Eco-efficiency Assessment at Firm Level: An Application to the Mining Sector

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Abstract. Assessing firms' Eco-efficiency is important to ensure they succeed in creating wealth without compromising the needs of future generations. This work aims to extend the Eco-efficiency concept by including in the assessment new features related to environmental benefits. Eco-efficiency is evaluated using a DEA model specified with a Directional Distance Function. The new methodology proposed in this paper is illustrated with an application to world-class mining companies, whose results and managerial implications are discussed.

Keywords: Eco-efficiency, Directional Distance Function, Mining Companies.

1 Introduction

The Eco-efficiency concept has gained momentum during the 1990s, with the release of two seminal publications: "Environmental rationality" (Schaltegger and Sturm, 1990) and "Changing Course" (Schmidheiny, 1992). As a result, eco-efficiency issues began to figure prominently in the scientific fields of Sustainable Development and Business Management (e.g., Choucri, 1995; Cramer, 1997; Esty and Porter, 1998). In the transition to the 2000s, the World Business council of Sustainable Development (WBCSD) has described Eco-efficiency at the firm level as follows:

> "*keeping the business competitive while reducing material and energy requirements, minimizing the dispersion of toxic wastes and maximizing the sustainable use of renewable resources"* (WBCSD, 2000, p.10).

The literature includes a variety of studies that intend to quantitatively reflect the Schmidheiny's definition in contexts involving several indicators, such as Glauser and Müller, 1997; Kortelainen and Kuosmanen, 2007; Zhang et al., 2008; Picazo-Tadeo and Prior, 2009. These applications have expressed Eco-efficiency by ratios of the economic achievements to the environmental burdens associated with wealth generation. In the presence of multiple indicators, these have to be aggregated using predefined or optimized weights. The studies available in the literature do not cover entirely the WBCSD criteria for assessing Eco-efficiency at the firm level, specially concerning the sustainable use of renewable resources.

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The first contribution of this paper is to provide a comprehensive view of firms Eco-efficiency by using an ehanced range of indicators. These indicators are aligned with the Eco-efficiency criteria of WBCSD and are classified in three dimenions: economic benefits (e.g., value-added), environmental benefits (e.g., use of renewable resources) and environemntal burdens (e.g., emissions of pollutants). The second contribution of this paper is the development of an enhanced model, based on a directional distance function (DDF), which proposes simultaneous adjustsments to indicators from different categories. The third contribution consists of the application of the model to world-class mining firms. Mineral exploitation can be considered one of the most environmentally impacting economic activities in the planet, so the assessment of good environmental practices in this sector is clearly an important issue.

This paper is organized as follows: section 2 describes the enconomic and environmental indicators used for assessing Eco-efficiency of world-class mining companies. Section 3 presents the methodology of the enhanced Eco-efficiency assessment and describes the new model specified with a DDF. Section 4 discusses the results and section 5 concludes the paper.

2 Indicators Used for Eco-efficiency Assessment

The indicators selected for the Eco-efficiency assessment of mining companies, reported on Table 1, are aligned with the 10 principles of the International Council on Mining and Metals (ICMM). The ICMM sectorial initiative aligns with important international sustainability guidelines, such as ISO (2003) and GRI (2013).

Table 1 Indicators used for Eco-efficiency assessment

Dimension	Category	Indicator
Economic	Benefits (y_r)	Economic value-added (y_1)
Environmental	Benefits (h_q)	Renewable energy use (h_1)
		Recycled materials use (h_2)
		Water recycled or reused (h_3)
		Conservation areas supported (h_4)
		Investments on environment (h_5)
	Burdens (p_k)	Non-renewable energy use (p_1)
		Withdraw water use (p_2)
		Waste produced (solid and liquid) (p_3)
		Air emissions (GHG and pollutants) (p_4)
		Volume of significant spills (p_5)
		Total environmental fines (p_6)

For the economic dimension, economic benefits are related to firms' wealth generation. These are represented by the annual economic value-added.

The environmental dimension of this framework includes two categories of indicators: the burdens to be minimized (e.g. air emissions) and the benefits to be maximized (e.g. conservation areas supported). In the mining sector, waste generation is an issue of major concern. The amounts of mining waste generation depend on the quality of the extraction and transportation processes as well as on the ore contents in soil. This study only considers wastes from packaging, raw and hazardous materials, to ensure data comparability across firms.

The list of companies analyzed and the corresponding values of the indicators used for the Eco-efficiency assessment are available in the appendix (Table A.1 and A.2). The companies studied hold several mines around the world and may exploit various types of ores (e.g., Vale (U1) is a multinational company that exploits primarily metallic ores and operates in ten different countries). Despite the firms' different mix of products, they should observe the same international standards for environmental and economic performance, so their comparison based on the indicators reported on Table 1 is legitimate.

3 The DEA-Based Model for Extended Eco-efficiency

The quantification of the extended Eco-efficiency measure was accomplished using a Directional Distance Function (DDF) model, first proposed by Chambers et al. (1996). The formulation shown in (1) follows the approach adopted by Färe et al. (2014), which involves an equal treatment of all indicators representing burdens to be minimized, irrespectively of their intrinsic nature being an input (e.g., withdraw water use) or an output (e.g., air emissions). The assessment here proposed allows pursuing improvements of eco-efficiency by simultaneously decreasing environmental burdens and increasing benefits.

$$Max\ \beta_k \tag{1}$$

$$\sum_j \lambda_j y_{rj} \geq y_{rk} + \beta_k g_{y_r} \qquad r = 1, \dots, R \tag{1.1}$$

$$\sum_j \lambda_j h_{qj} \geq h_{qk} + \beta_k g_{h_q} \qquad q = 1, \dots, Q \tag{1.2}$$

$$\sum_j \lambda_j p_{lj} \leq p_{lk} - \beta_k g_{p_l} \qquad l = 1, \dots, L \tag{1.3}$$

$$\lambda_j \geq 0 \qquad j = 1, \dots, N$$

$$\beta_k \geq 0$$

In model (1), y_{rj} is the amount of economic benefit *r* generated by DMU j (with $r = 1, \dots, R$ and $j = 1, \dots, N$), h_{qj} corresponds to the environmental benefit q generated by DMU j (with $q = 1, \dots, Q$ and $j = 1, \dots, N$), and p_l is the environmental burden l generated by DMU j (with $l = 1, \dots, L$ and $j = 1, \dots, N$).

The indicators used for representing these dimensions in the assessment of mining firms are those presented in Table 1. The index k designates the DMU under assessment in each linear programming model. The directional vector $\boldsymbol{g} = \left(g_{y_r}, g_{h_q}, -g_{p_l} \right)$ specifies the direction of projection to the frontier used to obtain the Eco-efficiency score. Positive values mean that the indicators should be increased, whereas negative values mean that the indicators should be reduced. The components of the directional vector specified in the empirical study correspond to the observed values of the indicators for the DMU k under assessment. This allows a radial interpretation of the objective function value obtained by the DDF model. The left-hand side of the constraints (1.1) to (1.3) describes the convex combination of the peers, corresponding to the point on the frontier against which DMU k is compared to estimate the Eco-efficiency level.

Variable β_k is a measure of Eco-efficiency. It corresponds to the rate by which the benefits and burdens of DMU k can be adjusted to achieve eco-efficient levels. When $\beta_k = 0$ the DMU can no longer proportionally enhance its Eco-efficiency indicators and thus it is classified as efficient. Values of β_k greater than zero correspond to inefficient DMUs. The Eco-efficiency score can be here interpreted as the maximum feasible radial adjustment to benefits and burdens leading to firms operation at the frontier of the production possibility set.

4 Application: Mining Companies Assessment

Our real world application explored a sample of 25 world-class mining companies that published their environmental and ecological outcomes in sustainability reports. The reference year of assessment is 2011. All the companies studied are affiliated to the Global Reporting Initiative (GRI) and 80% of them are members of the ICMM.

The dataset had variables with missing data (3% of all data) and values equal to zero (16% of all data). For the indicators to be maximized (y_r and h_q), the missing data were replaced by the lowest positive value observed in the corresponding variable. For the indicators to be minimized (p_k), the missing values were replaced by the highest value observed in the corresponding variable. These procedures guarantee that no DMU assessed will be unduly benefited for not having data available for some indicators. Zeros were always replaced by the lowest value of the corresponding variable, in order to improve the discrimination of the model.

Three alternative scenarios were exploded to investigate inefficiencies using different perspectives. These allow the identification of improvements aligned with specific managerial preferences. Scenario 1 focuses on improvements to the environmental dimension, using the directional vector $\boldsymbol{g_1} = \left(0, h_{qk}, -p_{lk} \right)$. Scenario 2 allows exploring the potential for reducing exclusively environmental burdens, using the directional vector $\boldsymbol{g_2} = (0, 0, -p_{lk})$. Scenario 3 explores potential enhancements of environmental benefits according to the directional vector $\boldsymbol{g_3} = \left(0, h_{qk}, 0\right)$.

The results of the extended Eco-efficiency assessment revealed that 20 firms can be considered efficient in all scenarios explored. The score for the inefficient firms is reported in Table 2, alongside their ranking. The Eco-efficiency score $_k$ depends on the preferences specified in the directional vector regarding the performance improvements. For example, in the case of Sumitomo (U23), the radial improvement potential considering a proportional adjustment to all environmental indicators is 0.711 (see scenario 1). When each environmental category is explored in detail, we can conclude that the greatest potential for improvement lies on indicators representing environmental benefits, as the proportional improvement in scenario 3 ($_{U23}$ = 4.926) is higher than the proportional reduction to environmental burdens explored in scenario 2 ($_{U23}$ = 0.831). Regarding the ranking of inefficient DMUs, Table 2 shows that the ordering is not affected by the perspective of the assessment.

Table 2 Values of β_k for the extended Eco-efficiency assessment in 3 scenarios

	Scenario 1		**Scenario 2**		**Scenario 3**	
	$\boldsymbol{\beta_k}$	**Rank**	$\boldsymbol{\beta_k}$	**Rank**	$\boldsymbol{\beta_k}$	**Rank**
Vale (U1)	0.108	1	0.195	1	0.242	1
Yamana (U15)	0.377	2	0.547	2	1.208	2
Gold Fields (U17)	0.411	3	0.583	3	1.395	3
Hydro (U8)	0.637	4	0.779	4	3.512	4
Sumitomo (U23)	0.711	5	0.831	5	4.926	5

Model (1) also enables obtaining proportional improvement targets for each indicator, calculated using the Eco-efficiency score β_k. Table 3 presents the results obtained for Gold Fields (U17) to illustrate the interpretation of these results.

Table 3 Targets for Gold Field (U17)

	Observed	**Scenario 1 Target**	**Scenario 2 Target**	**Scenario 3 Target**
Enconomic Benefits				
Value-added (y_1)	3688.000	–	–	–
Environmental Benefits				
Renewable energy use (h_1)	0. 000	0.000	–	0.000
Recycled materials use (h_2)	*	*	*	*
Water recycled or reused (h_3)	33.450	47.198	–	80.11275
Conservation areas suported (h_4)	0. 000	0.000	–	0.000
Investiments on environment (h_5)	677. 000	955.247	–	1621.415
Environmental Burdens				
Non-renewable energy use (p_1)	5469784. 000	3221702.776	2280899.928	–
Withdraw water use (p_2)	78236. 000	46081.004	32624.412	–
Waste produced (p_3)	15000000. 000	8835000.000	6255000.000	–
Air emissions (p_4)	5.298	3.121	2.209	–
Volume of significant spills (p_5)	47000. 000	27683.000	19599.000	–
Environmental Fines (P_6)	*	*	*	*

* missing value

Considering scenario 1, Gold Fields (U17) obtained an Eco-efficiency score equal to 0.411. This means that this firm should increase environmental benefits proportionally by the factor $(1 + \beta_k)$ and reduce the burdens by the factor $(1 - \beta_k)$. For example, the indicator of withdraw water use (p_2) could reduce from 78236.000 to 46081.004 (i.e. 78236 × (1–0.411) = 46081.004) and investments on environment (h_5) could increase from 677.000 million USD to 955.247 million USD (i.e. 677.000 × (1+0.411) = 955.247). When exploring the potential for environmental benefits in isolation (scenario 3), without seeking changes to indicators from other categories, the target for investments on environment (h_5) is more demanding, reaching 1621415 million USD (i.e. 677.000 × (1+1.395) = 1621.415). A similar interpretation can be done for scenario 2, as the potential for reductions to environmental burdens in isolation is higher than when the firms have to focus on simultaneous improvements to environmental benefits and reductions to burdens.

5 Conclusions

In this study, we proposed an enhanced Eco-efficiency assessment model, aligned with the definition of the WBCSD. It advances the traditional measure of Eco-efficiency from the ratio of economic benefits to environmental burdens in order to also include environmental benefits related to companies' activities. Incorporating these new features in the Eco-efficiency analysis can help the design of policies to improve economic performance alongside avoiding undesirable impacts on the ecosystem or the exhaustion of natural resources. This can be achieved by either promoting the use of environmental friendly resources or investing in conservation plans.

By widening the focus of the Eco-efficiency evaluation, we believe this study succeeded in proposing a new framework to assess mining companies. In this sector, the efforts to reduce environmental impacts are particularly important. With the use of the model proposed in this paper, the companies that invest on environmental benefits can be credited with higher Eco-efficiency scores. Another noteworthy feature of this study is the possibility of setting reduction goals for air emissions, waste generation and materials consumption, alongside improvements to economic and environmental indicators that are associated with benefits both for the firms and the planet. Furthermore, customized directional vectors allowed exploring alternative scenarios for improvements in Eco-efficiency, aligned with specific managerial preferences.

We foresee as future research the assessment of Eco-efficiency over time, so that the evolution of environmental practices can be tracked systematically.

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Appendix

Table A.1 Companies dataset of benefits

Companies	y_1 mil. USD	h_1 GJ	h_2 mil. m^3	h_3 mil. m^3	h_4 ha	h_5 mil. USD
Vale (U1)	85.000	24000.000	0.000	953.000	2250.000	525.000
Alcoa (U2)	545.008	0.000	59.890	0.000	27816.460	8.132
Anglo American Ni (U3)	398.000	1106182.990	0.000	2823.200	11000.000	69.222
Rio Norte (U4)	0.778	1.000	2378.700	39.864	429600.000	9.280
Sama (U5)	94.609	0.000	62.760	0.000	2500.000	2.171
Samarco (U6)	1767.741	0.000	663.360	158.547	2228.490	94.300
Votorantim (U7)	5383.523	0.000	80.260	227.220	0.000	150.130
Alunorte Hydro (U8)	70.588	0.000	0.320	11.613	4600.000	10.691
Kinkross (U9)	1382.100	0.000	104.600	321.000	5661.000	15.000
Usiminas (U10)	1493.254	178680436.000	1.670	44.603	1250.000	92.838
Rio Tinto (U11)	38193.000	3000000.000	368.400	327.600	348500.000	21.168
Barrick (U12)	13000.000	38700000.000	4.332	24.471	118400.000	100.000
BHP (U13)	72299.000	30000000.000	1.181	79.640	25100.000	7.820
Glencore (U14)	0.000	16400000.000	0.074	240.000	289.000	3015.000
Yamana (U15)	7.120	6738121.137	0.000	3012.874	32700.000	9.328
Nipon (U16)	221000.000	3600.000	0.026	115.452	870.940	0.000
Gold Field (U17)	3688.000	0.000	*	33.453	0.000	677.000
MitiSubish Materials (U18)	22423.700	0.000	19.100	406.636	28600.000	7780.862
Gold Corp (U19)	2626.000	0.000	0.000	107.500	343100.000	107.500
Teck (U20)	0.500	13394000.000	0.000	200.839	28025.000	200.839
ARM (U21)	1007.248	0.000	0.000	0.000	11891.000	2.171
Coldeco (U22)	23083.000	0.000	0.779	490.165	2.651	490.165
Sumitomo (U23)	1597.696	0.000	0.160	0.000	151.000	2.171
De Beers (U24)	6400.000	0.000	0.000	30.110	195640.000	30.110

*missing value

Table A.2 Companies dataset of environmental burdens

Companies	p_1 GJ	p_2 mil. m^3	p_3 tons	p_4 tons	p_5 m^3	p_6 mil. USD
Vale (U1)	179700.000	420.700	686.000	52190000.000	350.500	3019.000
Alcoa (U2)	55328005.000	0.205	80821.000	2886227.000	53.000	0.000
Anglo American Ni (U3)	4786.000	3529.000	3729.000	2070.930	0.727	*
Rio Norte (U4)	0.778	18.163	2587.900	320777.000	18.163	0.000
Sama (U5)	948.714	1.694	125.080	38206.000	0.200	0.000
Samarco (U6)	14208818.400	2083.664	19138.120	783350.300	0.000	1.770
Votorantim (U7)	294281.974	227.221	4270.000	26000000.000	0.000	0.109
Alunorte Hydro (U8)	170190000.000	34.780	8178.460	929110.000	0.000	5.375
Kinkross (U9)	14191000.000	104.528	222.553	1.220	0.000	2700.000
Usiminas (U10)	179976814.000	181.608	17.633	12635316.000	0.000	0.505
Rio Tinto (U11)	516000000.000	465.000	1166.600	631170.124	3.000	80150.000
Barrick (U12)	54408761.000	57.100	45.548	50307341.005	45.548	764800.000
BHP (U13)	286180000.000	181.000	35.367	21000.000	0.000	2454.000
Glencore (U14)	164000000.000	500.000	500.000	130698.000	570.000	210000.000
Yamana (U15)	19818003.345	3766.092	3766.092	229365.357	*	29193.850
Nipon (U16)	16627000.000	21.453	21.453	0.005	0.000	0.000
Gold Field (U17)	5469784.000	78236.000	15000000.000	5.298	47000	*
MitiSubish Mat. (U18)	3923600.000	14.620	18557.000	24.290	0.000	0.000
Gold Corp (U19)	15400000.000	144.800	490696.000	1.415	0.000	0.000

Table A.2 (*continued*)

Teck (U20)	30849.000	118.955	0.767	304.610	0.206	0.000
ARM (U21)	9179218.800	15091.358	0.444	2396.000	0.000	0.000
Coldeco (U22)	764.125	174.891	253.643	5592875.158	30.000	216.554
Sumitomo (U23)	31344106.000	31.500	5.415	4940628.000	*	*
De Beers (U24)	11590.000	7.110	1602.000	1450000.000	*	102600.000
Anglo Platinum (U25)	25170.000	18.980	1566.070	12000770.000	0.900	2000.000

*missing value