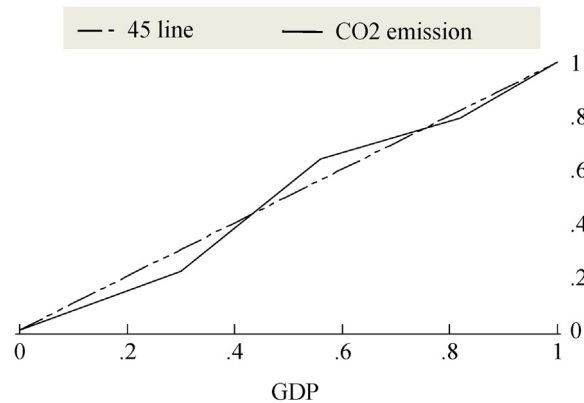


Fig. 4. Lorenz curve for pollutant emission.

Source: Research findings

and 14.2% of emission – and other countries – 17.9% of GDP and 21.4% of emission) and found the following results:

$$G = \left| 1 - \sum_{k=1}^{k=n-1} (\text{PIB}_{k+1} - \text{PIB}_k) (\text{CO2}_{k+1} + \text{CO2}_k) \right| = 0.016. \quad (16)$$

Expression (16) makes it clear that the CO₂ emission concentration is substantially high. In other words, it indicated that the cumulative proportion of pollution systematically responds to the cumulative proportion of income, *i.e.*, a country that has a significant share of income is also responsible for a significant portion of emissions. The USA can be cited as an example, because it represented 30.3% of world income and 22.4% of emissions. Graphically, Fig. 4 shows the Lorenz curve proposed.

The dotted line represents the perfect concentration of pollution (the cumulative proportion of the income and cumulative proportion of pollution — 45 line), while the solid line represents the relationship observed between the variables accumulated. The displacement of the solid line over the dotted was caused by China in the second group, since their emissions accounted for about 34.1% of the total, relatively increasing the participation of this group to 42% and accumulating the emissions of the first two groups in 64.3%, while the 45° line projected a participation of 55.8%. The existing approximation between the lines in the other points highlights the importance of the relationship between income and pollution: the closer they are, the higher pollutant concentration degree is observed. Consequently, Fig. 4 reinforces the estimated result of the Gini coefficient in expression (16).

4.2. Indicators for environmental efficiency and inefficiency over the metafrontier and the subgroup frontiers

Environmental efficiency indicators were built from the DEA-VRS model, considering variable returns to scale and technological heterogeneity among the analyzed countries. The efficiency indicators results, MTR and inefficiency on the metafrontier and the subgroup frontiers are reported in Table 3. Columns (2) and (9) relate to the efficiency disregarding the technological heterogeneity effect on the indicator, *i.e.*, it is the metafrontier estimation. Columns (3) and (10) show the group environmental efficiencies HH, HM, LM and LL. A (4) and (11) present the MTR indicator. Columns (5), (6), (7) – and the continuation of these results in (12), (13) and (14) – represent the inefficiencies caused by the technological gap (TGI), the inadequate resource management (GMI), and the environmental inefficiency (ITM), respectively.

Out of the 60 countries that surveyed, only nine were environmentally efficient (2, 5, 7, 8, 9, 16, 26, 53 and 59), considering both the metafrontier and the group frontiers. Six of them (2, 5, 7, 8, 9 and 16) belong to the developed countries group (HH), one belongs to the second developed group (MH — 26) and two belong to the poor countries group (LL — 53 and 59).

When considering the environmental efficiency of subgroups, the number of efficient countries increased to 32 (see Table 3). This fact makes the heterogeneity between the metafrontier and the group frontiers clear. Countries such as Belarus (0.667), China (0.599) and Moldavia (0.467) can be highlighted, for their TGI indicator which was substantially

Table 3
Environmental efficiency and inefficiency measures on the metafrontier and the subgroup frontier.

(1) OBS	(2) ETAM	(3) ETAG	(4) MRT	(5) TGI	(6) GMI	(7) ITM	(8) OBS	(9) ETAM	(10) ETAG	(11) MRT	(12) TGI	(13) GMI	(14) ITM
1	0.781	0.781	1.000	0.000	0.219	0.219	31	0.637	1.000	0.637	0.363	0.000	0.363
2	1.000	1.000	1.000	0.000	0.000	0.000	32	0.802	1.000	0.802	0.198	0.000	0.198
3	0.774	0.774	1.000	0.000	0.226	0.226	33	0.592	1.000	0.592	0.408	0.000	0.408
4	0.812	0.812	1.000	0.000	0.188	0.188	34	0.704	0.978	0.720	0.274	0.022	0.296
5	1.000	1.000	1.000	0.000	0.000	0.000	35	0.555	0.747	0.742	0.192	0.253	0.445
6	0.932	0.932	1.000	0.000	0.068	0.068	36	0.699	0.970	0.721	0.271	0.030	0.301
7	1.000	1.000	1.000	0.000	0.000	0.000	37	0.715	1.000	0.715	0.285	0.000	0.285
8	1.000	1.000	1.000	0.000	0.000	0.000	38	0.706	1.000	0.706	0.294	0.000	0.294
9	1.000	1.000	1.000	0.000	0.000	0.000	39	0.685	0.980	0.700	0.294	0.020	0.315
10	0.832	0.832	1.000	0.000	0.168	0.168	40	0.669	1.000	0.669	0.331	0.000	0.331
11	0.941	0.941	1.000	0.000	0.059	0.059	41	0.782	1.000	0.782	0.218	0.000	0.218
12	0.990	0.990	1.000	0.000	0.010	0.010	42	0.698	1.000	0.698	0.302	0.000	0.302
13	0.939	0.939	1.000	0.000	0.061	0.061	43	0.757	1.000	0.757	0.243	0.000	0.243
14	0.906	0.909	0.997	0.003	0.091	0.094	44	0.629	0.856	0.735	0.227	0.144	0.371
15	0.872	0.872	1.000	0.000	0.128	0.128	45	0.613	1.000	0.613	0.387	0.000	0.387
16	1.000	1.000	1.000	0.000	0.000	0.000	46	0.793	0.941	0.843	0.148	0.059	0.207
17	0.935	0.935	1.000	0.000	0.065	0.065	47	0.604	1.000	0.604	0.396	0.000	0.396
18	0.755	0.956	0.790	0.201	0.044	0.245	48	0.333	1.000	0.333	0.667	0.000	0.667
19	0.777	1.000	0.777	0.223	0.000	0.223	49	0.609	1.000	0.609	0.391	0.000	0.391
20	0.737	1.000	0.737	0.263	0.000	0.263	50	0.714	1.000	0.714	0.286	0.000	0.286
21	0.787	1.000	0.787	0.213	0.000	0.213	51	0.536	0.649	0.826	0.113	0.351	0.464
22	0.632	0.804	0.785	0.173	0.196	0.368	52	0.924	1.000	0.924	0.076	0.000	0.076
23	0.658	0.823	0.800	0.165	0.177	0.342	53	1.000	1.000	1.000	0.000	0.000	0.000
24	0.580	0.763	0.760	0.183	0.237	0.420	54	0.576	0.773	0.745	0.197	0.227	0.424
25	0.564	0.880	0.641	0.316	0.120	0.436	55	0.472	0.852	0.554	0.380	0.148	0.528
26	1.000	1.000	1.000	0.000	0.000	0.000	56	0.533	1.000	0.533	0.467	0.000	0.467
27	0.600	0.825	0.727	0.225	0.175	0.400	57	0.898	1.000	0.898	0.102	0.000	0.102
28	0.725	1.000	0.725	0.275	0.000	0.275	58	0.691	0.835	0.827	0.144	0.165	0.309
29	0.616	0.881	0.700	0.264	0.119	0.384	59	1.000	1.000	1.000	0.000	0.000	0.000
30	0.401	1.000	0.401	0.599	0.000	0.599	60	0.911	1.000	0.911	0.089	0.000	0.089

Source: Research findings

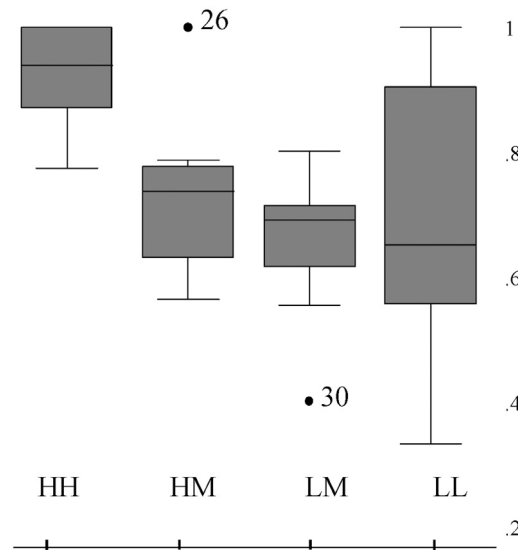


Fig. 5. Box plot of the environmental efficiency over the metafrontier.

Source: Research findings

high. It is also important to note that the values closer to the indicated unit increased technological heterogeneity across frontiers (its average was 0.181). Fig. 5 shows further evidence on environmental efficiency in the metafrontier per subgroups.

The average group efficiency of HH (0.924) was higher than the average of other groups (HM 0.721, LM 0.672, and LL 0.701, respectively), indicating that developed countries have better environmental performance. In Fig. 5, the line cutting the rectangles is the median of the group environmental efficiency. More developed countries (HH) were more efficient, whereas the poorer ones (LL) were less efficient. This result is intuitive, because the HH group performed better in the desirable good production, even generating significant amount of pollutant. In this group, Canada (3) showed the worst efficiency indicator. Malta (26), a country that belongs to HM group, shown as the second most efficient and developed, was the outlier of its group. In the LM group, China deserves attention (30), because its coefficient was significantly lower than the average in its group. Regarding LL group, it showed a larger standard deviation than the others did.

It is possible to note that environmental efficiency is closely related to the capacity of the country to produce desirable goods while emitting the lowest level of pollutants. In developed countries the pollution level was compensated by income generation, which did not occur for the developing countries.

As seen in this study, environmental inefficiency of metafrontier (ITM) could be decomposed into inefficiency caused by the technological gap (TGI) and the mismanagement (GMI). When the subgroup efficiency is identical to the metafrontier efficiency, inefficiency caused by technological factor tends to be null, which is the case of the developed countries, such as the USA, Japan, Germany, United Kingdom, Denmark and others. Therefore, the inefficiency observed in these cases can be fully attributed to excessive inputs used, the desirable product failure, and/or excessive pollution levels, as observed in countries like France, Finland, Canada, Denmark, etc. On the other hand, when TGI is higher than GMI, we can assign more importance to the technological gap, such as China, Belarus, Moldova, Panama and others (see Table 3). This result shows that the main source of environmental inefficiency is the technological gap between them and developed countries.

As expected, developed countries showed no significant technological gap, as they are at the forefront of development in the metafrontier. As for the others, they can assign part of the environmental inefficiency to this factor, especially the LM group, led substantially by the China's emission. The HH group (0.076) showed the lowest environmental inefficiency indicator (ITM), followed by HM (0.279), LL (0.299), and LM (0.335). However, the LM (0.042) group showed the lowest management inefficiency indicator, followed by LL (0.059), HH (0.075), and HM (0.086).

The results of this study showed that the greatest environmental problem faced by the LM group, which includes countries like Brazil, Argentina, Chile and China, is technological in nature. Conversely, in the HH group, composed

of developed countries, the mismanagement of resources stands out. This evidence implies that, unlike the developed countries (which are technologically enabled and reached its current technological stages without any restriction on their emission levels), developing countries will have their technological trajectories affected by environmental issues and must learn how to deal with this new and current restriction.

5. Conclusions

There is a consensus today regarding the interrelationship between economic activity (desirable product) and environmental degradation (undesirable product). The pollution aspect should be considered a part of the process and included in the production function. Nevertheless, environmental efficiency indicators built by these frontiers could lead to an erroneous analysis when the observations do not belong to the same frontier. We can note that it is not a realistic assumption. Therefore, this paper proposes to estimate the environmental efficiency for 60 countries, considering heterogeneity among the general production function and specific frontiers. This allows separate the metafrontier inefficiency by the technological gap and the mismanagement of the resources.

The results showed that the developed countries group (HH) is more environmentally efficient than the others, while the group of low-income and middle-competitiveness countries (ML) was less efficient. This last result was due mainly to the performance of the Chinese (the most polluting economy in 2010). We perceived that developing countries pollution was compensated by income generation, which did not occur for the others.

Additionally, it is important to note that the main source of ML inefficiency was caused by the technological gap. If there were no difference between the frontiers, its inefficiency would be almost similar to the HH group. The managerial inefficiency was more relevant in developed countries (HH and HM). This result was expected, because they are part of the highest technological frontier. On the other hand, we could conclude that pollution was heavily concentrated in the higher income countries. It is clear that developing countries will have their technological trajectories affected by environmental issues and therefore must learn how to deal with this new and current restriction. Finally, we conclude that environmental issues should be considered in the environmental efficiency analysis, since social welfare could be related to increasing desirable products and to reduction of the undesirable ones.

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