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Greening of brick and tile production: an index to evaluate its environmental performance

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ABSTRACT

This work presents an index to evaluate the environmental performance of brick and tile manufacturing. The steps used were: 1) process study; 2) waste analysis; 3) determination of the potential impact of waste; 4) normalization of the potential impact; 5) comparative weighting among the potentials; 6) creation of the index. The index considers three parameters: the amount of waste produced, the disposal of waste, and the spatial dispersion of waste. The index was called CIRI (Ceramic Industry Rating Index) and was tested in a ceramic company. The field application showed that the waste that offered the highest environmental impact were gases generated from the burning of chips (30.850%), ashes generated from the burning of chips (30.483%), and steel drums (28.937%), which total of 90.27%. The CIRI index was 28.732%, which shows bad waste management. In view of the findings, two points must be considered: 1) the impacts generated by gaseous could be mitigated by companies by using technologies for drying tiles and bricks with a lower level of environmental impact; 2) entrepreneurs should be concerned about the fate given to the ashes because the dispose practiced is not environmentally correct. The index is useful for assessing the environmental impact of the brick and tile industry. It is useful for managers insofar as a proposal for process improvements. The novelty of this study lies in the index developed, which was designed to consider: the potential for environmental impact, the amount of waste, the spatial coverage, and the adequacy of waste disposal.

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INTRODUCTION

When raw materials and inputs extracted from the environment are used in industrial activity, there is a tendency to affect and harm nature, as is the case of the ceramic sector, which has clay as its main raw material and firewood as an energy input. There are impacts on the physical, biotic and anthropic environment, resulting from mining and reforestation. There are also the impacts of waste generated in the production process (Dias et al., 1999; Sánchez, 2008; Leite and Gonçalves-Fujaco, 2013; Sangwan, Choudhary and Batra, 2017; Türkmen et al., 2021a). When these wastes are not reused or redirected in the production process, they are absorbed by the air, water, or soil, which can cause negative impacts on the environment (Barbieri, 2016, Abrahão and Carvalho, 2017).

The term "ceramic materials" derives from the Greek word *keramus*, which means burned clay, that is, non-metallic material contracted after firing at high temperatures (Oliveira, 2015).

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Thus, the production of red ceramic materials, such as tiles and bricks, requires clay as the main raw material (Callister and Rethwisch, 2011; Abrahão and Carvalho, 2017). In Brazil, the ceramic industry is considered as one of the most important economic activities. However, most of the time, the production of ceramic materials is carried out in rudimentary, resulting in negative environmental impacts. The production of ceramic materials is closely linked to civil construction, being carried out in small and medium-sized industries and in potteries, located close to clay deposits (Junior et al., 2012; Alves, 2015).

This sector is considered the oldest in civilization and one of the most important to the global economy (Sindecer, 2015; Correia and Fraga 2018), with an estimated share of 1% in gross domestic product (GDP) and in the international market with the expansion of exports. Thus, the ceramic industry is in continuous growth, demanding high consumption of natural resources to produce tiles and bricks and, consequently, producing large amounts of waste (Sangwan, Choudhary and Batra, 2017).

The production process of the ceramic industry generates large amounts of waste, and its destination is systematically sent to sanitary landfills (El-Gamal, 2017). The combustion in ceramic manufacturing furnaces and dryers drives NOx, SOx, CO, and CO_2 emissions. Simultaneously with the high energy consumption, ceramic productive processes deliver mixed particulate matter and volatile organic compounds (VOC). Additionally, dangerous air contaminants such as hydrochloric acid (HCl) and hydrofluoric acid (HF) are created (Türkmen et al., 2021b). In Brazil, the amount of waste that is generated varies according to the production method, and may be defective parts, breakage in burning or transport (Sales et al., 2014) (Muneron et al., 2021).

It is never over emphasized that the advances in industrial processes with the increased consumption of natural resources and the propagation of toxic and highly dangerous substances have been causing problems for the environment and human health (Song, Fisher and Cui, 2016; Zui, Jian and Liu, 2017). In this way, it becomes fundamental the introduction of production goals that involve environmental quality assessment, making inevitable the insertion of tools to measure the environmental aspects of the industry. In the current picture, with the technological evolution allied to the improvement of the industrial processes, new scientific methodologies have introduced innovative mechanisms that collect information on environmental aspects, such as Multicriteria Assessment Methods and Environmental Performance Indicators (Hermann et al., 2007).

The environmental performance evaluation must meet the essence of the adopted processes, since each company creates and disposes of numerous chemicals, gases, particulate materials, metals, compounds, organic solvents, among others (Rodrigues et al., 2015). Environmental performance indicators must analyze the peculiarities of the products and the characteristics of the adopted processes. Considering these issues, the evaluation of environmental performance aims to be a facilitator in decision-making about environmental performance through indicators, data collection, data analysis, evaluation of information on environmental performance, reviews, and improvements of processes (Abnt, 2015).

The Environmental Performance Assessment (EPA) is essential in assisting companies in the examination of their environmental management, corroborating the evaluation of environmental aspects, defining issues that can be addressed with relevance, suggesting criteria, and evaluating the company's environmental performance according to established criteria (Hariz and Bahmed, 2013). EPA enables companies to compare their environmental performance obtained in the past and in the present and allows comparing their objectives and environmental goals through key performance indicators, based on correct and verifiable data. With this, organizations may consistently measure, evaluate, and communicate their performance to stakeholders (Abnt, 2015).

Given this, this paper intends to answer the following problem: how to elaborate an index for environmental performance evaluation for the ceramic industry?

Given this research problem, this work creates an index for evaluating environmental performance valid to the production process of bricks and roof tiles.

There is a perennial worldwide concern with the quantity and destination of waste from the industries because, if disposed of inappropriately in the environment, it can cause significant environmental impacts (Toensmeier, 2016). It is known that the building sector depletes more natural materials than any other industrial sector and it even applies increased fuel consumption (Almeida et al., 2015). The construction sector is assumed to be the most elevated energy consumer in the EU, accounting for nearly 40% of the absolute power consumption and contributing practically 36% to the EU's total greenhouse gas (GHG) emissions (Almeida et al., 2016). Few scientific studies focus on the development of assessment indices of environmental performance applied to the ceramic sector. Public academic works on the environmental threats caused by the ceramic industry and assessment methodologies are restricted (Muthukannan et al., 2019). In this way, this study cooperates with ceramic companies insofar as it offers an index applicable in practice and establishes scientific parameters for evaluating residues from bricks and roof tiles production.

THE PRODUCTION PROCESS OF BRICKS AND ROOF TILES

The bricks and roof tiles production process is divided into 19 steps (Figure 1). The brick and tiles production process detailed in Figure 1, beginning with the extraction of clay. Subsequently, the extracted clay receives the proper treatment in an industrial context. This treatment includes several steps, such as mixing, disintegration, lamination, production of tiles and bricks, and their shipment.

MATERIAL AND METHODS

For the scope and limits of this research, only the waste and byproducts generated by its productive operations are considered (Figure 2).

The proposed index, established to assess the environmental performance of the bricks and roof tiles manufacturing process, presents the logic underlyed in Figure 3 and the calculation schematic presented in Figure 4.

The research method used in this article was composed of six stages:

1) Study of the productive stages of the process – mapping of the production process.

2) Study of waste – gathering of the residues/sub-products data (Table 1).

3) Impact potentials – calculation of the impact potentials using the RECIPE (2016) method. RECIPE (2016) is a Life Cycle Assessment (LCA) method. LCA methods are based on the analysis of the force that a manufacturing process exerts on the environment. Currently, there are several LCA methods, and all of them go through the stages of the product's life cycle, from its conception, through its use to its disposal due to breakage or obsolescence. The purpose of the LCA is to compare alternative manufacturing processes or even determine steps in the manufacturing process that generates waste with higher levels of pressure on the environment. RECIPE (2016) provides characterization factors representative for the global scale, allowing the possibility of using different impact categories on a national and continental scale. It is a method based on cause-effect logic, which shows the relationship between environmental interference (for example, the emission of a gas into the atmosphere) and its potential impacts on the environment. An example of cause-effect could be the release of a harmful chemical into the water, leading to increased chemical concentrations in freshwater and ultimately the extinction of certain aquatic species (Huijbregts et al., 2017). This method was chosen because of its global application scope, and encompassment of numerous environmental categories. At

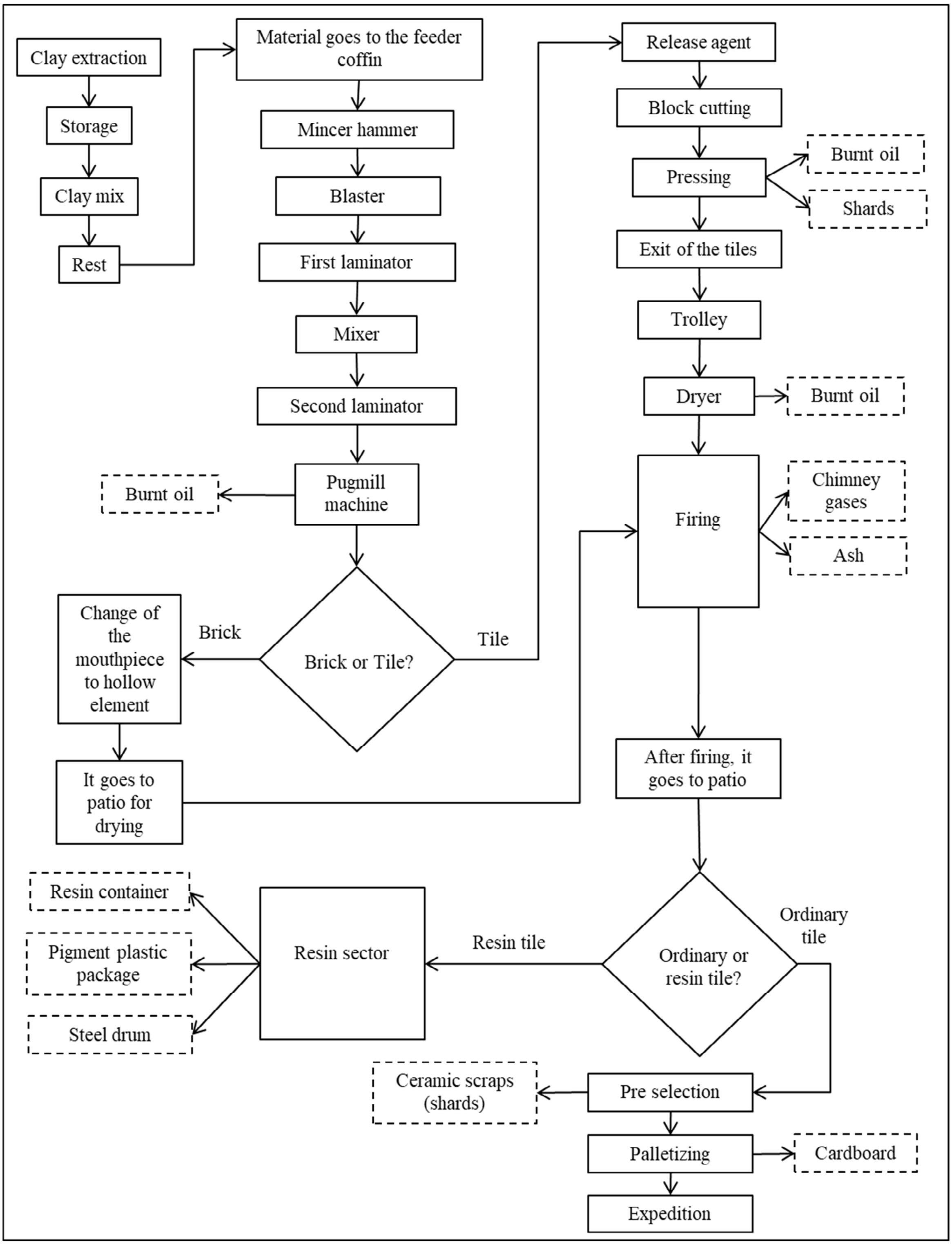

Fig 1. The bricks and roof tiles production process

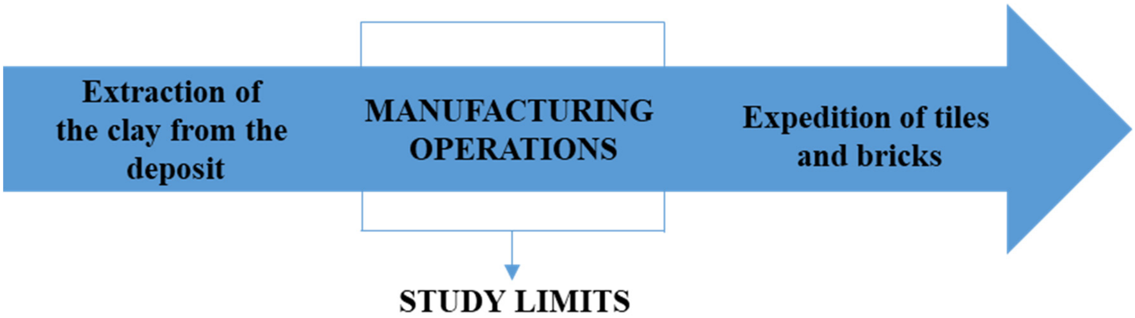

Fig. 2. Definition of the system limits

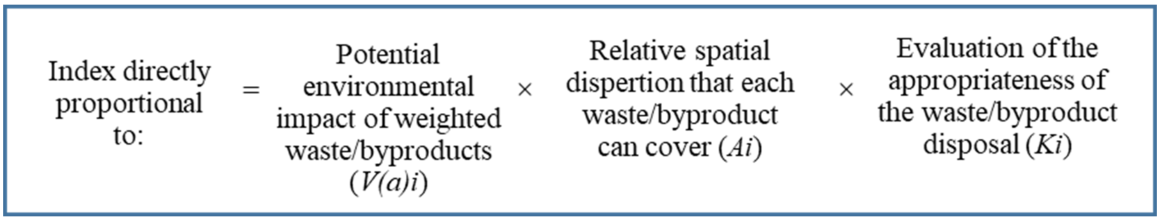

Fig. 3. Development of the index

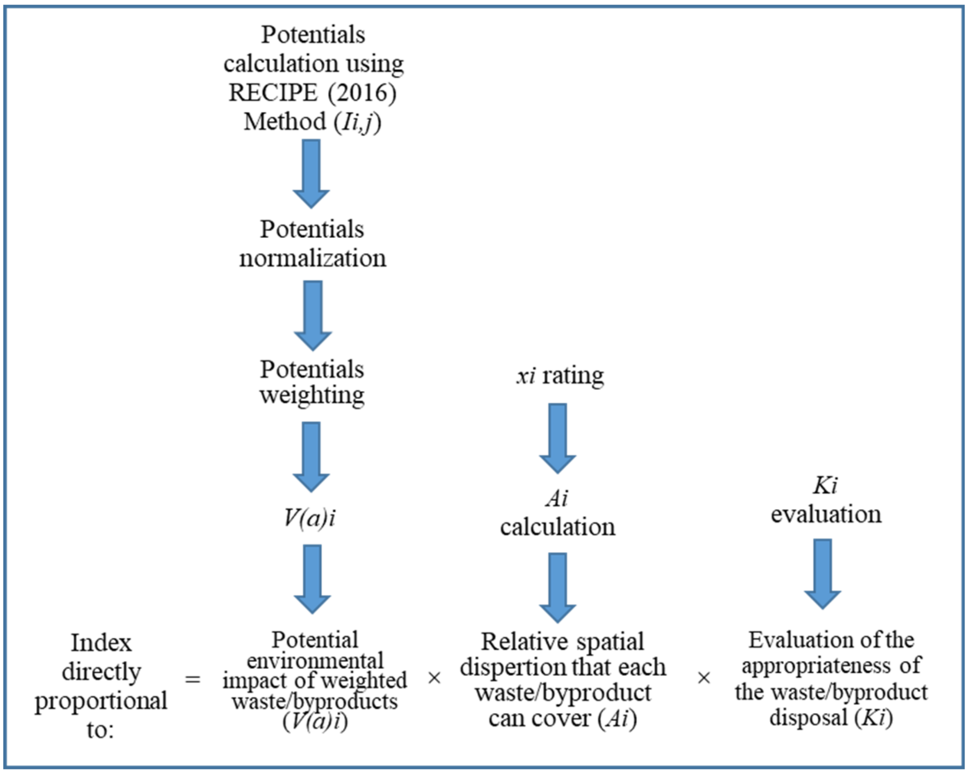

Fig. 4. Calculation schematic

Table 1. Waste, origin process, and chemical composition

Waste	Origin process	Chemical composition	References
Ceramic remains (shards)	Product pre-selection	SiO_2 (64.79%), Al_2O_3 (16.26%), Fe_2O_3 (7.22%), MgO (2.38%), K_2O (2,68%), CaO (0.4%), TiO_2 (0.91%), MnO (0.09%)	Rosales-Laderos et al. (2013)
Ashes from burning eucalyptus chips	Burning of eucalyptus chips	Mg (2.9%), Al (8.1%), Si (2.1%), P (2.2%), S (1.7%), K (6.7%), Cl (2%), Ca (56%), Ti (2.8%), Mn (0.8%), Fe (14.7%)	Resende et al. (2012)
Cardboard	Palletization	Lignin (6.6%), cellulose and hemicelluloses (20%), C, H, O, N, S, and ashes (63.4%)	Pereira (2015); Hummel et al. (2015)
Burnt/used oil	Pug mill, dryer and pressing	Cr (23,24 mg/kg), naphthalene (26,58 mg/kg), phenanthrene (43.68 mg/kg), anthracene (29.54 mg/kg), Pb (12.45 mg/kg), benzo(b,j,k)fluoranthene (41.68 mg/kg), benzo(a)pyrene (129.87 mg/kg), indeno(1,2,3-cd)pyrene (135.54 mg/kg), Fe (3254.65 mg/kg), Mn (12,35 mg/kg), benzo(g,h,i)perylene (63.25 mg/kg), acenaphthylene (7,32 mg/kg), fluoranthene (34.52 mg/kg), Cd (24.85 mg/kg), Zn (54.12 mg/kg), 2-bromonaphthalene (29.98 mg/kg), Ni (11.84 mg/kg), pyrene (39.21 mg/kg), acenaphthene (26.41 mg/kg), V (8.21 mg/kg), benzo(a)anthracene (42.05 mg/kg), fluorene (42.09 mg/kg), Cu (33.54 mg/kg), chrysene (116.54 mg/kg), dibenzo(a,h)anthracene (34.63 mg/kg)	FISPQ (2015)
Plastic	Resin sector	polypropylene (PP) (100%)	Coltro (2018)
Clay remains (rebar)	Pressing	SiO_2 (61%), Al_2O_3 (22%), Fe_2O_3 (3.6%), MgO (0.3%), CaO (0.3%), Na_2O (0.1%), K_2O (0,9%), TiO_2 (1.6%)	ITCG (2019); Correia et al. (2009)
Steel drum	Resin sector	Fe (74%), Cr (18%), Ni (8%), phenolic compounds and epoxy polymer	Kings certified industrial packaging (2019); Losinox (2017); Steel drum (2019)
Gases from the ceramic furnace chimneys	Burning of eucalyptus chips	N_2 (62.5203%), H_2O (12.3227%), CO_2 (25,0304%%), SO_2 (0.0281%), NO_2 (0.0985%)	ITCG (2009)

this stage, potential impact of the environmental categories of RECIPE was calculated for each waste. RECIPE (2016) defines the impact potential with the expression:

$$Ii,j = \sum_{i=1}^{n}\sum_{j=1}^{m} Qi,j \cdot m \quad (1)$$

Where:

- *Ii,j* - is the result of the indicator (potential impact) for the intervention (substance) *i* (for midpoint) in category *j;*
- *m* - is the magnitude (mass) of the intervention (for example, the mass of CO_2 released into the air);
- $Q_{i,j}$ – is the characterization factor that links the substance *i* with the impact category *j*.

4) Potentials standardization – in fact, this is the normalization step, which has the objective to put all *Ii,j* in the same dimension. Impact potentials are presented mostly in heterogeneous units and depict environmental impacts in a way that does not fully translate issues before normalization is done. Therefore, normalization provides an orientation position of the pressure on the environment for each impact category. The common reference is person/year.

5) Relative weighting of the calculated potentials – at this stage, IAHP (*Improved Analytic Hierarchy Process*) method was used. IAHP is a variant of the Analytic Hierarchy Process (AHP) method. AHP is a multi-criteria decision-making (MCDM) method that assists the decision-maker fronting an intricate issue with numerous inconsistent and subjective conditions (for example, asset selection, company location, project scale, and so on) (Ishizaka and Ashraf, 2009). Its development is divided into two phases: the construction of the hierarchy and its evaluation. In the hierarchy construction phase, the hierarchical structure is graphically configured as an "inverted tree" (Figure 5), which descends from the general objective to the criteria, sub-criteria, and alternatives, in successive levels (Granemann and Gartner 2000; Saaty and Saaty, 2016; Nayak and D'Souza, 2019).

After the problem has been ranked, the evaluation phase begins, by using a parity comparison between the criteria and between the sub-criteria, if any. Through this comparison, the relative

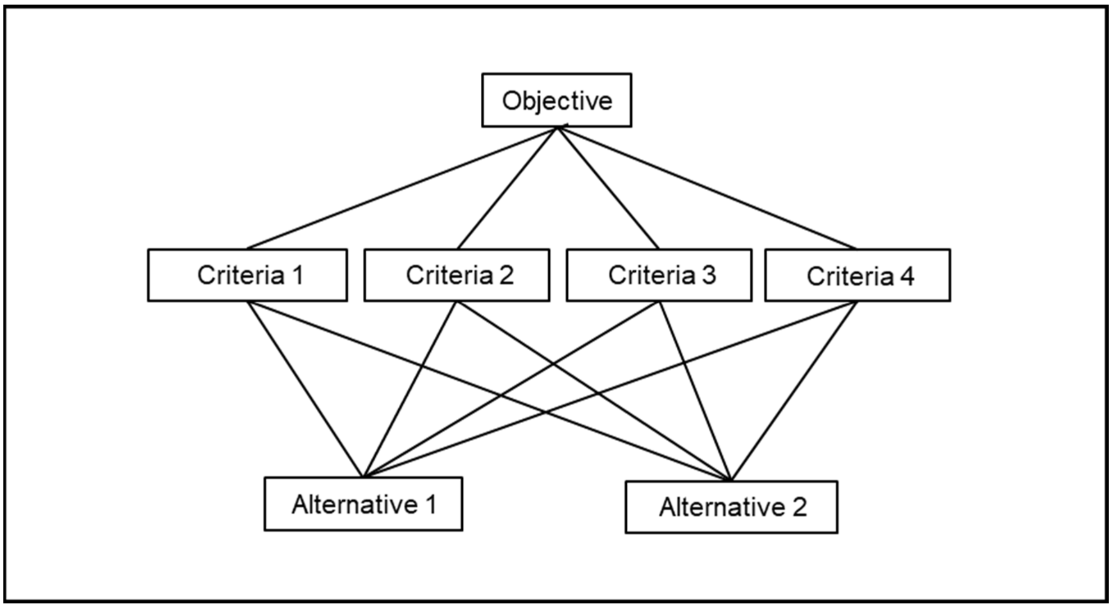

Fig. 5. AHP hierarchical structure (Source: Saaty, 1990)

Table 2. Fundamental scale of absolute numbers

Intensity of Importance	*Definition*	*Explanation*
1	Equal Importance	The two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is flavored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A reasonable assumption
1.1-1.9	If the activities are very close	May be difficult to assign the best value but when compared with other contrasting activities the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities

Source: Saaty (2008)

importance of each criterion, also known as "weights", is determined. The criteria are compared according to the judgment scale described in Table 2 (Granemann and Gartner, 2000).

The results of the comparisons are presented in the following matrix form:

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1 \end{bmatrix}$$

The results must meet the following conditions:

a) aij = α;

b) aji=1/α;

c) aii=1.

Where:

a = parity comparison between the criteria.

α = value of intensity of importance.

The resolution of matrix A results in the priority eigenvector, which expresses the relative importance of each criterion, or weights. The problem evaluation phase proceeds with an equal comparison of the alternatives in each criterion, to determine the level of preference, proceeding in the same way the way it was described to obtain the relative importance of the criteria. With the relative importance of the criteria and the preference levels of the alternatives, we start with the global valuation of each one of the alternatives, according to the weighted sum method, as well as calculated below (Granemann and Gartner, 2000):

$$V(a) = \sum_{j}^{n} pjvj(a) \tag{2}$$

With

$$\sum_{j=1}^{n} pj = 1 \quad \text{and } 0 < pj < 1 \; (j = 1,\ldots,n) \tag{3}$$

where:

V(a) is the global value of the analyzed alternative;

pj is the relative importance of criterion *j*;

vj is the preference level of the analyzed alternative in criterion *j*.

The AHP technique has been widely employed in multicriteria judgment. But it is exceptionally challenging to fulfill the consistency condition of a comparison matrix (CM) in AHP. IAHP can enhance and improve CM consistency of AHP by employing a sorting and scale methodology. This way, IAHP is a refinement of the AHP method (Li et al., 2013). Otherwise, the AHP process can be enhanced by employing a recurring pattern of standardizing the weights of the attributes and the modification of subjective weights into objective significances. In the earliest arrangement of AHP, the process needs a pairwise comparison of diverse alternatives concerning attributes separately and a pairwise comparison of attributes themselves. The length and quantity of the comparison matrices increase rapidly as the number of alternatives and/or attributes increases. The AHP technique is enhanced by eradicating the comparison matrices required for the alternatives. Furthermore, by systematically normalizing the weights of attributes, the class reversal problem is released in IAHP (Rao, 2013).

The aim of this step was to weigh the potentials against each other. That is, the different impacts are weighted among themselves having as the final result a relative value of the alternatives and related categories to calculate the total impact of the system under study (Westkämper, Altaing and Arndt, 2000; Oliveira, Cristobal and Saizar, 2016). For this, it was used the *MindDecider* software (www.minddecider.com). *MindDecider* offers an important option in the study, which is the option "auto resolution dependencies". This option decreases the number of queries based on the connection acceptances established earlier, which makes the comparison work less exhausting.

6) Development of the Ceramic Industry Rating Index (CIRI) - the index is an evolution of Rebelato et al. (2019), and was developed to be directly proportional to:

a) The potential of relative environmental impact (*V(a)i*) of each waste originating in the production processes since the nature among them is extremely diverse.

b) The relative amount of each waste generated in a certain period.

c) The relative spatial coverage (relative spatial spreading) that the waste can cover, since each one can reach different degrees according to the chemical composition, disposal course (water, soil or air) and its physical state.

d) The categorical evaluation of the final suitability of the disposal practiced by the company for each residue.

The CIRI formula is:

$$\sum_{i=1}^{n} \frac{V(a)i \cdot Ai}{\sum_{j=1}^{n} V(a)j \cdot Aj} \cdot Ki \cdot 100 \tag{4}$$

Where:
n = quantity of waste/byproducts.
$V(a)$i = relative value of environmental impact of each waste/byproduct i.
Ai = relative weight of the spatial dispersion of waste/byproduct i. The Ai formula is:

$$Ai = \frac{xi \cdot 100}{\sum_{j=i}^{n} xj} \tag{5}$$

Where:
xi = value taken according to the spatial dispersion of each waste/byproduct (Figure 6).
Ki = evaluation coefficient of the disposal of each waste/byproduct i. Two alternatives are

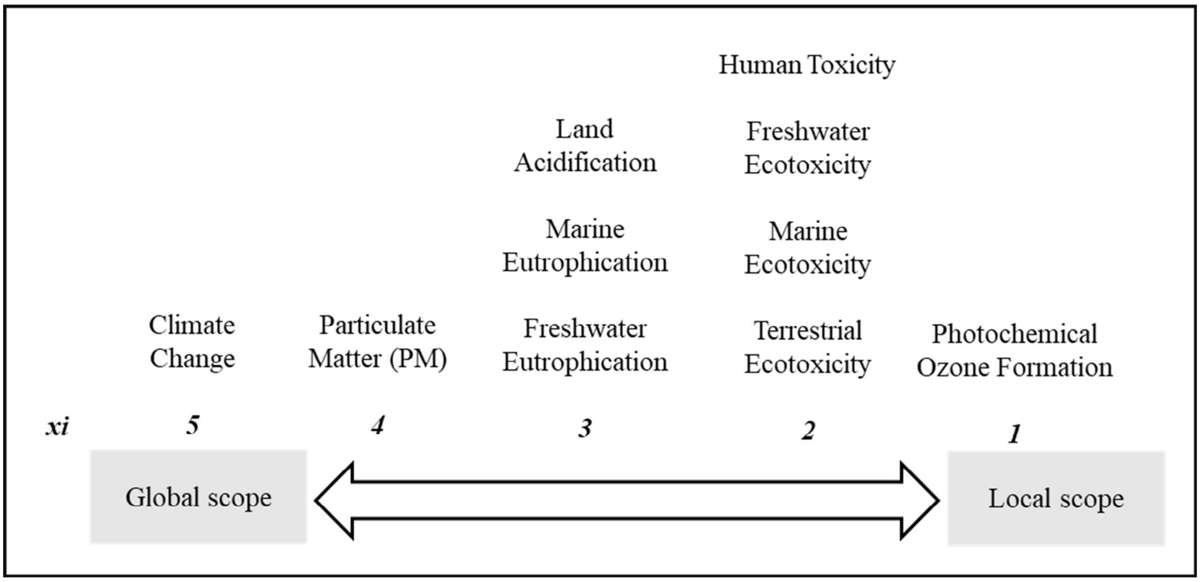

Fig. 6. Structure for determination of *xi*

Table 3. Waste, annual quantity and disposal

Waste	Annual quantity	Disposal
Ceramic remains (shards)	58,585 kg	Sent to rural owners (application on stretches of bumpy roads)
Ashes from burning eucalyptus chips	2,070 kg	Sent to rural owners (application on stretches of bumpy roads)
Cardboard	1,200 kg	Recycling
Burnt/used oil	576 L	Used to lubricate the trolleys
Plastic	720 kg	Recycling
Clay remains (Rebar)	10,800,000 t	Reused in the production process
Steel drum	624 kg	Recycling
Gases from furnace chimneys	3,553,000 kg	Released into the air

Table 4. Calculations of environmental potential impact (*Ii,j*) for each RECIPE (2016) category

Waste/ Byproduct	Climate change (kg CO_2 eq)	Land acidification (kg SO_2 eq)	Eutrophication of freshwater (kg P eq)	Marine eutrophication (kg N eq)	Human toxicity (kg 1,4-DB eq)	Photochemical ozone formation (kg NMVOC)	Particulate material (kg PM10 eq)	Earth ecotoxicity (kg 1,4-DB eq)	Ecotoxicity of freshwater (kg 1,4-DB eq)	Marine ecotoxicity (kg 1,4-DB eq)
Ceramic remains (shards)	0	0	0	0	7.49×10^{1}	0	0	4.78×10^{-1}	4.78×10^{-1}	2.29×10^{-3}
Ashes from burning eucalyptus chips	0	0	4.55×10^{1}	0	7.07×10^{3}	0	0	3.22×10^{2}	1.23×10^{1}	1.19×10^{2}
Clay remains (rebar)	0	0	0	0	0	0	0	0	0	0
Cardboard	0	4.42	0	3.60×10^{3}	0	0	0	0	0	0
Plastic	0	0	0	0	0	0	0	0	0	0
Burnt/used oil	0	4.6	3.40×10^{-1}	0	3.65	0	0	5.38	4.70×10^{-1}	1.00×10^{-1}
Steel drum	0	0	0	0	6.10×10^{1}	0	0	5.46×10^{2}	2.67×10^{2}	1.53×10^{2}
Gases from the ceramic furnace chimneys	4.80×10^{6}	1.09×10^{4}	0	7.37×10^{2}	0	1.89×10^{4}	5.24×10^{3}	0	0	0

p/year: person/year. P: phosphorus. N: nitrogen. DB: dichlorobenzene. NMVOC: non-methane volatile organic compound. PM: particulate matter.

possible for *Ki*:

a) If the waste/byproduct does not have a correct disposal, $K = 0$.

b) Otherwise, $K = 1$.

RESULTS AND DISCUSSION

To test the proposed index, field research in a ceramic company were carried out. Data referring to the annual production of waste from each manufacturing step were collected from documents available in the company (Table 3).

Table 4 presents the calculated potential impact (*Ii,j*) of the environmental categories of RECIPE (2016) (Huijbregts et al., 2017) for each waste. The following categories were considered: climate change, particulate matter, land acidification, marine eutrophication, freshwater eutrophication, human toxicity, fresh water ecotoxicity, marine ecotoxicity, land ecotoxicity and photochemical ozone formation.

The normalization step was carried out based on the computated potentials as shown in Table 2, divided by the normalization factor, as shown in Table 5. These categories equivalencies are established using the RECIPE (2016) method (Huijbregts et al., 2017).

The normalized results can be seen in Table 6. From Table 6, as expected, ceramic remains (shards), ashes from burning eucalyptus chips, clay remains (rebar), cardboard, plastic, burnt/used oil, and steel drums had no impact on the climate change category and land acidification. As for the freshwater eutrophication category, only ashes from burning eucalyptus chips had any impact. In the marine eutrophication category, cardboard and gases from the ceramic furnace chimneys had an impact. Interestingly, in the human toxicity category, ashes from burning eucalyptus chips had some impact, while ceramic remains, burnt/used oil and steel drums had negligible results. In the photochemical ozone formation and particulate matter categories, only gases from the ceramic furnace chimneys had an impact. In the three ecotoxicity categories, only ashes from burning eucalyptus chips and steel drum had a significant impact.

With the previous data, the IAHP method was applied using *MindDecider* software, providing the calculation of the relative weight *Va(i)* (Table 7). The IAHP method works with objective, criteria and alternatives. It was considered as objective the impacts of the waste/sub-products in the production process. As criteria were considered the categories: climate change, particulate matter, land acidification, marine eutrophication, freshwater eutrophication, human toxicity,

Table 5. Standardization factor used

Environmental Impact Category	Unit/Dimension	Normalization factor
Climate change	kg CO_2 eq/p/year	6.89×10^{3}
Land acidification	kg SO_2 eq/p/year	3.82×10^{1}
Eutrophication of freshwater	kg P eq/p/year	2.90×10^{-1}
Marine eutrophication	kg N eq/p/year	7.34
Human Toxicity	kg 1,4-DB eq/p/year	3.26×10^{2}
Photochemical ozone formation	kg NMVOC/p/year	5.67×10^{1}
Particle material	kg PM10 eq/p/year	1.41×10^{1}
Earth ecotoxicity	kg 1,4-DB eq/p/year	5.93
Ecotoxicity of freshwater	kg 1,4-DB eq/p/year	4.30
Marine ecotoxicity	kg 1,4-DB eq/p/year	2.46

p/year: person/year. P: phosphorus. N: nitrogen. DB: dichlorobenzene. NMVOC: non-methane volatile organic compound. PM: particulate matter.

Source: RECIPE (2016)

Table 6. Normalized potentials

Waste/ Byproduct	Climate change (p/year)	Land acidification (p/year)	Freshwater eutrophication (p/year)	Marine eutrophication (p/year)	Human toxicity (p/year)	Photochemical ozone formation (p/year)	Particulate matter (p/year)	Terrestrial ecotoxicity (p/year)	Freshwater ecotoxicity (p/year)	Marine ecotoxicity (p/year)
Ceramic remains (shards)	0	0	0	0	2.30×10^{-1}	0	0	8.06×10^{-2}	1.11×10^{-1}	9.29×10^{-4}
Ashes from burning eucalyptus chips	0	0	1.57×10^{2}	0	2.17×10^{1}	0	0	5.43×10^{1}	2.86	4.84×10^{1}
Clay remains (rebar)	0	0	0	0	0	0	0	0	0	0
Cardboard	0	0	0	4.90×10^{2}	0	0	0	0	0	0
Plastic	0	0	0	0	0	0	0	0	0	0
Burnt/used oil	0	0		0	1.12×10^{-2}	0	0	9.07×10^{-1}	1.09×10^{-1}	4.07×10^{-2}
Steel drum	0	0	0	0	1.87×10^{-1}	0	0	9.20×10^{1}	6.20×10^{1}	6.23×10^{1}
Gases from the ceramic furnace chimneys	6.97×10^{2}	2.84×10^{2}	0	1.00×10^{2}	0	3.33×10^{2}	3.71×10^{2}	0	0	0

p/year: person/year

Table 7. Relative weight of environmental potential for each waste

WASTE	*V(a)i* (%)
Gases from the burning of chips	30.850
Ashes from chip burning	30.483
Steel drum	28.937
Cardboard	9.434
Used oil/ Burnt oil	0.194
Ceramic remains (shards)	0.102
Clay waste (burr)	0
Plastic	0
TOTAL	100

Table 8. Results of *V(a)i*, *Ai*, *Ki*, *CIRI*, and percentage of participation in the general CIRI for the test company

Waste/Byproducts	Relative ponderation (*V(a)i*)	Relative geographic coverage of the emission (*xi*)	Disposal evaluation (*Ki*)	CIRI (%)	Contribution to CIRI (%)
Gases from the burning of chips	30.85000	5	0	0.00000	0.000000000
Ashes from burning eucalyptus chips	30.48300	2	0	0.00000	0.000000000
Steel drum	28.93700	2	1	19.16459	66.699704960
Cardboard	9.43400	3	1	9.37202	32.618015858
Used/burned oil	0.19400	2	1	0.12848	0.447169463
Ceramic remains (shards)	0.10200	2	1	0.06755	0.235109718
Clay remains (rebar)	0.00000	1	1	0.00000	0.000000000
Plastic	0.00000	1	1	0.00000	0.000000000
TOTAL	100	21		**28.73265**	100.00000

freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity and photochemical ozone formation. As alternatives, we considered the eight waste/byproducts of the production process: 1) ceramic remains (shards); 2) ash from the burning of eucalyptus chips; 3) clay remains; 4) cardboard; 5) plastics; 6) burnt/used oil; 7) steel drums; 8) gases from the burning of chips. In this way, a parity comparison of the alternatives was made (two by two comparisons) through the *Mind Decider* software. The result of this step is the relative weight potential list, as can be seen in Table 7.

From the determination of *V(a)i*, *xi* and *Ki*, the CIRI index was calculated (Table 8). The major finding of this study concerns the potential for environmental impact on the manufacture of tiles and bricks. The residues with the greatest environmental impact, in the production of tiles and bricks, on a decreasing scale, are gases from the burning of chips (1.45´10^3 person/year), cardboard (4.90´10^2 person/year), ash from the burning of eucalyptus chips (2.84´10^2 person/year) and steel drum (2.16´10^2 person/year).

From Table 7, the residue with the highest relative weight *Va(i)* calculated was the gases originating from the burning of chips (30.850%). The burning of eucalyptus chips from produces N_2, H_2O, O_2, SO_2, and NO_2 gases. CO_2 gas was disregarded in the calculations because eucalyptus is a renewable power source. It is a waste with high potential for environmental impact on the following environmental categories: climate change, land acidification, marine eutrophication, photochemical ozone formation and particulate matter. It is estimated that the company under study generated about 11,999,600 kg of N_2; 2,365,100 kg of H_2O; 5,400 kg of SO_2 and 18,900 kg of NO_2 through the burning of eucalyptus chips in 2020.

From Table 8, the relative participation of this waste in the CIRI was zero. That is, this residue had a negative impact on the formation of the CIRI. This is because the environmental suitability (*Ki*) of the disposal was rated $K = 0$. The ceramic industry releases these gases directly into the environment. This practice was considered environmentally inappropriate, even though it is legally licit.

The ash from the chip firing was the waste with the second largest relative weight *Va(i)* calculated (30.483%) (Table 7). The ashes present a wide spectrum of potentially hazardous chemical elements: Mg, Al, Si, P, S, K, Cl, Ca, Ti, Mn and Fe. It is a waste with high potential in terms of the following: fresh water eutrophication, human toxicity, terrestrial ecotoxicity, fresh water ecotoxicity and marine ecotoxicity. From Table 7, the ashes received a negative rating in terms of the final suitability of their disposal. These are destined to rural owners to be placed on bumpy roads. This way, $K = 0$. Therefore, the ashes had a negative impact on the final calculated CIRI.

The third residue (Table 7) with the highest relative weight *Va(i)* were the steel drums (28.937%). This waste is composed of stainless steel, having in its composition Fe, Cr and Ni. It affects the following categories: human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity and marine ecotoxicity. This waste is directed to the selective recycling collection, therefore, $K = 1$. Its percentage participation in the calculated CIRI corresponded to 66.69% (Table 8).

The fourth residue (Table 7) with the highest relative weight *Va(i)* was cardboard (9.434%). It is a waste rich in lignin, cellulose and hemicellulose (C, H, O, N and S). It has a potential impact on marine eutrophication. For the company studied, $K = 1$, as it is sent to a selective collection for recycling. These residues participate in 32.61% of the CIRI (Table 8).

The used/burned oil appears in the fifth place (Table 7) in terms of relative weight (*Va(i)*=0.194%). This waste is composed of S, Ca, Zn, Pb, Fe, Mg, Na, Si, B, Mn, Cu, Mo, Al, Sn, Cr, Ba, Ni, V and polycyclic aromatic hydrocarbons. The potential impact categories are: human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity and marine ecotoxicity. The disposal of this waste is considered adequate (selective collection for recycling) and therefore $K = 1$. Its percentage share in the final CIRI calculated was 0.447%.

The sixth waste (Table 7) with the highest relative weight *Va(i)* were the remains of ceramics (shards), with 0.102%. This waste is rich in SiO_2, Al_2O_3, Fe_2O_3, MgO, K_2O, CaO, TiO_2 and MnO, and impacts the following: human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity and marine ecotoxicity. The company generates about 58,585 kg of ceramic waste (shards) per year. All this waste is donated to rural landowners for placement on rural bumpy roads in the municipality. This way, $K = 1$. The ceramic fragments participate in 0.235% of the CIRI (Table 8).

In the seventh place of *Va(i)* (Table 7) appears the clay remains (burr), with the influence of 0%. Thus, this residue did not contribute to the formation of the CIRI. This is because clay remains (burr), had no impact on any category. To this waste, $K = 1$. This is because the burr leftovers are reused in the production process.

Also, with zero percent (0%), in terms *Va(i)*, are the plastic appears. This waste is composed exclusively of polypropylene, (PP), and does not impact on any analyzed category. It is reused in the company itself and, after that, it is destined to selective-recycling collection in the municipality, therefore, $K = 1$. Its contribution to CIRI is zero percent (0%).

The higher the CIRI, the better the company's environmental assessment. From Table 8, it can be observed the final CIRI calculated of 28.73% for the test company. This means that only 28.73% of the weighted mass of waste/byproducts has correct environmental management. This poor result is due to the inadequate disposal of gases from the burning of chips and ashes from the burning of eucalyptus chips.

Abrahão and Carvalho (2017), in consonance with this study, verified that most of the solid ceramic remains are just abandoned in unoccupied spaces nearby. A change in the fuel used in the kilns is suggested by the authors to manage the problem of the unequal burning process. This is not an affordable suggestion, as a transition to natural gas, for example, implies altering the way the kilns are fed, with structural modifications. Classic ceramic kilns (made to burn firewood or oil) can be transformed to burn natural gas or biogas, with an easier process and burning, resulting in more reasonable yields but with increased operating costs. Nonetheless, technological progress can certainly boost the competitiveness and survival of ceramic companies.

CONCLUSION

In this work, we developed an index for evaluating the environmental performance of the ceramic industry production process. The proposed index is directly related to the environmental impact of the waste, the spatial dispersion of the waste and the evaluation of waste disposal. It demonstrates, in percentage value, the adequacy of the disposal of the residues and byproducts generated by the manufacturing operations. This tool allows managers to aggregate efforts in the right direction to reduce the environment impact of waste.

This study found that: 1) the residues from the manufacture of ceramics with the greatest environmental impact are: gases from the burning of chips, cardboard, ash from the burning of eucalyptus chips and steel drums; 2) it is possible to create a rational index to assess the environmental performance of the industry, considering the amount of waste produced, as well as the environmental potential impact of each of them and the type of disposal that is carried out by the company. This study can be beneficial for companies in the ceramic sector and can help researchers uncover critical areas in the evaluation of production processes, driving the creation of new indices and mechanisms for the environmental assessment of industries of the most varied types. That is, new theories of environmental assessment on manufacturing processes can be created by academia and used in the future by manufacturers.

A great challenge found in this study was the collection and organization of production data in the company where the index was tested. It is possible that most companies in this sector practice a lot of informality in the information on the factory floor, that is, they do not maintain a systematic mechanism for collecting and organizing production information, which will prove to be difficult when performing environmental assessments.

It seems correct to say that, for those manufacturers that burn wood or biomass to dry the tiles, maybe in the case of the larger number of manufacturers in Latin America, the results found in this study are very illustrative. The waste whose disposal was considered inadequate in the case study (gases from the burning of chips and ashes from the burning of eucalyptus chips) probably have the same incorrect disposal in most companies.

The test company obtained a CIRI index of 28.732%, which means that 28.732% of the waste and byproducts have a destination considered environmentally adequate. This obviously cannot be considered a good result.

The test study has indicated that the proposed index is an adequate tool for evaluating the environmental performance of the ceramic sector. The gases originating from chip burning, as N_2, H_2O, SO_2 and NO_2, are released into the atmosphere, affecting global warming. Ashes from the burning of chips are disposal inappropriately in the ground, and from there they can be dragged by the action of rain to water courses.

For future works, the proposed index can be expanded to encompass mining activities (clay extraction). Clay extraction in flat alluvial terrain is one of the most impactful forms of mining, as it is carried out in the open and in areas close to water resources. An analysis integrating environmental and landscape impacts can be added to the new index. Otherwise, future studies may consider the environmental fragility of the watershed where the manufacturing company is located, in order to develop an environmental assessment index with considerations on terrain slope, rainfall, pedology and land use and land occupation.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research

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