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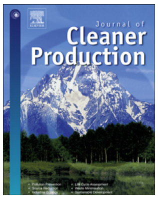

A Life Cycle Assessment study of iron ore mining

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ABSTRACT

This paper assessed the cradle-to-gate life cycle of an iron ore mining. The study was based on production data from an open pit mine located in the Iron Quadrangle/Brazil. The functional unit was defined as “one tonne of iron ore concentrate produced” and the data used were collected directly from the company's production reports covering the time of one year. The evaluation included the classification and characterization of life cycle impacts, not including normalization and weighting as well as sensitivity analysis of results. The evaluation of impacts used SimaPro-7, Ecoinvent 2.0, Eco indicator'99 and IPCC 2007. The results indicated that the use of grinding media in the processes is the main source of environmental impacts in the iron ore production chain, highlighting its contribution to life cycle impacts on human health and quality of ecosystems. Ore transportation by conveyor belts powered by electricity was more efficient in relation to the generation of impacts on the abiotic resources depletion and on climate changes than ore transportation by diesel trucks because the electricity generation matrix in Brazil has significant participation from hydroelectric plants.

1. Introduction

Iron is the fourth most abundant element and accounts for about 5% of the earth's crust. Commonly found in the form of iron ore, iron has been used for over four thousand years in the making of weapons and tools. Essential part in the manufacture of steel, it is difficult to imagine modern society without iron ore. The estimated world reserve of this mineral good is about 170,000 million tonnes of crude iron ore, and Brazil accounts for 18% of this total (USGS, 2013; Statista, 2015a). According to USGS (2013), the total annual production should be over 607 million tonnes in 2000 to 1670 million tonnes in 2015, which undoubtedly will increase impacts derived from this activity. World's third largest producer, Brazil is responsible for 25% of world exports, which corresponds to eight times the production in the European Union and six times production in the United States (USGS, 2015; Statista, 2015b).

Iron ore extraction is almost exclusively performed on surface mines through open pit mining operations, which is characterized by high productivity and low security risks compared to underground mining systems. However, this mining method has significant environmental impacts that need to be properly assessed in order to make it a sustainable activity (Ripley et al., 1996). LCA – Life Cycle Assessment – is currently one of the most promising methods to evaluate and rank environmental aspects and impacts of a product (Durucan et al., 2006; Blengini et al., 2012). Life Cycle Assessment (LCA) is an environmental approach that considers the quantification of natural resource consumption and pollutant emissions of a product, not only in the production phase, but also in the earlier stages of production (manufacturing of inputs and raw materials) and the later stages of use of this product to its disposal as waste (Blengini et al., 2012). This is therefore a comprehensive tool for the quantification and interpretation of environmental impacts of a product or service from cradle to the grave. However, depending on the nature and intended purpose of a LCA study, the system limits in study can be modified, resulting in the evaluation of any other cradle-to-gate or door-to-gate system (Awuah-Offei and Adekpedjou, 2011).

Although the LCA technique has been used to assess environmental impacts associated with various production processes of the mining industry since the end of the last century (Hake et al., 1998; Azapagic and Clift, 1999; Guo et al., 2002; Valderrama et al., 2012), its use in the evaluation of mining processes and processing of mineral resources is still very limited (Durucan et al., 2006), which is in part due to the difficulty of quantifying the various inputs and

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outputs involved (Norgate et al., 2007). Moreover, as each ore corresponds to specific geological, exploitation and processing conditions, environmental impacts are different for each mineral good extracted, requiring specific studies for each case (Norgate and Haque, 2010). This is particularly true for operations with iron ore, where existing studies show the mining processes reduced to a step within the steel production system (Li et al., 2002; Norgate et al., 2007; Bieda, 2012).

There are few studies on the application of LCA to specific mining systems (Awuah-Offei and Adekpedjou, 2011; Blengini et al., 2012.). Among these, those related to coal production in the USA (Ditsele, 2010; Ditsele and Awuah-Offei, 2012) and South Africa (Mangena and Brent, 2006); bauxite in the USA (Durucan et al., 2006) and in Australia (Norgate and Haque, 2010); Copper in 11 countries in South and North America, Asia and Oceania (Northey et al., 2013.); red clay in Spain (Bovea et al., 2007); and gold in Australia, North America, Africa and Asia (Mudd, 2007) stand out.

So far, only the study by Norgate and Haque (2010) presented results of the application of Life Cycle Assessment in an iron mine; however, focusing its analysis on impacts related to water and energy consumption and emissions related to global warming. Seeking to fill this gap, this study evaluated the effect of mining activities and cradle-to-gate iron ore processing in a mine in Brazil. To this end, water use, land use, energy consumption and use of key inputs were evaluated. The following categories of impacts were also quantified: damage to human health; loss of ecosystem quality; abiotic resources depletion and climate changes.

2. Iron ore surface mining product system

2.1. Case study

This paper presents a survey of environmental aspects and impacts related to the iron ore life cycle based on primary data of the process used by Samarco Mineração in its plant in Germano, Iron Quadrangle/Brazil.

The Samarco operations, typical of a complex for iron ore exploitation in surface mines, involve mining, processing and pelletizing activities. Iron ore is extracted from Alegria mines, with average grade of 43%. The final product, iron ore concentrate, exclusively dedicated for export (34 customers in 25 countries) is delivered through its own sea terminal in the city of Anchieta-ES-Brazil. The concentrate is transported to the port through two iron ore pipelines 400 km long.

The production of Samarco in 2012 was 23 million tonnes/year of pellets, a little over 6% of Brazil's total production that year.

2.2. Product system

The iron ore production system target of this study is composed of three units: Mining, Processing and Support System. The mining activity can be described by operations of dismantling, loading and transportation of ore and waste. Dismantling is done mainly by tractors or dozers and to a lesser extent with the use of explosives. Loaders load trucks with waste and shippers feed conveyor belts with ore. Waste is transported to final repositories exclusively by off-road diesel trucks, but ore is transported to the processing facilities mostly by electric conveyor belts. Mining activities use tractors, excavators, loaders, diesel trucks and stationary equipment such as shippers and electric conveyor belts. The environmental aspects of this processing unit are characterized by diesel and electricity consumption, land occupation and transformation, generation of waste rocks that are arranged in waste dumps and generation of particulate matter and combustion gases emitted into the air.

In Processing, ore is crushed and classified into particle size sieves and then feed the Concentration Plant. In the Concentration Plant, ore undergoes a milling step to release silica and then is conducted to flotation cells where silica is removed to form two products: tailings (primarily SiO_2) and concentrate (mainly Fe_2O_3). The tailings are conducted to dams for final disposal and water recovery, while concentrate is led to a secondary grinding for adjustment of the final particle size. Processing activities use crushers, screens, mills and water pumps, all electric driven. Grinding processes use ball grinders composed of metallic alloys. In the concentration step, the main chemicals used are: amine, starch and caustic soda. The environmental aspects of this process step are related to the consumption of reagents and inputs, as well as to the generation of industrial effluents through emissions to tailings dams.

The Support System describes the impacts of personnel and generation transportation activities, in addition to transportation and disposal of industrial waste. In personnel transportation activities, buses and trucks are used and the transportation of industrial waste is done by trucks, all diesel driven. The executive transportation of people in travels is done by gasoline cars. Environmental aspects are linked to fuel consumption and emissions of exhaust gases.

The scope of this study considered all impacts generated from the steps of ore mining (cradle) to the final delivery of concentrated ore (gate). Cradle activities also comprise previous activities such as extraction, production and transportation of raw materials, supplies and equipment to the company, as well as the generation of electricity and its transmission to the mining site. To this end, “one tonne of iron ore concentrate at the gate” was considered as a functional unit.

Fig. 1 shows the initial product system for extraction and processing of iron ore in surface mining using the cradle-to-gate approach.

3. Life cycle inventory analysis

For the mining activity, data on production and consumption of the following inputs were collected: diesel in mining equipment, electricity on conveyor belts, explosives and land use and occupation with mining, waste dumps and industrial facilities. For the definition of impacts related to the recovery of areas, the expected degraded area up to total ore extraction during the company's life cycle was calculated.

For Processing, in addition to the total concentrate production and the total amount of ore fed, the following consumptions were also assessed: water, electricity, chemicals (amines, starches, caustic soda, etc.) and grinding media. Wastewaters from processing that are directed to tailings dams were also quantified.

The survey of impacts of the Support System covered the kilometers traveled both for transportation of personnel and for collection and disposal of all waste generated in the process. All vehicles used are powered by diesel or gasoline. Regarding waste, all information related to the generation of metallic and nonmetallic industrial waste, organic waste used for composting and industrial waste contaminated with oil and grease for incineration, as well as data on the internal transport of waste through diesel trucks was surveyed.

Fig. 2 shows the final product system used for determining LCI.

From primary data on inputs, outputs and emissions, life cycle inventory was elaborated for the three Processes units: Mining, Processing and Support Systems (Table 1).

The LCI analysis was made using the SimaPro 7-spreadsheet manager and unavailable data (on the production and transportation of equipment, raw materials and inputs, whose impacts

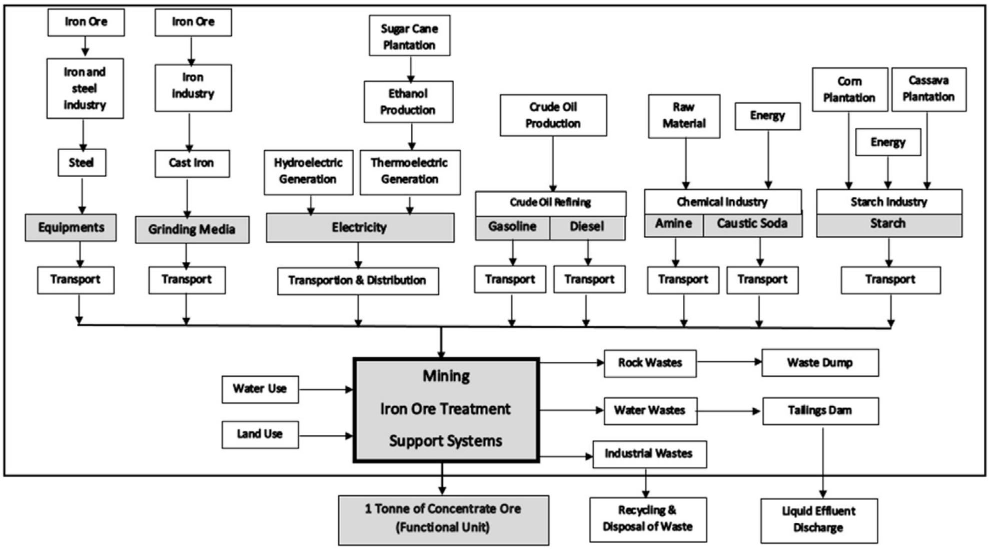

Fig. 1. Initial product system.

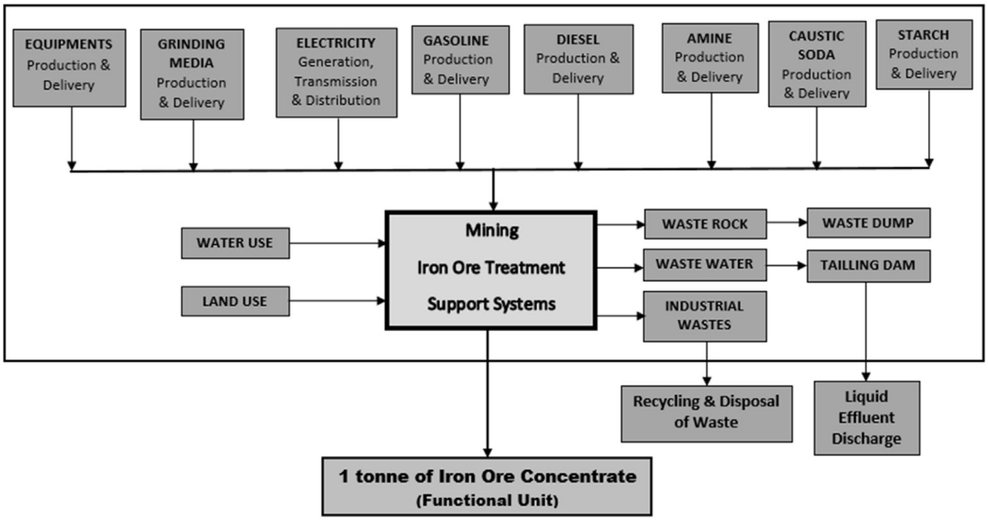

Fig. 2. Final product system.

are generated by previous activities) were estimated by the Ecoinvent 2.0 database, which although based on industries in Europe (Frischknecht and Rebitzer, 2005) was used as an approximation due to the lack of an equivalent database for the industry in Brazil. To calculate the impact of the Life Cycle Inventory – LCI, the Eco-indicator'99 was used (Goedkoop and Spriensma, 2001), which presents its results into three categories of impacts, namely: damage to human health, damage to ecosystem quality and natural resources depletion. The impacts on climate changes were calculated using the IPCC-2007 method. Fig. 3 shows how methodologies used to assess life cycle impacts relate to Life Cycle Inventory spreadsheet.

4. Life Cycle Impact Assessment

Table 2 shows the results of the life cycle impacts evaluation (LCIA). The presentation of results was performed by the levels of impact categories, showing the units of processes where increased environmental impacts were observed and in which activities the most significant impacts can be found. The two major impacts of each category will be presented below. In addition, the results achieved for emissions related to global warming will also be presented.

4.1. Impacts on human health

4.1.1. Emission of inhalable inorganic compounds

This impact showed total value of 5.6×10^{-5} DALY/tonnes of concentrate produced. Fig. 4 shows the impact potential in terms of percentage of the main inhalable inorganic compounds in this study. Table 3 shows the participation (% of total impact) of the main company's activities in relation to the emission of inhalable inorganic substances.

The emission of fine inhalable particles (PM-10 and PM-2.5) is the main aspect responsible for this impact, with 81% of the total. The results show that only the ore mining activity is involved in 56% of the total impact. The results also show that grinding machines are important contributors to the emission of inhalable inorganic

Table 1
Life cycle inventory.

Impacts from mining for 1.0 kg iron ore produced			
Diesel consumption		2.1×10^{-4}	$\mathrm{kg_{DIESEL}/kg_{ORE}}$
		8.87×10^{-3}	$\mathrm{MJ/kg_{ORE}}$
Conveyor belt		4.73×10^{-9}	$\mathrm{m_{BELT}/kg_{ORE}}$
Electricity consumption		1.13×10^{-3}	$\mathrm{kwh/kg_{ORE}}$
Explosives		8.78×10^{-3}	$\mathrm{kg_{EXPL}/kg_{ORE}}$
Surface mining equipments		2.38×10^{-10}	$\mathrm{kg_{EQP}/kg_{ORE}}$
Land use	Mining occupied area	9.05×10^{-7}	$\mathrm{m^2.yr./kg_{ORE}}$
	Mining modified area	1.21×10^{-8}	$\mathrm{m^2.yr./kg_{ORE}}$
	Plants occupied area	9.31×10^{-7}	$\mathrm{m^2.yr./kg_{ORE}}$
	Plants modified area	1.24×10^{-10}	$\mathrm{m^2/kg_{ORE}}$
	Plants impacts	4.77×10^{-11}	$\mathrm{m^2/kg_{ORE}}$
Land reclamation	Modified area	1.21×10^{-8}	$\mathrm{m^2/kg_{ORE}}$
	Diesel consumption	8.87×10^{-3}	$\mathrm{MJ/kg_{ORE}}$
Impacts from iron ore treatment for 1.0 kg concentrate produced			
Iron ore consumption		2.32	$\mathrm{kg_{ORE}/kg_{CONC}}$
Water consumption		8.74×10^{-4}	$\mathrm{m^3/kg_{CONC}}$
Electricity consumption		9.86×10^{-1}	$\mathrm{kwh/kg_{CONC}}$
Amines consumption		1.21×10^{-4}	$\mathrm{kg/kg_{CONC}}$
Other chemicals consumption		6.84×10^{-6}	$\mathrm{kg/kg_{CONC}}$
Floculant consumption		3.13×10^{-5}	$\mathrm{kg/kg_{CONC}}$
Coagulant consumption		1.67×10^{-6}	$\mathrm{kg/kg_{CONC}}$
Starch consumption		1.17×10^{-3}	$\mathrm{kg/kg_{CONC}}$
NaOH consumption		6.84×10^{-4}	$\mathrm{kg/kg_{CONC}}$
Slaked lime consumption		9.73×10^{-6}	$\mathrm{kg/kg_{CONC}}$
Grinding media consumption		1.15×10^{-3}	$\mathrm{kg/kg_{CONC}}$
Industrial wastes issues		0.43	$\mathrm{kg/kg_{CONC}}$
Impacts from support systems people transportation and wastes management			
Buses		0.031	$\mathrm{km/DMT_{CONC}}$
Pickups and vans		0.085	$\mathrm{km/DMT_{CONC}}$
Cars		0.031	$\mathrm{km/DMT_{CONC}}$
Waste transportation – Trucks		0.09	$\mathrm{MJ/DMT_{CONC}}$
Organic wastes		1.35×10^{-3}	$\mathrm{kg/DMT_{CONC}}$
Industrial wastes (Tiles and conveyor belts)		1.03×10^{-2}	$\mathrm{kg/DMT_{CONC}}$
Industrial wastes (Civil construction)		5.44×10^{-3}	$\mathrm{kg/DMT_{CONC}}$
Grease wastes (to incineration)		2.0×10^{-3}	$\mathrm{kg/DMT_{CONC}}$

substances, with about 10% of this impact, highlighting the emission of particulate material during the production of this raw material (steel metallurgy). Dispersed in all systems, an 11% participation of nitrogen oxides is observed, which are derived from fuel combustion by mobile devices, for example, in mining activities, recovery of areas and support systems (adding 7.34% of the impact). Another source of emission of inhalable inorganic substances is the burning of natural gas in the production of grinding media (10.63%) and biomass in electricity generation (2.9%) used in the production of various inputs and operation of machines and lighting in the mining and processing activities.

4.1.2. *Emission of carcinogenic substances*

The impact of emissions of carcinogenic substances obtained the value of 1.05×10^{-5} DALY per tonne of concentrate produced. Fig. 5 shows the participation of each of these carcinogenic substances in terms of percentage of the total impact. Table 4 shows the participation of the company's activities in relation to the emissions of carcinogenic substances.

The inventory showed the presence of cadmium and arsenic ions in tailings dams as the main responsible for this impact, with 69% of the total, this because they receive all the effluents from the ore processing steps. As these elements are not found in the

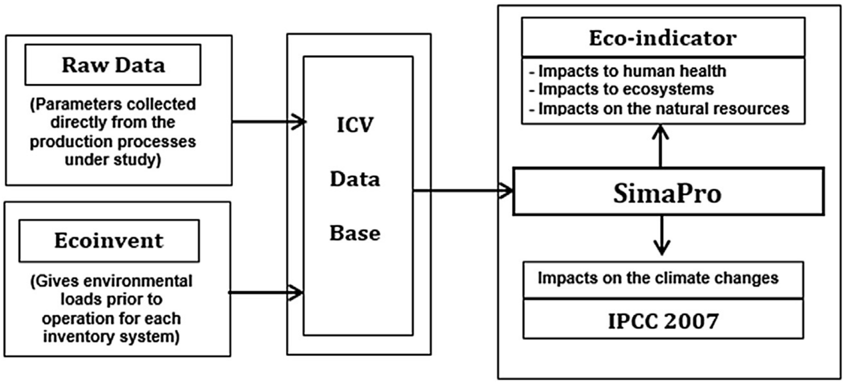

Fig. 3. Life Cycle Impact Assessment flowchart.

Table 2
Life cycle impact assessment results.

Eco-Indicator 99	Impacts on human health	For 1.00 DMT Conc
	Carcinogenic substances	1.05×10^{-5} DALY
	Inhalable organic material	1.90×10^{-8} DALY
	Inhalable inorganic material	5.06×10^{-5} DALY
	Climate changes	3.39×10^{-6} DALY
	Radiation	5.24×10^{-8} DALY
	Ozone depletion	8.96×10^{-10} DALY
	Damage to ecosystem	For 1.00 DMT Conc
	Ecotoxicity	20.8 PAF. m^2.yr.
	Acidification/Eutrofication	0.561 PDF. m^2.yr.
	Land use	5.26 PDF. m^2.yr.
	Natural resources depletion	For 1.00 DMT Conc
	Mineral resources depletion	44.8 MJ *Surplus*
	Fossil fuel depletion	16.5 MJ *Surplus*
IPCC 2007	Impacts on the climate changes	For 1.00 DMT Conc
	Greenhouse gases emissions	23.32 kg CO2 eq

analysis made in the waters of dams, a likely explanation for this impact is that these ions enter the process by wear of grinding media during ore processing and reach the dam along with the effluent.

The inventory also shows that due to mining and land recovery activities, arsenic and cadmium appear in elemental form as soil contaminants, and this contribution may be explained as coming from the steel manufacturing process that makes up the mobile equipment. Inputs also appear as large responsible for this impact, namely: electricity (As-soil, 6.44%), corn starch (Cd-soil 5.19%). The modeling done by Eco-indicator 99 showed that cadmium and arsenic are emitted through the use of fertilizers (used in the production of plant origin inputs) and electricity generation (in part using biomass as fuel in thermal power plants).

4.2. *Impacts on the quality of ecosystems*

4.2.1. *Ecotoxicity — emissions of toxic substances for ecosystems*

This impact was quantified in 20.8 PAF × m^2 x/tonne of concentrate produced. Fig. 6 shows that the main contribution with ecotoxicity potential are emissions of metals such as chromium, nickel, zinc and copper, either in the elementary form as in the ionic form.

The inventory in Table 5 shows that the most responsible for these emissions are grinding media that contribute, throughout their life cycle, with more than 83% of the total impact. The contributions of Cr^{+2} and other ions to the atmosphere can be attributed to emissions during the metallurgical process in the manufacture of grinding media. Tailings dams are the sector that most contributes to impacts related to the disposal of copper, nickel and cadmium ion in water bodies, accounting for 6% of the total impact. Again, the wear of grinding media in the ore grinding process is the main source of these ions.

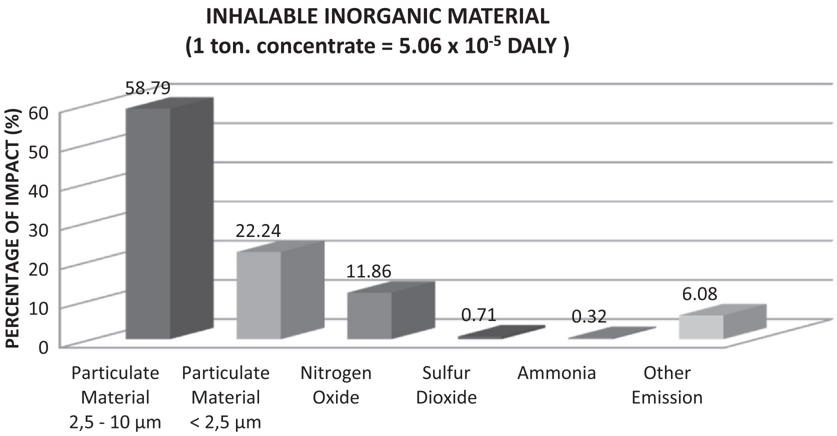

Fig. 4. Description of the impacts on human health related to the inhalable inorganic material emissions.

Table 3
Inhalable inorganic substances emissions.

Inhalable inorganic material								
Unit process	Activities	Partic. Material (2.5–10 µM)	Partic. Material (<2.5 µM)	Nitrogen oxide	Sulfur dioxide	Ammonia	Others	%
Mining	Rom vale	5.33	2.25	3.48			0.52	**11.58**
	Mining Operation	46.30	9.60					**55.90**
	Mining operation trucks		1.11	1.28			0.18	**2.57**
	Waste rock transportation trucks		0.85	1.04			0.12	**2.01**
	Land reclamation		1.25	1.54			0.16	**2.95**
	Mining plant						1.89	**1.89**
	Totals	51.63	15.06	7.34			2.87	76.90
Iron ore treatment	Vale concentrate	3.41	1.44	2.23			0.33	7.41
	Minding media	3.09	5.74	1.04	0.71		0.05	10.63
	Electricity	0.66		0.75			0.68	2.09
	Corn starch			0.39		0.32	0.41	1.12
	Plant operation						1.65	1.65
	Totals	7.16	7.18	4.41	0.71	0.32	3.12	22.90
Support systems	Buses, cars, trucks, etc.			0.11			0.09	0.20
Total		58.79	22.24	11.86	0.71	0.32	6.08	100

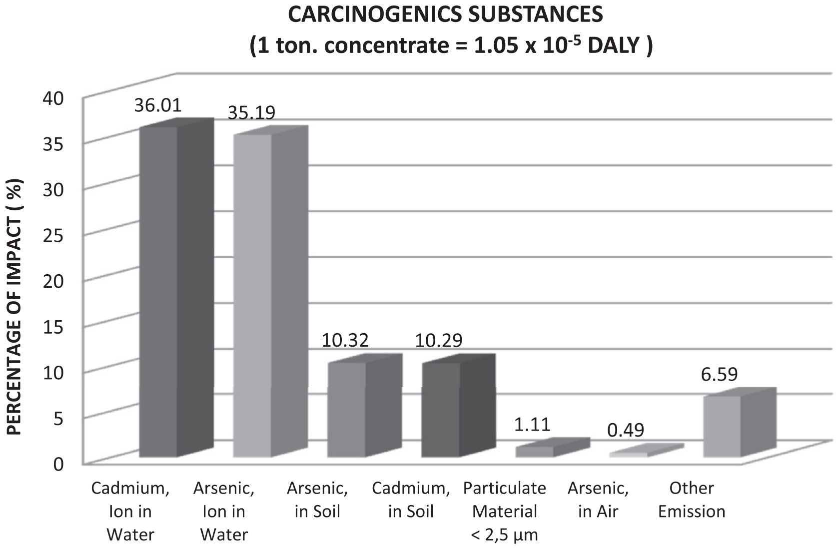

Fig. 5. Description of the impacts on human health related to the carcinogenic substances emissions.

Table 4
Carcinogenics substances emissions.

Carcinogenic substances									
Unit process	Activities	Particulate material (<2.5 μM)	As in soil	Cd in soil	Cd – ion, water	As – ion, water	As in air	Others	Total
Mining	Rom vale	0.46	0.21	0.32				0.85	**4.46%**
	Mining operation	0.65							
	Mining operation trucks		0.13	0.17				0.19	
	Mining operation loaders		0.17	0.09				0.12	
	Land reclamation			0.20				0.16	
	Mining plant							0.74	
		1.11	**0.51**	**0.78**				**2.06**	
Iron ore treatment	Vale concentrate		3.23	3.50				0.34	**95.40%**
	Waste dam				35.92	33.15			
	Electricity		6.44					1.37	
	Corn starch			5.19				0.39	
	Cassava starch			0.96				0.15	
	Minding media					2.04	0.49	1.47	
	Plant operation							0.76	
			9.67	**9.65**	**35.92**	**35.19**	**0.49**	**4.48**	
Support systems	Buses, cars, trucks, etc.				0.09			0.05	**0.14**
Total		**1.11**	**10.32**	**10.29**	**36.01**	**35.19**	**0.49**	**6.59**	**100%**

4.2.2. *Land use*

The impact caused by land use and transformation showed a total value of 5.26 PDF. m^2.year/tonne of concentrate produced.

Fig. 7 shows the contribution of the main activities for the impact on land use. Table 6 shows the participation of each activity in the impact on land use.

This inventory shows that most of the impacts on land use is linked to processing raw materials (43.05% of the total), which are derived from agricultural activities (occupied areas) related to the production of corn and cassava starch and therefore outside processes directly developed by the mining company. Mining activity accounts for 33.35% of this impact due to the transformation of land in mining and industrial area and its occupation during the time of company activity. Impacts associated with diesel fuel consumption refer to the mixture of 5% of biodiesel, which is primarily derived from soybean oil, and this input requires large areas for soybean planting. The same occurs for the electricity consumed, which is mostly composed of hydroelectric sources with the transformation and occupation of large areas for the installation of power plants.

4.3. *Abiotic resource depletion impacts*

4.3.1. *Mineral resource depletion*

Mineral resource depletion impacts totaled 44.8 MJ Surplus/tonne of concentrate produced. Fig. 8 shows the process activities, highlighting the natural resources depletion and Table 7 shows the participation (% of total impact) of the company's activities in relation to mineral resource depletion impacts.

The main contribution to Mineral resource depletion was the iron ore mining activity, with about 80% of the impact. However, grinding media have a significant participation in this impact, around 11%. The inventory of environmental impacts revealed that this value is almost entirely due to nickel extraction for the production of grinding media.

4.3.2. *Fossil fuel depletion*

The total impact related to the consumption of fossil fuels totaled 16.5 MJ Surplus/tonne of concentrate produced, lower than that found by Norgate and Haque (2010) for iron mine, which was 152.7 MJ Surplus/tonne of concentrate produced. Fig. 9 shows that

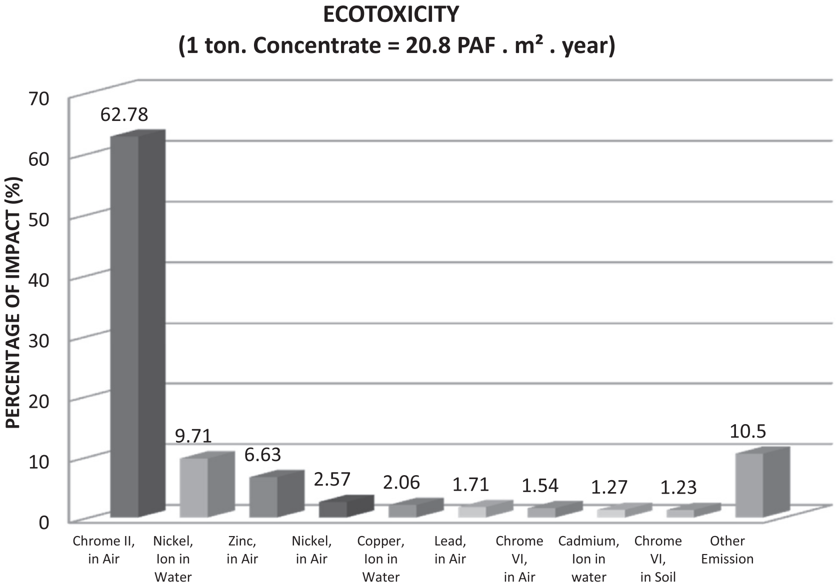

Fig. 6. Description of the damage to ecosystems related to the ecotoxicity from some emissions.

Table 5
Ecotoxicity.

Ecotoxicity												
Unit process	Activities	Cr II air	Cr VI air	Cr VI soil	Ni air	Ni ion water	Zn air	Cu ion water	Lead air	Cd ion water	Others	%
Mining	Rom vale	0.65			0.08		0.16				0.98	1.87
	Plants				0.08		0.16				0.14	0.38
	Trucks	0.27									0.11	0.38
	Loaders	0.09									0.24	0.33
	Operation										0.73	0.73
	Sub-total	1.01			0.16		0.32				2.20	**3.69**
Iron ore treatment	Vale concentrate		0.01	0.01	0.04	0.10	0.06	0.02	0.01	0.01	0.69	0.95
	Waste dam					1.87		1.93		1.26	1.17	6.23
	Grinding media	61.77	1.53		1.97	7.74	6.25		1.70		2.18	83.14
	Electricity			1.22	0.40						1.33	2.95
	Operation										2.83	2.83
	Sub-total	61.77	1.54	1.23	2.41	9.71	6.31	1.95	1.71	1.27	8.20	**96.1**
Support systems	Buses, cars, trucks, etc.							0.11			0.10	0.21
	Sub-total											**0.21**
Total		62.78	1.54	1.23	2.57	9.71	6.63	2.96	1.71	1.27	0.11	**100**

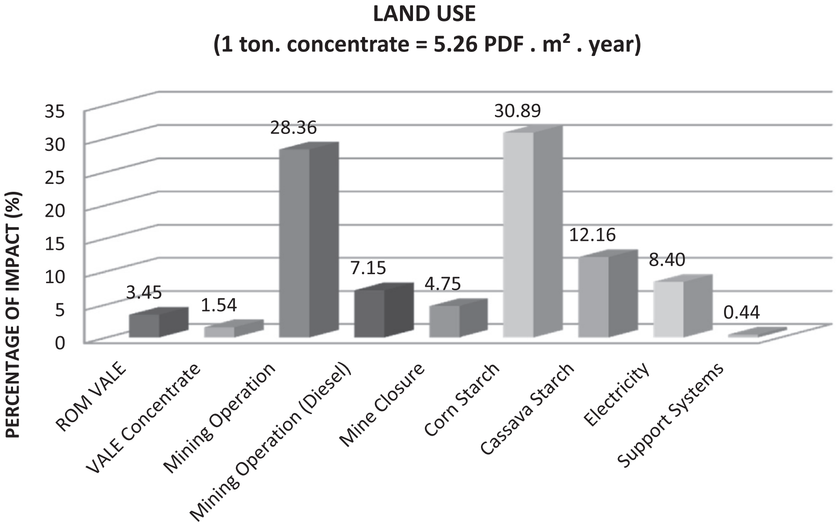

Fig. 7. Description of the impacts on the ecosystem quality related to the land use.

Table 6
Land use.

Land use									
Unit process	Activities	Occupation land	Soy planting	Cornfield	Cassava planting	Sugar cane plantation	Hydro power plant	Others	Total
Mining	Rom vale	3.45							3.45%
	Mining operation	28.36							28.36%
	Mining operation (Bio-Diesel)		7.15						7.15%
	Reclamation land (Bio-diesel)		4.75						4.75%
	Plant							1.00	1.00%
Iron ore treatment	Vale concentrate	1.54							1.54%
	Starch			30.89	12.16				43.05%
	Electricity					3.00	5.40		8.40%
	Plant							1.86	1.86%
Support systems	Diesel		0.44						0.44%
Total		33.35%	12.34%	30.89%	12.16%	3.00%	5.40%	2.86%	100%

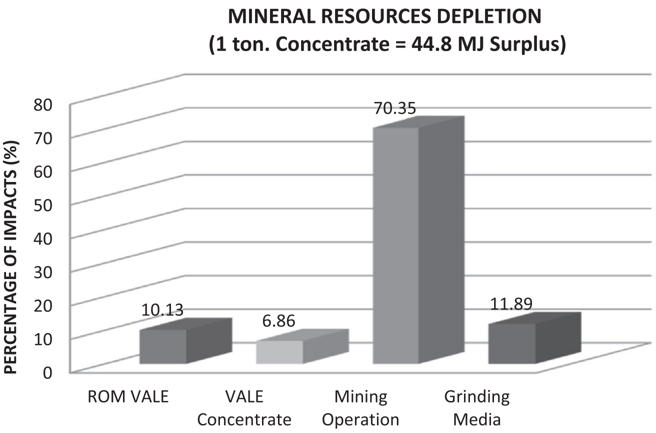

Fig. 8. Description of the impacts on abiotic resources related to the mineral resource depletion.

the consumption of electricity was the most relevant aspect related to fossil fuel depletion, accounting for 25% of the total impact. If evaluated from the perspective of the Brazilian electricity, unlike in Australia, it has low dependence on fossil fuels, and must be the cause found for the large difference found between inventories.

Table 8 shows the participation (% of total impact) of the company's activities in relation to impacts on the depletion of these resources. Once all the processes studied depend on energy, it is expected that most of these processes contribute in some way to this category of impact, either by the consumption of fuels (diesel, natural gas or fuel oil) or by the national grid electricity consumption, comprising about 10% of energy from fossil sources. This portion is relatively low when compared to other countries or even the world average, which depends on average of 80% of fossil fuels (MME, 2013).

Diesel consumption in mining activities equipment significantly participates in the composition of the impact of fossil fuel depletion (Table 8), with 34% of the total impact (trucks with loaders and transport of waste). Grinding media appear with 10.78% of the total impact on fossil fuels due to the consumption in production and transportation to the company. The remainder of this impact is due to the production and transportation of raw materials used in the concentration plant such as corn starch, cassava starch, and caustic soda. Impacts caused by Support Systems are basically due to fuel consumption in the transport of waste and personnel.

4.4. *Impacts on climate changes (Global warming)*

4.4.1. *Greenhouse gases (GHG)*

The total impact found for this category was 13.32 kgCO_2eq/tonne of concentrate produced, very similar to that found by Norgate and Haque (2010), which was 11.9 kgCO_2eq/tonne of concentrate produced. Fig. 10 highlights that the electricity consumed in the process has in its life cycle the potential to produce almost the same amount of GHG emitted by all other inputs in their own life cycles together. The production and transportation of grinding media is the second largest contributor to this impact, followed by chemicals used in ore flotation: starch, caustic soda and amine. These data show that due to specific processes, GHG emissions are around 5 kgCO_2eq (i.e., about 37% of the total impact).

Table 9 shows that this aspect is basically due to the burning of diesel fuel in virtually all activities of the process under study. An analysis of these issues shows that the most responsible are previous processes, external to the company. Thus, the most significant contributions to this impact come from inputs used in the ore beneficiation process, electricity, grinders, starches, amine, caustic soda and other inputs, totaling 8.53 kgCO_2eq (63.39% of total).

Table 7
Mineral resources depletion.

Mineral resources depletion						Total
Unit process	Activities	Reserves				
		Iron	Nickel	Molybdenum	Others	
Mining	Rom vale	10.09			0.04	**10.13%**
	Mining operation	70.35				**70.35%**
	Mining plant				0.27	**0.27%**
Iron ore treatment	Grinding media		11.25	0.26	0.38	**11.89%**
	Vale concentrate	6.83			0.03	**6.86%**
	Treatment plant				0.50	**0.50%**
Total		**87.27%**	**11.25%**	**0.26%**	**1.22%**	**100%**

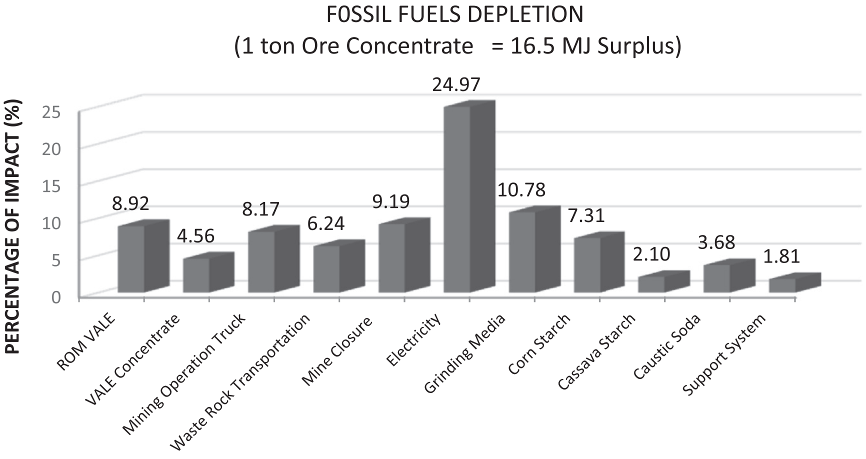

Fig. 9. Description of the impacts on abiotic resources related to the fossil fuels depletion.

Table 8
Fossil fuels depletion.

Fossil fuels depletion						
Unit process	Activities	Reserves				Total
		Crude oil	Natural Gas	Natural coal	Others	
Mining	Rom vale	7.92	0.97		0.03	8.92
	Mining operation trucks	7.40	0.74		0.03	8.17
	Waste rock transportation	5.94			0.30	6.24
	Mining operation loaders	3.76	0.64		0.03	4.43
	Mine closure (Reclamation)	8.74			0.45	9.19
	Others				2.04	2.04
Iron ore treatment	Electricity	15.66	8.75		0.56	24.97
	Grinding media	5.76	3.83	0.91	0.28	10.78
	Corn starch	3.89	3.38		0.04	7.31
	Cassava starch	1.09	1.00		0.02	2.10
	Caustic soda	1.37	2.10		0.21	3.68
	Vale concentrate	4.03	0.52		0.01	4.56
	Others				5.80	5.80
Support systems	Buses, cars, trucks, etc.	1.63			0.18	1.81
Total						**100.00%**

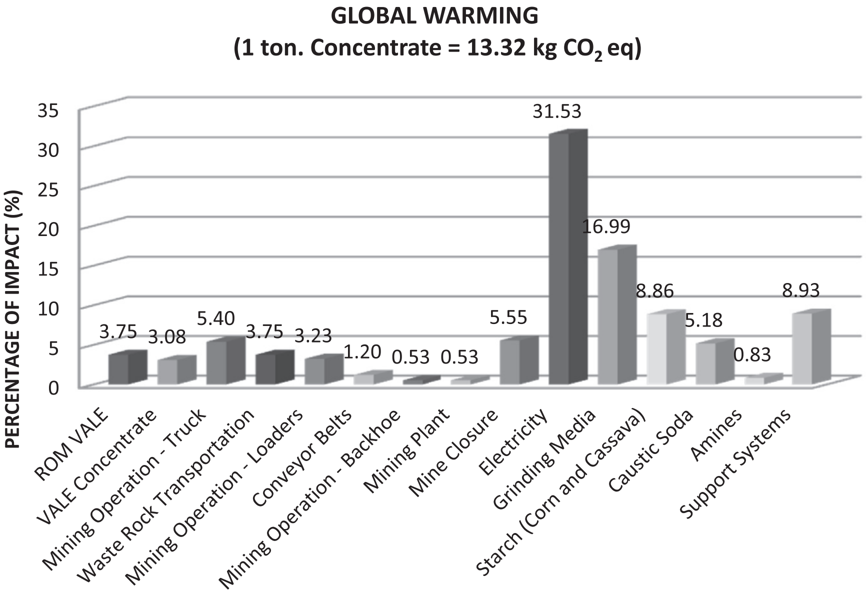

Fig. 10. Description of the impacts about the global warming related to the greenhouse gases emissions.

Table 9
Greenhouse gases emissions.

Greenhouse gas emissions				
Unit process	Activities	Impact		Total
		Kg CO_2 eq	%	
Mining	Rom vale	0.50	3.75	**23.94%**
	Mining operation trucks	0.72	5.40	
	Waste rock transportation	0.50	3.75	
	Mining operation loaders	0.43	3.23	
	Conveyor belt	0.16	1.20	
	Backhoe	0.07	0.53	
	Mine plant	0.07	0.53	
	Mine closure (Land reclamation)	0.74	5.55	
Iron ore treatment	Electricity	4.20	31.53	**67.13%**
	Grinding media	2.26	16.99	
	Starch	1.18	8.86	
	Amine	0.11	0.83	
	Caustic soda	0.69	5.18	
	Vale concentrate	0.41	3.08	
	Others inputs	0.09	0.66	
Support systems	Buses, cars, trucks, etc.	1.19	8.93	**8.93%**
Total		**13.32**	**100.00**	

5. Conclusions

LCA – Life cycle assessment – proved to be a powerful tool in the assessment of environmental impacts produced by an iron open pit mine. The impact assessment has identified grinding media as an important contributor in different categories, such as the emission of inhalable inorganic substances with 10.63% in this category, ecotoxicity with 83.14%, mineral resource depletion with 11.89%, inorganic substances with 10.63% and fossil fuel depletion with 10.78%. Therefore, if life cycle is considered, this input is of paramount importance for any guidance with respect to environmental management of an iron mine.

Diesel consumption in mining activities equipment is presented as the main source of fossil fuel depletion, totaling 36% of the total impact. This could suggest the adoption of an increased use of biodiesel as an alternative in order to minimize “climate changes” and “consumption of fossil fuels” impacts. However, since plant fuel has other impacts related to extensive crop plantations, for example, “land use” and “emissions of carcinogenic substances”, these aspects should be considered before carrying out a simple fuel exchange. The results also show how mining can influence the production chain of its inputs and impacts associated with this chain. For example, the area required to obtain some inputs such as starch is as significant as the area needed for ore mining and tailings dams. That is, many times, the lower use of inputs can be more significant for environmental conservation than the limitation of its own production, proving that the eco-efficiency concept propagates environmental benefits obtained for the entire chain of the process under analysis.

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