International Journal of Sport Finance, 2017, **12**, 265-293,

A Country-Level Efficiency Analysis of the 2016 Summer Olympic Games in Rio: A Complete Picture

Julio del Corral[1], Carlos Gomez-Gonzalez[1], and José Manuel Sánchez-Santos[2]

[1] University of Castilla-La Mancha

[2] University of A Coruña

Julio del Corral, PhD, is an associate professor of economics in the Department of Economics and Finance. His current research focuses on the economics of sport, specifically the topics of demand, competitive balance, productivity, discrimination, and betting.

Carlos Gomez-Gonzalez is a PhD candidate in the Department of Economic Analysis and Finance. He is also a researcher in Group IGOID. His research interests include sport economics and management, with a focus on consumer behavior and discrimination.

José Manuel Sánchez-Santos, PhD, is an associate professor of economics in the Department of Economics. His research is developed mainly in the fields of socioeconomics and sport economics and it is particularly focused on social capital, subjective wellbeing, and sport participation.

Abstract

Studying the performance and efficiency of countries participating in the Olympic Games is a topic of interest in the area of economics and operations research. Commonly, efficiency in this area has been analyzed using outputs like number of medals, the number of medals weighted by category, and the number of diplomas, while the most common inputs are gross domestic product (GDP) and population. This paper contributes to the literature by analyzing the countries' efficiencies in the Rio 2016 Summer Olympics with stochastic frontier models. Moreover, this study aims to fill three research gaps in the literature. On the one hand, given that the athletes' qualification for the Games is a great achievement itself for many countries, the analysis uses the number of participants as the output. On the other hand, the analysis weights the number of medals in relation to the number of participants in each competition (i.e., two in tennis doubles, 14 in handball). Finally, this paper develops a measure to calculate the inefficiency of countries with zero medals, since traditional frontier methods do not consider them.

Keywords: Summer Olympic Games, efficiency, stochastic frontier

Introduction

The Olympic Games is viewed as the most prestigious international sporting event due to its history, tradition, global impact, and universal participation. This competition gathers outstanding athletes from more than 200 countries and consists of both team and individual sports. The economics of the Olympic Games has developed a research line that focuses on the efficiencies of the participating nations. In this context, the definition of efficiency is the relationship between the observed output-level and the ideal (or potential) output-level (Greene, 2008), which can be obtained using frontier methods (i.e., DEA and stochastic frontier models). Lozano, Villa, Guerrero, and Cortés (2002) are pioneers in this strand of the literature.[1]

Previous research has used the number of medals or diplomas to determine success and has incorporated the relative value of medals into the analyses (Churilov & Flitman, 2006; Lozano et al., 2002; Zhang, Li, Meng, & Liu, 2009). Nevertheless, the computation of medals, weighted points (e.g., 3-gold; 2-silver; 1-bronze), or diplomas might not be the most appropriate system to define success in the Olympic Games. The qualification of athletes for the Games is a great success by itself for many participating countries, because they can enhance their international image. However, very few studies use the number of participants as the outcome in the Olympic Games. Johnson and Ali (2004) included the number of participants as a dependent variable to identify economic and political factors that determine success. Similarly, Li, Lei, Dai, and Liang (2015) also considered the number of participating athletes as the output in a previous process (the athletes' preparation stage) for competition in the Olympic Games. This paper contributes to this literature by incorporating the number of participating athletes as an output in stochastic frontier models that analyze the efficiency of the participating nations.

The competition in the Summer Olympic Games includes both individual and team sports. Team sports require the participation of more than one athlete, and there are big differences regarding the number of competing athletes (e.g., 18 athletes in field hockey, 12 athletes in volleyball, and two athletes in tennis doubles). Thus, team sports that require a higher number of athletes to compete force the participating countries to prepare more athletes. To consider the difference in the number of athletes required in individual and team sports, we included a weighted number of medals as the output, in which the weight is positively correlated to the number of participants. Thus, this study contributes to the literature by incorporating the importance of medals won in individual and team sports into the analyses of efficiency in the Olympic Games.

Finally, to the best of our knowledge, countries with zero medals are typically excluded from efficiency analyses in the literature because their efficiency is always zero. However, not all countries with zero medals have the same economic resources. Therefore, in this paper, we implement a measure that differentiates the performance of countries with zero medals. For this purpose, we use a probit model to calculate the probabilities of obtaining at least one medal in Rio 2016. Our methodology follows the line of del Corral, Maroto, and Gallardo (2015) and van Ours and van Tujil (2016) that calculate the efficiency of managers as comparing the actual performance with a predicted performance.

Thus, on the one hand, the aim of this paper is to examine the efficiencies of the competing nations in the 2016 Summer Olympics by incorporating the value of participation and medals in team and individual sports. For this purpose, stochastic frontier models are used. The population size of the competing nations and the gross domestic product (GDP) are the inputs, while the number of participants, medals, and weighted medals are the chosen outputs. On the other hand, this paper aims to calculate the efficiency of countries with zero medals using an expected performance measure extracted from betting odds.

Literature Review

The *Measurement* of performance and rankings in the Olympic Games has attracted the attention of academicians in the fields of economics and operations research. Most of the contributions in this field of study can be classified into two groups: 1) research has analyzed the determinants of medal success in the Olympic Games (explanation and forecasting); and 2) a wide range of papers has evaluated the relative efficiencies of the nations participating in the Olympics.

With regard to the first group, since the contribution of den Butter and van der Tak (1995), a large body of literature, which investigates factors determining performance in the Olympics, has emerged. There is a certain consensus that GDP, population, and the host country's status are the most consistent predictors of Olympic success. However, the list of determinants of success in the Olympic Games is much longer, and includes political regimes (Bernard & Busse, 2004; Rathke & Woitek, 2008), public expenditure on recreation (Forrest, Sanz, & Tena, 2010), expenditure on health (Moosa & Smith, 2004), climatic factors (Hoffmann, Ging, & Ramasamy, 2004; Johnson & Ali, 2004), life expectancy and education (Lui & Suen, 2008), macroeconomic indicators other than GDP (Vagenas & Vlachokyriakou, 2012), poverty and income distribution (Mitchell & Stewart, 2007), regions' cultural traits (Andreff, Andreff, & Poupaux, 2008; Otamendi & Doncel, 2014), geographic situations (Noland & Stahler, 2016; Tcha & Pershin, 2003), sporting traditions (Stamm & Lamprecht, 1999), number of athletes (Moosa & Smith, 2004), prior performance (Celik & Gius, 2014), infrastructures (Condon, Golden, & Wasil, 1999), religion (De Bosscher, Heyndels, De Knop, van Bottenburg, & Shibli, 2008), and previous hosting (Hoffmann, Ging, & Ramasamy, 2002).

In addition, due to the need for understanding the performance of nations in absolute terms, researchers are concerned about the methods to measure achievements in the Olympics effectively and fairly. With the aim of designing an objective system of analysis for the Olympic Games, the nonparametric data envelopment analysis (DEA) model has become increasingly popular. In particular, Lozano et al. (2002) pioneered the application of this method to evaluate the relative efficiencies of participants in the Olympics.

In DEA models, every participating nation is treated as a decision-making unit (DMU), which produces multiple outputs with a certain number of inputs. In this framework, the first problem is that different outputs could be used. Some of the most frequently used in the literature are the total number of medals and the number of medals won on a per capita basis.

Moreover, lexicographic orders, in which winning a gold medal is preferred to winning a silver medal, which in turn is preferred to winning a bronze medal, have been used (i.e., Lins, Gomes, Soares de Mello, & Soares de Mello, 2003; Lozano et al. 2002; Zhang et al., 2009). The aggregation of the outputs "number of medals" as a single indicator can be obtained by means of a weighted sum in which the weights are the measure of the importance of each type of medal. The main difficulty is that the weights involve value judgements about the relative value of medals (a problem of preferences).

Other studies have suggested that participating countries should be grouped into four categories: low income, lower/middle income, upper/middle income, and high income (Li, Liang, Chen, & Morita, 2008). They justified this classification on the grounds that nations may value gold, silver, and bronze medals differently.

Issues that are more controversial have also been addressed using modified versions of DEA models. For example, Lins et al. (2003) showed the need to consider the limited number of medals available to be won. Another problem is that some outputs, such as the number of medals, are integers (Wu, Zhou, & Liang, 2010).

In addition to the aforementioned methodological challenges, the literature has also identified several biases to be corrected. For instance, some evidence suggests that participating nations may have different performance levels in the Summer Olympics and in the Winter Olympics. If Summer and Winter Games are not considered together, assuming similar levels of performance for the participating nations might constitute a bias. Soares de Mello, Angulo-Meza, and Da Silva (2009) provided a ranking using a DEA approach that included the results of both games combined. Lei, Li, Xie, and Liang (2015) also considered the Summer and Winter Olympic Games and their results suggest that the majority of nations have different performance levels in each of them, which are consistent with their geographical features.

More recently, a key issue that has emerged when assessing the performance of nations in the Olympic Games is the distinction between the stages of athlete preparation and athlete competition (Li et al., 2015). The output in the athletes' preparation stage (i.e., the number of participating athletes) is also defined as an intermediate measure that links both stages. In the athlete competition stage, the number of participating athletes is used as the input to produce three final outputs (namely the numbers of gold, silver, and bronze medals). Li et al. (2015) developed several models to measure the efficiencies of nations in these two individual stages. They found that the efficiency in the athlete participation stage is usually higher than it is in the athlete competition stage.

Most of the literature analyzing the efficiency of nations participating in the Olympic Games is based on non-parametric approaches. However, there have also been some attempts to estimate a frontier production function using parametric methods. Rathke and Woitek (2008) used stochastic frontier analysis to identify the determinants of performance differences in the Olympic Games.

To summarize, conventional DEA models and modifications are considered as adequate approaches to measure the efficiency of nations participating in the Olympic Games. Research on the issue offers a set of alternative and complementary measures to achieve results that are more reliable with regard to success and efficiency in the

Games. There is no doubt about the useful contributions of the aforementioned studies in two directions. First, the methods can be used as measuring tools for participating countries to identify significant biases towards some of the participants (Churilov & Flitman, 2006). Second, they help to evaluate the performance of nations in comparison to their potential, and enable them to determine realistic goals for future Olympic Games (Wu et al., 2010).

Methodology

Stochastic Frontier Models

A production function is the maximum output attainable given a set of inputs (Greene, 2008). Thus, to estimate a production function, a frontier model must be used. There are two main alternative methods to estimate frontier production functions: DEA[2] and stochastic frontier models. DEA are non-parametric and deterministic.[3] Conversely, stochastic frontier models[4] are parametric and stochastic.[5] Parametric refers to the functional form that needs to be assumed. The most common are the Cobb-Douglas and the translog. Stochastic means that some countries could be above the frontier, which reduces the influence of outliers on the results.

In this paper, we prefer to rely on stochastic frontier methodology because some countries could be labeled as outliers due to missing inputs such as genetics. Moreover, the parametric nature of this methodology allows hypothesis testing, which could be particularly relevant in order to test the input selection.

A stochastic frontier production function can be written as follows:

$$y=f(x)\cdot\exp(\varepsilon);\ \varepsilon=v-u$$

where y represents output, x is a vector of inputs, $f(x)$ represents the technology, and ε is a composed error term. The component v captures noise and other stochastic shocks entering into the definition of the frontier (e.g., luck, referees' decisions, and so on), which is assumed to follow a normal distribution centered at zero. The component u is assumed to follow a one-sided distribution, capturing the inefficiency relative to the stochastic frontier. In this paper, it was tested which distribution fits better to the data among half-normal, truncated normal, and exponential by using Wald tests. Based on the assumption that the two components are independent of each other, maximum likelihood estimates can be obtained (Aigner, Lovell, & Schmidt, 1977). In so doing, it is important to set the parameter $\lambda=\sigma_u/\sigma_v$, where σ_u is the standard deviation of the u component, and σ_v is the standard deviation of the v component. If σ_v is statistically equal to zero, the model collapses to a determinist model in which all the deviations from the frontier are due to inefficiency while, if σ_u is statistically equal to zero, there is no inefficiency component. Therefore, if either $\lambda=0$ or λ is very large, the empirical application of the model will be problematic and hence the decision is not to use models under these circumstances.

Once the production frontier has been estimated, a technical efficiency index can be computed as the ratio between actual output and potential output. Actual output is $f(x)\cdot\exp(v-u)$ while potential output is $f(x)\cdot\exp(v)$. Therefore, technical efficiency can be computed as $\exp(-u)$, which is specifically calculated as $E(\exp(-u)|\varepsilon)$.

Moreover, one of the assumptions of production frontiers is the monotonicity of inputs, which implies that the output is positively related to the levels of each of the inputs. Hence, if any input shows a negative elasticity, such a model is rejected. Lastly, the Cobb-Douglas was tested against the translog using Wald tests for all models.

Performance of Zero-Medal Countries

Frontier methods cannot provide any information on countries with zero level of output (zero medals) other than their efficiency is zero. Thus, in order to get a complete list of the performance of countries participating in the Olympic Games alternative methodologies should be used. In this line, Pieper, Nüesch, and Franck (2014), del Corral et al. (2015), van Ours and van Tujil (2016), and Humphreys, Paul, and Weinbach (2016) proposed to calculate the efficiency of managers as comparing the actual performance with the performance predicted by bookmakers. In this framework, the probability for a country to obtain at least one medal can be estimated using a probit model. After doing so, an "efficiency index" can be created by calculating efficiency=1-p, where p is the predicted probability from the probit model. In this way, countries expected to obtain at least one medal will have lower efficiency values than countries with lower probability of obtaining medals.

Data

Data from the 206 countries participating in the Rio 2016 Summer Olympic Games were obtained from both the International Olympic Committee (IOC) website and the World Bank database. From the IOC website, we collected the number of participants, the number of medals, and the sports in which the medals were awarded. From the World Bank database,[6] we obtained the two main inputs identified in the literature, namely GDP and population.[7]

With regard to the number of participants, it is important to note the following. First, countries face a small maximum number of entries in all individual sports even if they have more potential qualified athletes in the rankings,[8] and therefore, some bias can exist in the analysis. Second, the host country (in this case, Brazil), is invited to participate in all team and individual sports. Hence, the host country is expected to participate with a huge delegation. Another important fact is that several Olympic spots are allotted on a continent basis. This is especially important in Oceania, where Australia and New Zealand are the only countries with a great development in most Olympic sports. Therefore, their likelihood to compete with a large delegation is higher than for other developed countries from other continents. Therefore, their efficiencies regarding the number of participants have to be cautiously interpreted. Moreover, this fact implies that a continent-by-continent analysis could be useful when analyzing the number of participants. Due to space limitations, this analysis is only included at the European level.[9] Finally, it is important to acknowledge that occasionally some countries have refused the participation of some qualified athletes or team squads.[10]

Thus far, the literature has acknowledged that a gold medal is not the same as a bronze medal by incorporating some weights.[11] However, to the best of our knowledge, there is no paper that considers a gold medal to be more valuable in some team sports (e.g., handball or basketball) than in some individual sports.[12] A greater number of influential players is needed to obtain a medal in team sports (instead of only one star). In order to create an alternative output to the number of medals, we have used the following formula:[13]

$$Team\ weighted\ medals_j = \sum_i (log(n_{ij}) + 1) \cdot d_{ij}$$

where n_{ij} indicates the number of athletes for participant i from country j, and d_{ij} is a dummy variable that takes the value one if participant ij has obtained at least one medal and zero otherwise. Table 1 shows the team-weighted values of medals for each possible number of participants, as well as some examples.

Table 1.Team Weighting Values

Number of athletes	Weighted value	Example
1	1.00	100 meters
2	1.30	Tennis doubles
3	1.48	Cycling track team sprint
4	1.60	Swimming relays
5	1.70	Rhythmic gymnastics
9	1.95	Synchronized swimming
12	2.08	Volleyball
13	2.11	Waterpolo
15	2.18	Handball
16	2.20	Field hockey
18	2.26	Football

With regard to the GDP, there are two clear outliers: China and the United States. Dealing with outliers is not straightforward in econometrics, and no clear procedure is preferred. In this study, we believe that the benefit of calculating the efficiency of these two countries is lower than the cost of (possibly) biasing the estimates from the rest of the sample. Hence, we have decided to exclude them from the sample.[14]

Table 2 provides the descriptive statistics for the 204 countries used in the estimates.

Table 2. Descriptive Statistics

	Obs.	**Mean**	**Standard deviation**	**Minimum**	**Maximum**
Participants	204	51.24	87.25	1	470
Gold medals	204	1.15	3.20	0	27
Silver medals	204	1.24	3.08	0	23
Bronze medals	204	1.45	3.38	0	21
Total medals	204	3.83	9.14	0	67
3-2-1 weighted medals	204	7.36	18.27	0	144

Table 2. (Cont.) Descriptive Statistics

	Obs.	Mean	Standard deviation	Minimum	Maximum
Team weighted medals	204	4.39	10.77	0	81.69
GDP (US dollars 2014)	204	2.21E+11	5.50E+11	3.79E+07	4.12E+12
Population (inhabitants)	204	2.77E+07	9.81E+07	9,916	1.31E+09

Note: Obs.- number of observations.

Results

Number of Participants

The preferred models for the number of participants are the Cobb-Douglas that includes only GDP using the truncated normal in the world analysis and the Cobb-Douglas that includes both inputs using the exponential distribution for inefficiency in Europe. Figure 1 shows the relationship between the number of participants and GDP for all countries. This figure also includes the stochastic frontier production function, the OLS quadratic regression, and its associated R-squared.

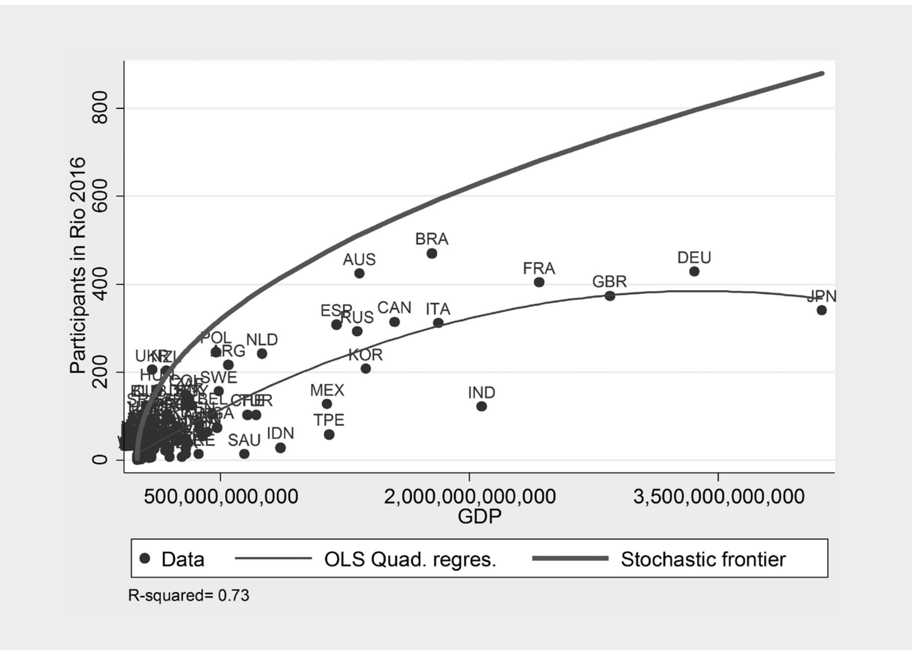

Figure 1. Relationship between participation and GDP for all countries in Rio 2016

The R-squared for the entire sample is 0.73, which indicates the large and positive relationship between these two variables. Table 3 shows the estimates for the preferred models while Table 4 shows the efficiencies associated with these preferred models.

Table 3. Estimates of Preferred Models for Participation

	World	**Europe**
Constant	-7.186***	-6.643***
GDP	0.481***	0.166*
Population		0.450***
σ_u	0.930***	0.488***
σ_v	0.377	0.308***
λ	2.467***	2.467***
Log-likelihood	-262.954	-38.953
Number of observations	204	50
Distribution of *u*	Truncated normal	Exponential

Note: * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Table 4. Countries' Efficiency in Participation

Country	**Region**	**Code**	**World**	**Position in top 15 GDP**	**Europe**
Fiji	Oceanía	FJI	0.82 (1)		
Cook Islands	Oceanía	COO	0.82 (2)		
Ukraine	Europa	UKR	0.80 (3)		0.81 (13)
Serbia	Europa	SRB	0.76 (4)		0.87 (6)
Belarus	Europa	BLR	0.75 (5)		0.86 (7)
Montenegro	Europa	MNE	0.75 (6)		0.91 (1)
New Zealand	Oceanía	NZL	0.73 (7)		
Jamaica	América	JAM	0.73 (8)		
Hungary	Europa	HUN	0.72 (9)		0.88 (2)
Cuba	América	CUB	0.71 (10)		
Croatia	Europa	HRV	0.67 (11)		0.87 (5)
Australia	Oceanía	AUS	0.66 (12)	1	
Mongolia	Asia	MNG	0.66 (13)		
Brazil	América	BRA	0.65 (14)	2	
Poland	Europa	POL	0.65 (15)		0.80 (14)
Georgia	Europa	GEO	0.60 (16)		0.75 (22)
Lithuania	Europa	LTU	0.60 (17)		0.86 (9)
Marshall Islands	Oceanía	MHL	0.60 (18)		

Table 4. (Cont.) Countries' Efficiency in Participation

Country	Region	Code	World	Position in top 15 GDP	Europe
Bahamas, The	América	BHS	0.60 (19)		
Kenya	África	KEN	0.59 (20)		
Tonga	Oceanía	TON	0.58 (21)		
Argentina	América	ARG	0.58 (22)		
Slovenia	Europa	SVN	0.57 (23)		0.87 (3)
Armenia	Europa	ARM	0.57 (24)		0.72 (28)
Estonia	Europa	EST	0.57 (25)		0.87 (4)
Spain	Europa	ESP	0.57 (26)	3	0.80 (15)
Netherlands	Europa	NLD	0.56 (27)		0.86 (8)
Tunisia	África	TUN	0.56 (28)		
Colombia	América	COL	0.55 (29)		
France	Europa	FRA	0.54 (30)	4	0.80 (16)
Moldova	Europa	MDA	0.53 (31)		0.58 (39)
Korea, Dem. People's Rep.	Asia	PRK	0.53 (32)		
Russian Federation	Europa	RUS	0.53 (33)	5	0.58 (40)
Canada	América	CAN	0.53 (34)	6	
Uzbekistan	Asia	UZB	0.53 (35)		
Samoa	Oceanía	WSM	0.53 (36)		
Palau	Oceanía	PLW	0.53 (37)		
South Africa	África	ZAF	0.51 (38)		
Zimbabwe	África	ZWE	0.51 (39)		
Micronesia, Fed. Sts.	Oceanía	FSM	0.51 (40)		
Germany	Europa	DEU	0.51 (41)	7	0.77 (18)
Czech Republic	Europa	CZE	0.50 (42)		0.77 (19)
Kazakhstan	Asia	KAZ	0.50 (43)		
Italy	Europa	ITA	0.50 (44)	8	0.75 (23)
Seychelles	África	SYC	0.49 (45)		
Azerbaijan	Europa	AZE	0.49 (46)		0.62 (34)
United Kingdom	Europa	GBR	0.48 (47)	9	0.77 (20)
Denmark	Europa	DNK	0.48 (48)		0.86 (10)
Romania	Europa	ROU	0.48 (49)		0.64 (33)
Antigua and Barbuda	América	ATG	0.47 (50)		
Sweden	Europa	SWE	0.47 (51)		0.84 (12)
Bulgaria	Europa	BGR	0.47 (52)		0.65 (31)

Table 4. (Cont.) Countries' Efficiency in Participation

Country	Region	Code	World	Position in top 15 GDP	Europe
Egypt, Arab Rep.	África	EGY	0.46 (53)		
Kiribati	Oceanía	KIR	0.46 (54)		
Portugal	Europa	PRT	0.45 (55)		0.73 (24)
Greece	Europa	GRC	0.45 (56)		0.72 (27)
Kyrgyz Republic	Europa	KGZ	0.44 (57)		0.37 (45)
St. Kitts and Nevis	América	KNA	0.44 (58)		
Grenada	América	GRD	0.43 (59)		
Latvia	Europa	LVA	0.43 (60)		0.75 (21)
Eritrea	África	ERI	0.41 (61)		
Bahrain	África	BHR	0.41 (62)		
Trinidad and Tobago	América	TTO	0.40 (63)		
Korea, Rep.	Asia	KOR	0.40 (64)	10	
Honduras	América	HND	0.40 (65)		
Senegal	África	SEN	0.39 (66)		
Japan	Asia	JPN	0.39 (67)	11	
Slovak Republic	Europa	SVK	0.38 (68)		0.66 (30)
Djibouti	África	DJI	0.36 (69)		
Belgium	Europa	BEL	0.36 (70)		0.71 (29)
Morocco	África	MAR	0.35 (71)		
Algeria	África	DZA	0.35 (72)		
Ireland	Europa	IRL	0.35 (73)		0.78 (17)
Lesotho	África	LSO	0.35 (74)		
Barbados	América	BRB	0.34 (75)		
Ethiopia	África	ETH	0.34 (76)		
Burundi	África	BDI	0.34 (77)		
Sao Tome and Principe	África	STP	0.33 (78)		
Virgin Islands (US)	América	VIR	0.32 (79)		
Comoros	África	COM	0.32 (80)		
Venezuela, RB	América	VEN	0.32 (81)		
Nauru	Oceanía	NRU	0.32 (82)		
Cayman Islands	América	CYM	0.32 (83)		
Central African Republic	África	CAF	0.32 (84)		
Guinea-Bissau	África	GNB	0.32 (85)		
Tuvalu	Oceanía	TUV	0.31 (86)		

Table 4. (Cont.) Countries' Efficiency in Participation

Country	**Region**	**Code**	**World**	**Position in top 15 GDP**	**Europe**
American Samoa	Oceanía	ASM	0.31 (87)		
St. Vincent and the Grenadines	América	VCT	0.30 (88)		
Cameroon	África	CMR	0.30 (89)		
Switzerland	Europa	CHE	0.30 (90)		0.73 (26)
Aruba	América	ABW	0.29 (91)		
Puerto Rico	América	PRI	0.29 (92)		
Vanuatu	Oceanía	VUT	0.29 (93)		
Turkey	Europa	TUR	0.29 (94)		0.31 (46)
Uganda	África	UGA	0.29 (95)		
British Virgin Islands	América	VGB	0.29 (96)		
Gambia, The	África	GMB	0.29 (97)		
Mexico	América	MEX	0.28 (98)	12	
St. Lucia	América	LCA	0.28 (99)		
Austria	Europa	AUT	0.28 (100)		0.61 (36)
Ecuador	América	ECU	0.28 (101)		
Finland	Europa	FIN	0.27 (102)		0.62 (35)
Cabo Verde	África	CPV	0.26 (103)		
Congo, Rep.	África	COG	0.26 (104)		
Cyprus	Europa	CYP	0.26 (105)		0.56 (41)
Nigeria	África	NGA	0.26 (106)		
Mauritius	África	MUS	0.25 (107)		
San Marino	Europa	SMR	0.25 (108)		0.85 (11)
Dominican Republic	América	DOM	0.24 (109)		
Norway	Europa	NOR	0.24 (110)		0.65 (32)
Bermuda	América	BMU	0.24 (111)		
Haiti	América	HTI	0.24 (112)		
Iran, Islamic Rep.	Asia	IRN	0.24 (113)		
Guyana	América	GUY	0.24 (114)		
Kosovo	Europa	KSV	0.23 (115)		0.28 (47)
Qatar	Asia	QAT	0.22 (116)		
Israel	Europa	ISR	0.22 (117)		0.45 (43)
Namibia	África	NAM	0.21 (118)		
India	Asia	IND	0.21 (119)	13	
Guam	América	GUM	0.21 (120)		

Table 4. (Cont.) Countries' Efficiency in Participation

Country	Region	Code	World	Position in top 15 GDP	Europe
Botswana	África	BWA	0.21 (121)		
Thailand	Asia	THA	0.21 (122)		
Chile	América	CHL	0.21 (123)		
Bosnia and Herzegovina	Europa	BIH	0.20 (124)		0.24 (48)
Guatemala	América	GTM	0.20 (125)		
Andorra	Europa	AND	0.20 (126)		0.73 (25)
Angola	África	AGO	0.20 (127)		
Suriname	América	SUR	0.20 (128)		
Solomon Islands	Oceanía	SLB	0.20 (129)		
Ghana	África	GHA	0.20 (130)		
Dominica	América	DMA	0.19 (131)		
Tajikistan	Asia	TJK	0.18 (132)		
Togo	África	TGO	0.18 (133)		
Rwanda	África	RWA	0.18 (134)		
Timor-Leste	Asia	TLS	0.18 (135)		
Uruguay	América	URY	0.18 (136)		
Hong Kong SAR, China	Asia	HKG	0.17 (137)		
Malta	África	MLT	0.17 (138)		
Peru	América	PER	0.17 (139)		
Maldives	Asia	MDV	0.17 (140)		
Belize	América	BLZ	0.17 (141)		
Cote d'Ivoire	África	CIV	0.16 (142)		
Paraguay	América	PRY	0.16 (143)		
Bolivia	América	BOL	0.16 (144)		
Benin	África	BEN	0.16 (145)		
Malaysia	Asia	MYS	0.15 (146)		
Iceland	Europa	ISL	0.15 (147)		0.51 (42)
Papua New Guinea	Oceanía	PNG	0.15 (148)		
Malawi	África	MWI	0.15 (149)		
Guinea	África	GIN	0.15 (150)		
Madagascar	África	MDG	0.15 (151)		
Macedonia, FYR	Europa	MKD	0.15 (152)		0.19 (49)
China Taipei	Asia	TPE	0.14 (153)	14	
Sierra Leone	África	SLE	0.14 (154)		

Table 4. (Cont.) Countries' Efficiency in Participation

Country	Region	Code	World	Position in top 15 GDP	Europe
Niger	África	NER	0.14 (155)		
Iraq	África	IRQ	0.14 (156)		
Albania	Europa	ALB	0.14 (157)		0.16 (50)
Vietnam	Asia	VNM	0.14 (158)		
Costa Rica	América	CRI	0.14 (159)		
Lao PDR	Asia	LAO	0.13 (160)		
West Bank and Gaza	África	PSE	0.13 (161)		
Mali	África	MLI	0.13 (162)		
El Salvador	América	SLV	0.13 (163)		
Gabon	África	GAB	0.13 (164)		
Mozambique	África	MOZ	0.12 (165)		
Singapore	Asia	SGP	0.12 (166)		
Nepal	Asia	NPL	0.12 (167)		
Zambia	África	ZMB	0.12 (168)		
Turkmenistan	Asia	TKM	0.12 (169)		
Burkina Faso	África	BFA	0.12 (170)		
Panama	América	PAN	0.11 (171)		
Cambodia	Asia	KHM	0.11 (172)		
Nicaragua	América	NIC	0.11 (173)		
Bhutan	Asia	BTN	0.11 (174)		
Luxembourg	Europa	LUX	0.11 (175)		0.41 (44)
Liberia	África	LBR	0.11 (176)		
Lebanon	África	LBN	0.11 (177)		
Jordan	África	JOR	0.11 (178)		
Libya	África	LBY	0.11 (179)		
Liechtenstein	Europa	LIE	0.10 (180)		0.6 (37)
Monaco	Europa	MCO	0.10 (181)		0.59 (38)
Syrian Arab Republic	África	SYR	0.09 (182)		
Tanzania	África	TZA	0.09 (183)		
Indonesia	Asia	IDN	0.09 (184)	15	
Sri Lanka	Asia	LKA	0.09 (185)		
South Sudan	África	SSD	0.08 (186)		
Swaziland	África	SWZ	0.08 (187)		
Myanmar	Asia	MMR	0.08 (188)		

Table 4. (Cont.) Countries' Efficiency in Participation

Country	Region	Code	World	Position in top 15 GDP	Europe
Mauritania	África	MRT	0.07 (189)		
Philippines	Asia	PHL	0.07 (190)		
Somalia	África	SOM	0.07 (191)		
Brunei Darussalam	Asia	BRN	0.07 (192)		
United Arab Emirates	África	ARE	0.06 (193)		
Afghanistan	Asia	AFG	0.06 (194)		
Congo, Dem. Rep.	África	COD	0.06 (195)		
Yemen, Rep.	África	YEM	0.06 (196)		
Sudan	África	SDN	0.06 (197)		
Equatorial Guinea	África	GNQ	0.06 (198)		
Chad	África	TCD	0.05 (199)		
Saudi Arabia	África	SAU	0.05 (200)		
Bangladesh	Asia	BGD	0.05 (201)		
Oman	África	OMN	0.05 (202)		
Pakistan	Asia	PAK	0.04 (203)		
Guinea Ecuatorial	África	GUE	0.04 (204)		

Note: Ranking of countries in parentheses. The region refers to the continent to which each Olympic National Committee belongs.

The Cobb-Douglas estimates show decreasing returns to scale technologies, since the sum of the coefficients are statistically lower to one in both models (χ^2=374.26 and χ^2=77.99, respectively). The most efficient countries in the world are Fiji, Cook Islands, Ukraine, and Serbia, while in the European model the most efficient countries are Montenegro, Hungary, and Slovenia. If the analyzed sample consisted of the 15 countries with the highest GDP, the most efficient countries would be Australia, Brazil, and Spain. A possible explanation for the high efficiency of Australia is that the process of qualification in Oceania might be easier than in other continents. An explanation for the high efficiency of Brazil is that it was the host country, which involves direct participation in all sports competitions. However, there is no specific reason that explains Spain's success other than the organization of the sporting system.

Medals

Three different models are estimated with regard to the number of medals. The first one uses the number of medals. The second model uses a weighted measure of the number of medals, in which a gold medal is rated as three, a silver as two, and a bronze as one (labeled as 3-2-1 weighted medals). The last model includes the team-weighted number of medals, which is described in detail in the data section. As in the number of participants' model for the world, the population was rejected as the input when using the models of the three alternative medal outputs. Figure 2 shows the relationship between the number of medals and GDP for countries with at least one medal, since countries with no medal were excluded from the estimates. Finally, Figure 3 shows the relationship between the 3-2-1 weighted number of medals and GDP.

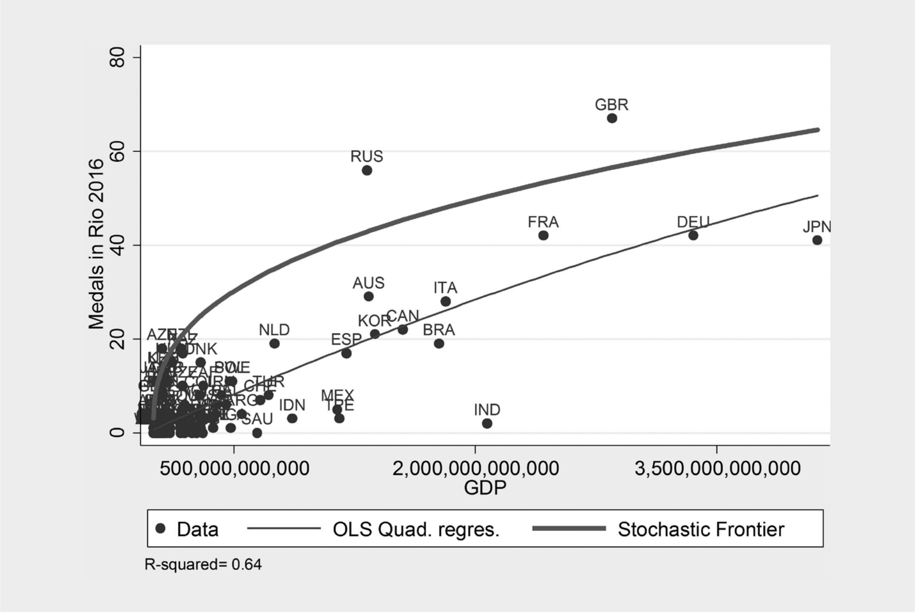

Figure 2. Relationship between number of medals and GDP in Rio 2016

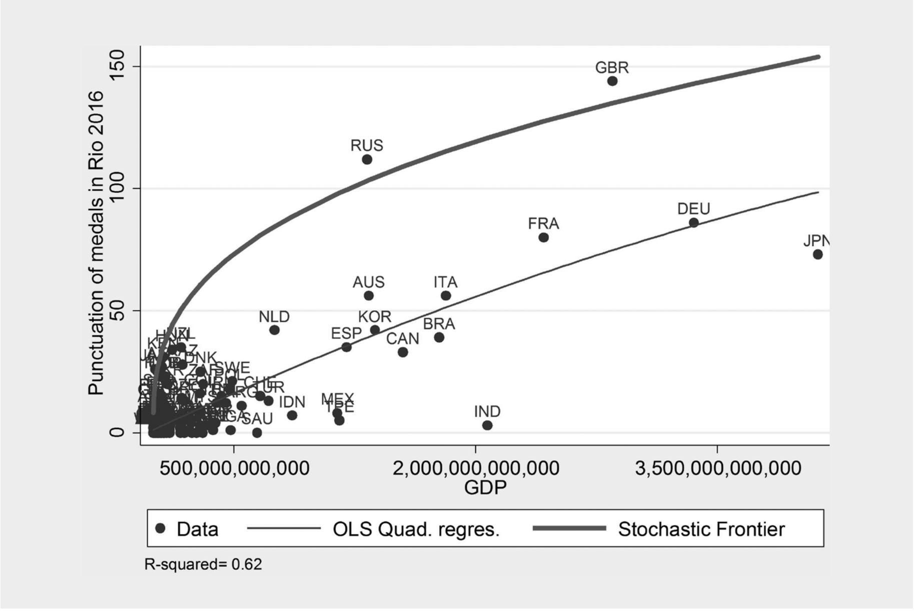

Figure 3. Relationship between 3-2-1 weighted number of medals and GDP in Rio 2016

The R-squared values are 0.64 and 0.62 for the number of medals and the 3-2-1 weighted medals, respectively, which is lower than it is for the participation models. Two countries are clearly located above the frontier, namely Russia and the United Kingdom, while India is clearly located below the frontier. Table 5 shows the preferred estimates for the number of medals and the 3-2-1 weighted medals, while Table 6 shows the efficiencies associated with these models.

Table 5. Estimates of Preferred Models for Number and 3-2-1 Weighted Medals

	Number of medals	**3-2-1 weighted medals**
Constant	-6.319***	-5.215***
GDP	0.361***	0.353***
σ_u	1.726***	1.472***
σ_v	0.294***	0.242
λ	5.869***	6.083***
Log-likelihood	-118.503	-126.073
Number of observations	84	84
Distribution of *u*	Half normal	Truncated normal

Note: * p<0.10, ** p<0.05, *** p<0.01

Table 6. Countries' Efficiencies in Number of Medals and 3-2-1 Weighted Medals

Country	**Eff. number of medals**	**Eff. 3-2-1 weighted medals**	**Country**
Azerbaijan	0.86 (1)	0.75 (5)	Tunisia
Jamaica	0.86 (2)	0.88 (1)	Romania
Russia	0.86 (3)	0.85 (2)	Turkey
United Kingdom	0.84 (4)	0.84 (3)	Bulgaria
Kenya	0.78 (5)	0.78 (4)	Thailand
Uzbekistan	0.77 (6)	0.63 (10)	Switzerland
Korea, Rep.	0.77 (7)	0.68 (8)	Burundi
New Zealand	0.77 (8)	0.68 (9)	Belgium
Georgia	0.75 (9)	0.58 (14)	Malaysia
Hungary	0.75 (10)	0.73 (6)	Fiji
Kazakhstan	0.74 (11)	0.55 (16)	Cote d'Ivoire
France	0.73 (12)	0.62 (11)	Bahrain
Croatia	0.72 (13)	0.69 (7)	Kosovo
Cuba	0.69 (14)	0.61 (12)	Moldova
Germany	0.68 (15)	0.60 (13)	Niger
Serbia	0.67 (16)	0.55 (15)	Tajikistan
Ukraine	0.67 (17)	0.51 (18)	Norway

Table 6. (Cont.) Countries' Efficiencies in Number of Medals and 3-2-1 Weighted Medals

Country	**Eff. number of medals**	**Eff. 3-2-1 weighted medals**	**Country**
Australia	0.67 (18)	0.55 (17)	Argentina
Belarus	0.66 (19)	0.46 (23)	Mexico
Japan	0.64 (20)	0.48 (22)	Egypt
Denmark	0.61 (21)	0.42 (24)	Venezuela, RB
Italy	0.60 (22)	0.49 (20)	Estonia
Ethiopia	0.58 (23)	0.35 (27)	Algeria
Netherlands	0.57 (24)	0.50 (19)	Trinidad and Tobago
Armenia	0.56 (25)	0.49 (21)	Vietnam
Canada	0.51 (26)	0.31 (30)	Ireland
Korea, Rep.	0.51 (27)	0.41 (25)	Jordan
Czech Republic	0.50 (28)	0.28 (32)	Indonesia
Spain	0.44 (29)	0.36 (26)	Israel
Brazil	0.43 (30)	0.35 (28)	China Taipei
South Africa	0.42 (31)	0.33 (29)	Dominican Republic
Poland	0.40 (32)	0.26 (36)	Morocco
Sweden	0.39 (33)	0.30 (31)	Puerto Rico
Lithuania	0.35 (34)	0.17 (48)	Qatar
Slovenia	0.35 (35)	0.27 (34)	Portugal
Colombia	0.35 (36)	0.27 (33)	Finland
Grenada	0.34 (37)	0.26 (38)	Philippines
Bahamas, The	0.31 (38)	0.23 (39)	Singapore
Iran, Isl. Rep.	0.30 (39)	0.23 (41)	India
Greece	0.30 (40)	0.26 (37)	United Arab Emirates
Mongolia	0.28 (41)	0.16 (52)	Austria
Slovak Republic	0.27 (42)	0.26 (35)	Nigeria

The results show that the production functions show statistically significant decreasing returns to scale. In this case, the elasticities are close to 0.35. The most efficient countries in the model using the number of medals are Azerbaijan, Jamaica, Russia, the United Kingdom, and Kenya. In the 3-2-1 weighted model, Azerbaijan changed from the first to the fifth position.

Tables 7 and 8 show the preferred model of the team weighted medals and the associated efficiencies, respectively. A very similar list is obtained.

Table 7. Estimates of Preferred Models for Team Weighted Medals

Constant	-6.644***
GDP	0.378***
σ_u	1.729***
σ_v	0.321***
λ	5.395***
Log-likelihood	-119.71
Number of observations	84

Note: * p<0.10, ** p<0.05, *** p<0.01

Table 8. Countries' Efficiency in Team Weighted Number of Medals

Country	**Efficiency**	**Country**	**Efficiency**
Jamaica	0.87 (1)	Bulgaria	0.29 (43)
Russia	0.85 (2)	Iran, Islamic Rep.	0.27 (44)
United Kingdom	0.84 (3)	Mongolia	0.27 (45)
Azerbaijan	0.84 (4)	Tunisia	0.25 (46)
Serbia	0.80 (5)	Belgium	0.24 (47)
New Zealand	0.77 (6)	Malaysia	0.23 (48)
Kenya	0.74 (7)	Turkey	0.23 (49)
Korea, Dem. People's Rep.	0.74 (8)	Burundi	0.22 (50)
Hungary	0.74 (9)	Thailand	0.21 (51)
Croatia	0.74 (10)	Switzerland	0.21 (52)
Uzbekistan	0.73 (11)	Norway	0.21 (53)
Georgia	0.72 (12)	Cote d'Ivoire	0.19 (54)
Germany	0.71 (13)	Bahrain	0.18 (55)
France	0.71 (14)	Argentina	0.17 (56)
Australia	0.69 (15)	Kosovo	0.17 (57)
Kazakhstan	0.69 (16)	Moldova	0.17 (58)
Denmark	0.66 (17)	Niger	0.16 (59)
Ukraine	0.65 (18)	Tajikistan	0.16 (60)
Cuba	0.65 (19)	Trinidad and Tobago	0.16 (61)
Belarus	0.64 (20)	Mexico	0.12 (62)
Italy	0.61 (21)	Egypt, Arab Rep.	0.12 (63)
Japan	0.61 (22)	Venezuela, RB	0.11 (64)
Netherlands	0.60 (23)	Estonia	0.11 (65)
Ethiopia	0.54 (24)	Ireland	0.10 (66)
Canada	0.54 (25)	Algeria	0.10 (67)
Armenia	0.53 (26)	Vietnam	0.10 (68)

Table 8. (Cont.) Countries' Efficiency in Team Weighted Number of Medals

Country	Efficiency	Country	Efficiency
Czech Republic	0.51 (27)	Indonesia	0.09 (69)
Korea, Rep.	0.48 (28)	Jordan	0.09 (70)
Spain	0.46 (29)	China Taipei	0.09 (71)
Brazil	0.44 (30)	Israel	0.08 (72)
South Africa	0.43 (31)	Nigeria	0.08 (73)
Lithuania	0.40 (32)	Dominican Republic	0.07 (74)
Poland	0.40 (33)	Morocco	0.06 (75)
Fiji	0.40 (34)	Puerto Rico	0.06 (76)
Sweden	0.39 (35)	Qatar	0.05 (77)
Bahamas, The	0.38 (36)	Austria	0.05 (78)
Grenada	0.34 (37)	Portugal	0.05 (79)
Romania	0.32 (38)	Finland	0.05 (80)
Slovenia	0.32 (39)	Philippines	0.04 (81)
Colombia	0.31 (40)	Singapore	0.04 (82)
Slovak Republic	0.31 (41)	India	0.04 (83)
Greece	0.29 (42)	United Arab Emirates	0.04 (84)

Zero-Medal Countries

The inputs used in this model are the same as those used in the stochastic frontier models (i.e., GDP and population). However, population is not considered in the final model due to the hypothesis testing results.

Table 9. Probit Estimates. Dependent Variable: 1 if the Country Obtains a Medal in Rio 2016.

Variable	Coefficient
Constant	0.817***
GDP	5.51e-12***
Log-Likelihood	-98.11
Observations	204
Pseudo-R2	0.29

As expected, the GDP is positively correlated with the likelihood of obtaining a medal. Table 10 shows the efficiencies computed using this method. The results show that the higher the GDP, the lower the efficiency. Thus, most of the countries hold efficiency values in the range of 0.70 and 0.79. However, a few countries with higher GDP hold efficiency values below 0.40. This finding is interesting and has managerial implications for countries participating in the Olympic Games that do not obtain medals but still actively participate in the event.

Table 10. "Efficiency Scores" of Countries with Zero Medals

Country	Efficiency	Country	Efficiency
Saudi Arabia	0.00	Equatorial Guinea	0.78
Hong Kong SAR, China	0.19	South Sudan	0.78
Pakistan	0.25	Haiti	0.78
Chile	0.31	Congo, Rep.	0.78
Bangladesh	0.40	Benin	0.78
Peru	0.40	Rwanda	0.78
Iraq	0.46	Guinea	0.78
Angola	0.60	Kyrgyz Republic	0.78
Ecuador	0.60	Malawi	0.78
Sudan	0.64	Monaco	0.78
Sri Lanka	0.64	Somalia	0.78
Oman	0.67	Bermuda	0.78
Myanmar	0.68	Liechtenstein	0.78
Guatemala	0.68	Mauritania	0.78
Luxembourg	0.69	Suriname	0.79
Uruguay	0.70	Sierra Leone	0.79
Panama	0.70	Barbados	0.79
Costa Rica	0.70	Swaziland	0.79
Lebanon	0.71	Togo	0.79
Tanzania	0.72	Montenegro	0.79
Syrian Arab Republic	0.72	Eritrea	0.79
Ghana	0.73	Andorra	0.79
Turkmenistan	0.73	Guyana	0.79
Yemen, Rep.	0.73	Maldives	0.79
Congo, Dem. Rep.	0.73	Guam	0.79
Bolivia	0.74	Aruba	0.79
Cameroon	0.74	Lesotho	0.79
Libya	0.74	Liberia	0.79
Paraguay	0.75	Virgin Islands (US)	0.79
Latvia	0.75	Bhutan	0.79
Uganda	0.75	San Marino	0.79
El Salvador	0.75	Belize	0.79
Guinea Ecuatorial	0.76	Cabo Verde	0.79
Zambia	0.76	Djibouti	0.79
Nepal	0.76	Central African Republic	0.79
Honduras	0.76	Seychelles	0.79

Table 10. (Cont.) "Efficiency Scores" of Countries with Zero Medals

Country	Efficiency	Country	Efficiency
Cyprus	0.76	St. Lucia	0.79
Afghanistan	0.76	Timor-Leste	0.79
Cambodia	0.76	Antigua and Barbuda	0.79
Papua New Guinea	0.77	Solomon Islands	0.79
Iceland	0.77	Guinea-Bissau	0.79
Bosnia and Herzegovina	0.77	Cayman Islands	0.79
Brunei Darussalam	0.77	St. Kitts and Nevis	0.79
Mozambique	0.77	Gambia, The	0.79
Botswana	0.77	British Virgin Islands	0.79
Gabon	0.77	Vanuatu	0.79
Zimbabwe	0.77	Samoa	0.79
Senegal	0.77	St. Vincent and the Grenadines	0.79
Mali	0.77	American Samoa	0.79
Nicaragua	0.77	Comoros	0.79
West Bank and Gaza	0.77	Dominica	0.79
Lao PDR	0.77	Tonga	0.79
Namibia	0.77	Sao Tome and Principe	0.79
Mauritius	0.77	Micronesia, Fed. Sts.	0.79
Albania	0.77	Palau	0.79
Burkina Faso	0.78	Marshall Islands	0.79
Chad	0.78	Nauru	0.79
Macedonia, FYR	0.78	Kiribati	0.79
Madagascar	0.78	Cook Islands	0.79
Malta	0.78	Tuvalu	0.79

Discussion

The rankings that result from the implementation of several methods to assess countries' efficiency show significant differences, even when applied to the same Olympic Games. For example, in the Athens 2004 Olympic Games, the United States appeared fourth in the ranking of Zhang et al. (2009) and 64th in Azizi and Wang's (2013) ranking. In Beijing 2008, China appeared 54th in Chiang, Hwang, and Liu's (2011) ranking and third in Calzada-Infante and Lozano's (2016). With regard to Rio 2016, as this is one of the first research papers, the results cannot yet be compared. However, we may use Li et al. (2015) as an immediate reference. The authors analyzed the overall efficiency in London 2012, which included both participation and competition results. The results of this comparison need to be considered very cautiously due to many influential factors. However, we see countries such as Jamaica, Russia, Kenya, and the United Kingdom appearing in high-ranking positions. Moreover, it is also worth noting the case of Montenegro, which was ranked eighth by Li et al. (2015) and fifth in our ranking of efficiency in terms of participation. However, this country is not listed in any of the medal rankings, as Montenegrin athletes did not win any medals in Rio 2016. This example reveals the need for rankings of efficiency that consider not only the results of the competition, but also participation.

This study uses several outputs, which are included in the models of efficiency. The outputs used to determine countries' efficiencies are the number of participants, the number of medals, 3-2-1 weighted medals, and team-weighted medals. When exploring the relationship among the efficiencies, positive and large correlation coefficients (above 0.97) were found for the number of medals and its two weighted systems. However, correlation coefficients decrease (0.63-0.71) if the efficiencies considering the number of participants are compared to the other outputs. This is an interesting finding, and supports the idea of using the number of participants to calculate the efficiency of countries as it provides complementary information to the number of medal.

Finally, more research is needed to further develop these indicators in several directions. First, the number of athletes that a sport requires also affects the total number of participants for countries. For example, as a football (soccer) team will always increase the number of participants by 18 athletes, these 18 entries should be considered differently to 18 entries in athletics (track and field). Therefore, the use of an alternative weighting system that considers the number of participants with respect to the number of participants in each sport can help to develop the analyses of efficiency.[15] Second, in this paper we implement an objective measure to weight the number of participants, but it has some limitations. Does it have the same value for a country that earns a medal in the hammer throw than in the 100-meter dash? The answer is probably that a medal in the 100 meters has more value than the medal in the hammer throw, as the worldwide publicity/prestige for the country and the implications for the athlete are very different. Hence, the development of a methodology able to capture this difference is very interesting. Finally, the literature on countries' efficiency in the Olympic Games has neglected to identify the reasons why some countries are more efficient than others, and more importantly the steps for countries to follow in order to become more efficient. In this sense some questions need to be answered: Is it important to have a relevant university sport system? Is it relevant to have foreign coaches? Is it essential to have state-of-the-art sports facilities? The methodology used in Simar and Wilson (2007) or similar frameworks can help to further develop these issues.

Conclusions

The purpose of this study was to get a complete picture about the countries' efficiency in the Rio 2016 Olympic Games. Due to numerous factors that affect the ultimate success and achievement of medals, we consider the participation of athletes to be an important goal for the countries competing in the Olympic Games. Changes in the countries' efficiency rankings were found when the number of participants was included as the output in the models compared to the efficiencies calculated by including the number of medals. Moreover, the high correlation coefficients found between the outputs often used in the literature (i.e., number of medals and its medal-weighted systems) decreased when compared to the number of participants.

This study also contributes to the literature by incorporating the value of medals won in team and individual sports. Team sports require more than one athlete to compete. Thus, countries need to produce a greater number of professional athletes to qualify for international meetings. An effort has been made in this study to include this effect in the analysis of countries' efficiency in the Olympic Games.

The countries that do not obtain medals in the Olympic Games are always excluded from efficiency analyses, as the frontier methods (DEA and stochastic frontier models) do not consider them. In this analysis, we use the predicted probability of obtaining at least one medal to provide these countries with values of efficiency. Although many of these countries show similar results, differences do exist. Thus, this analysis has implications for zero-medal countries that do not have the same economic resources.

Furthermore, we believe that some team sports (e.g., basketball) might have a greater impact on nations' prestige than other individual (e.g., archery) and team sports (e.g., canoe double). Hence, further research should place an emphasis on determining the relative importance of sports and disciplines when assessing the final performance of countries.

Table A1. Estimates of Participation in All Models

	World				**Europe**			
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 1**	**Model 2**	**Model 3**	**Model 4**
Constant	-7.186***	2.978***	-7.702***	4.639***	-8.460***	4.911***	-6.643***	4.732***
GDP	0.481***	0.494***	0.593***	0.564***	0.524***	0.531***	0.166*	0.070***
GDP2		0.079***		-0.047		-0.063		-0.117***
Population			-0.142***	-0.122***			0.450***	0.484***
Population2				-0.210***				-0.213***
GDP · Population				0.149***				0.164***
σ_u	0.930***	0.413	0.876	0.759	0.935***	0.85	0.488***	0.655
σ_v	0.377	0.809***	0.387	0.337	0.402***	0.355	0.308***	1.21E-08
λ	2.467***	0.511	2.264	2.252	2.394***	1.584	2.467***	5.42E+07
Log-likelihood	-262.954	-255.397	-258.332	-244.686	-51.376	-50.394	-38.953	-28.873
Number of observations	204	204	204	204	50	50	50	50
Distribution of *u*	TN	HN	TN	TN	HN	TN	E	E
Preferred	Yes	No	No	No	No	No	Yes	No

Note: * p<0.10, ** p<0.05, *** p<0.01. In parenthesis standard errors. TN-truncated normal, HN-half normal, E-exponential. The efficiencies associated with these models can be requested from the authors by email.

Table A2. Estimates of Medals in All Models

	Number of medals				3-2-1weighted medals			
	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 1**	**Model 2**	**Model 3**	**Model 4**
Constant	-6.319***	2.364***	-6.604***	1.225	-5.215***	3.090***	-5.361***	3.186***
GDP	0.361***	0.257**	0.318***	-0.002	0.353***	0.201	0.316***	-0.018
GDP2		0.051		-0.005		0.077		0.007
Population			0.084	0.259**			0.065	0.323***
Population2				-0.504***				-0.431***
GDP · Population				0.259**				0.194**
σ_u	1.726***	1.734***	1.717***	0.071	1.472***	1.922***	1.490***	1.730***
σ_v	0.294***	0.274***	0.294***	0.921***	0.242	0.290***	0.255	0.354***
λ	5.869***	6.338***	5.847***	0.077	6.083***	6.639***	5.843***	4.881***
Log-likelihood	-118.503	-117.992	-118.100	-112.371	-126.073	-125.996	-125.875	-121.06
Number of observations	84	84	84	84	84	84	84	84
Distribution of *u*	HN	HN	HN	HN	TN	HN	TN	HN
Preferred	Yes	No	No	No	Yes	No	No	No

Note: * $p<0.10$, ** $p<0.05$, *** $p<0.01$. In parenthesis standard errors. TN-truncated normal, HN-half normal, E-exponential. The efficiencies associated with these models can be requested from the authors by email.

Table A3. Estimates of Team Weighted Medals

	Model 1	**Model 2**	**Model 3**	**Model 4**
Constant	-6.644***	2.479***	-6.785***	1.387
GDP	0.378***	0.239*	0.358***	0.016
GDP2		0.066		-0.01
Population			0.039	0.226*
Population2				-0.513***
GDP · Population				0.272**
σ_u	1.729***	1.764***	1.723***	0.153
σ_v	0.321***	0.267*	0.325***	0.934***
λ	5.395***	6.597***	5.298***	0.163
Log-likelihood	-119.71	-118.974	-119.631	-113.864
Number of observations	84	84	84	84
Distribution of u	HN	HN	HN	HN
Preferred	Yes	No	No	No

Note: ***$p<0.01$, **$p<0.05$, *$p<0.1$. In parenthesis standard errors.The efficiencies associated with these models can be requested from the authors by email.

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Endnotes

[1] A more detailed compendium of this body of literature is presented in the Literature Review section.

[2] It is usually referred as DEA. For a detailed overview, please see Cooper, Seiford, and Zhu (2011).

[3] In recent years, several papers have attempted to alleviate the deterministic nature of this methodology. Wen (2015) presented the milestones in the progression of uncertain DEA.

[4] For overviews of the topic, please see Álvarez and Arias (2014), and Kumbhakar, Wang, and Horncastle (2015).

[5] Hossain, Kamil, Baten and Mustafa (2012) explained fairly well the different strengths and weaknesses of both competing approaches: "*The main advantage of DEA is that it does not require any information more than input and output quantities. The efficiency is measured relative to the highest observed performance rather than an average. However, a DEA-based estimate is sensitive to Measurement errors or other noise in the data because DEA is deterministic and attributes all deviations from the frontier to inefficiencies. The strength of SFA is that it considers stochastic noise in data and also allows for the statistical testing of hypotheses concerning production structure and degree of inefficiency. Its main weaknesses are that it requires an explicit imposition of a particular parametric functional form representing the underlying technology and also an explicit distributional assumption for the inefficiency terms.*"

[6] Data for a few countries were not available from the World Bank database. In such cases, the data were obtained using alternative sources.

[7] It is important to note that the inputs for the production frontier for Olympic success should be money invested in sports competitions and people practicing sport. However, no reliable data exist, and GDP and population were used as proxies. In so doing, it was assumed that countries enjoy sports, especially competitive sports, in the same way.

[8] China in table tennis, Spain in male tennis, USA in 100 meters, and Kenya in 3,000 meters steeplechase are some examples of this issue.

[9] Results from the other continents are available upon request.

[10] For instance, South Africa refused to participate in female hockey and some other countries establish additional requirements than those established by the IOC. This is especially relevant in athletics and swimming.

[11] For instance, Lui and Suen (2008), and Mitchell and Stewart (2007) used the 3-2-1 weights for gold, silver, and bronze, while Moosa and Smith (2004) used 0.6-0.3-0.1.

[12] We thank a participant in the 2016 European Conference on Sports Economics for pointing out this issue.

[13] Other possibilities could have also been employed but this one produces sensible and objective differences among the number of participants.

[14] Once again, estimates and results are available upon request.

[15] This idea for future research was introduced by a referee in the peer-review process.

Authors' Note

The authors would like to thank Daniel Solís for his valuable comments and María Moraga, who was not able to work on the paper due to her time-demanding master's in economics program, but her undergraduate thesis analyzing the efficiency in London 2012 was really important for this paper.