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EMERGY ANALYSIS AND ENVIRONMENTAL INDICES APPLIED TO A COMPANY PRODUCING ALUMINIUM EXTRUDED BARS

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ABSTRACT

In this paper we apply two methodologies to a company that produces aluminium extruded bars: (1) the 'pollutant interaction matrix method', which allows the calculation of a global environmental protection index (Ep) in order to verify the eco-compatibility of the industrial activity, and (2) emergy analysis, a methodology used to evaluate the sustainability of an activity. The first methodology, which is applied to evaluate the environmental pollution risk, requires defining, for the whole industrial process, sectors of activities (defined as construction sites where activities of the same type are carried out) and a set of parameters (t = duration of pollution effect, P = quantity of pollutant produced, G = hazard of the pollutant) for each activity. Furthermore, to obtain information on the environmental cost of the whole industrial process, in terms of use of resources (fuel, electricity, water, etc.) we apply the emergy methodology as a complementary index for a global evaluation of sustainability. The environmental index results show that although the evaluated $\mathrm{Ep}_{\mathrm{ratio}}$ has a very low value (0.18), indicating that the whole process is non-polluting, some activities of the industrial process generate local pollution which could be dangerous for the workers' health. The emergy analysis indicates that the most remarkable emergy flows are mainly associated with the use of aluminium panels and the consumption of electricity and methane.

Keywords: aluminium extruded bars, emergy per unit, pollution risk, sustainability indicators.

1 INTRODUCTION

Production process externalities are the costs imposed on society and the environment, which are not included in the market price. They include damage to the natural and built environment, such as the effects of air pollution on health, buildings, crops, forests and global warming, occupational disease and accidents, and reduced amenity from visual intrusion of plants or emissions of noise. Traditional economic assessment of production processes has tended to ignore these effects; however, there is a growing interest in adopting a more sophisticated approach involving the quantification of these environmental and health impacts of energy and material use and their related external costs. For this purpose the International Standardization Organization (ISO) 9000/14000 and Eco-Management and Audit Scheme (EMAS) norms have been introduced [1, 2]; not only must products be in conformity with the ISO and EMAS requirements but the process is also required to guarantee the continuity of production by avoiding the risk of stopping the plant because of environmental violations and/or the occurrence of accidents. Environmental indices have been studied to track and understand ecosystems [3–6]. In this paper an integrated approach is proposed using:

1. a methodology to evaluate the environmental pollution risk of a company [7] that produces aluminium bars by means of the environmental protection index (Ep);
2. an ecological indicator, emergy analysis, to evaluate the environmental cost.

2 EVALUATION OF THE ENVIRONMENTAL PROTECTION INDEX (Ep)

2.1 Model implementation

The whole industrial productive cycle is described in Fig. 1.

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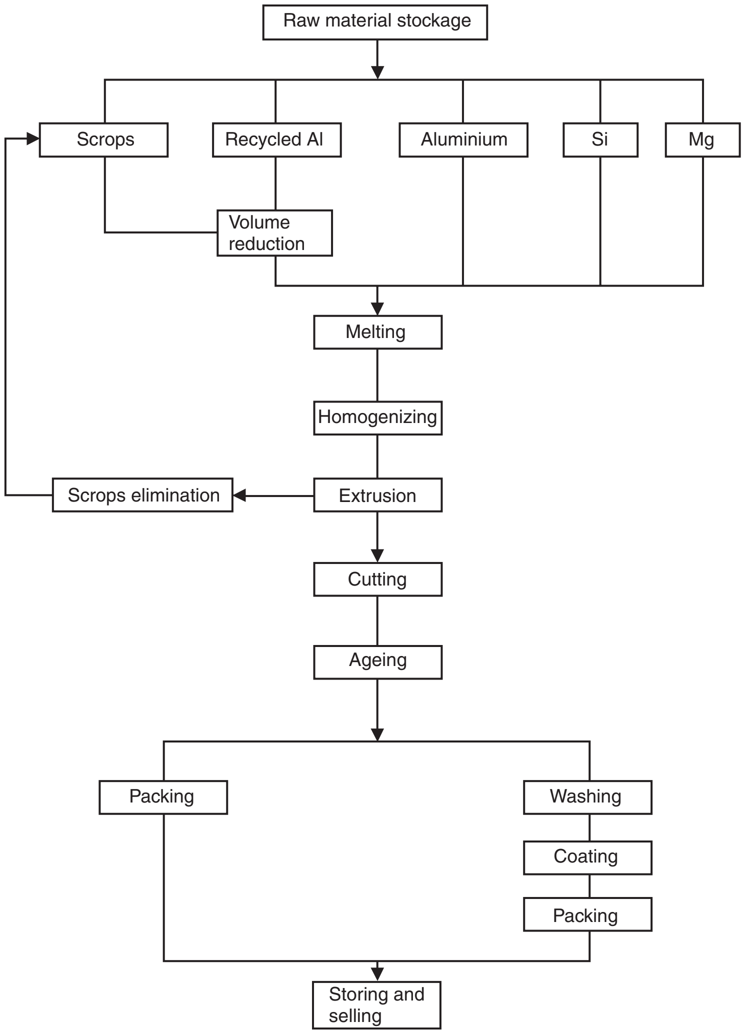

Figure 1: Description of the productive cycle.

The industrial building is divided into three sectors:

- Sector A: Foundry
- Sector B: Extrusion process
- Sector C: Coating and packing

Each sector is characterized by a set of 'variable parameters' (t, G, P) that are defined below:

- t is the duration (in hours) of pollution; the values range from 0 to 1 and correspond to 1/24 of the duration of the polluting effect for a determined activity; the reference unit is a working day of 24 h including fractions.
- G expresses the hazard of the pollutant; it depends on the severity of the consequences due to the specific pollutant.
- P is derived from the amount of pollutant thrown into the environment.

Table 1: Evaluation of parameters P and G by considering the amount of pollutants produced and the health risk involved.

P and G values	P	G
0	Absence of pollutant	No pollution
0.1	Very low production of pollutant, no hazard	Pollution without consequence
0.25	Low production of pollutant, no hazard	Limited and controlled pollution
0.50	Remarkable production of pollutant, no hazard	Remarkable but controlled pollution
0.75	High production of pollutant	Remarkable pollution, not controllable, health risk
1	Very high production of pollutant (limit of law)	High pollution, irreversible, severe health risk

Table 1 lists the data for the evaluation of parameters G and P, with reference to each sector. For each type of pollution, it is possible to determine the hazard and the pollutant indices whose values are included in the range 0–1.

The product of the factors t, G and P gives an index of pollution Y which refers to a specific operation as well as a specific type of pollution:

$$t \times G \times P = Y\text{sector/material/type of pollution.}$$

If there is no interaction, the result will be $Y = 0$.

If we consider each operation related to the raw material aluminium (Al) in sector A, it is possible to evaluate several indices of environmental pollution as follows:

$$Y_{\mathrm{A/Al/air}}, Y_{\mathrm{A/Al/water}}, Y_{\mathrm{A/Al/soil}}, Y_{\mathrm{A/Al/acoustic}}, \text{etc.}$$

This procedure is applied to all the raw materials and to all the operations in sector A in order to obtain more indices $Y_{\mathrm{A}/i/\mathrm{air}}$, $Y_{\mathrm{A}/i/\mathrm{water}}$, $Y_{\mathrm{A}/i/\mathrm{soil}}$, $Y_{\mathrm{A}/i/\mathrm{acoustic}}$, etc. (where i indicates a material or an operation), which allows the evaluation of a 'matrix of process pollutants' that lists the material involved in rows and the type of pollution in columns (Table 2). In accordance with this procedure, the pollution index (Y_L) value referring to each type of pollutant and each raw material in sector A is calculated as a summation by columns. Each obtained value represents the numerical measure of the environmental sustainability of the different operations in sector A. The same procedure should be applied to all sectors in order to obtain a new matrix, shown in Table 3, called 'polluting processes matrix' where the elements are given by all the Y_L values evaluated previously. The sum of elements contained in the rows of the 'polluting processes matrix' (see Tables 3 and 7) gives, for each homogeneous sector, an index L_{sector}. For each sector it is possible to evaluate two values of L: $L_{\max}$ (which is a theoretical value corresponding to G, P and t values $= 1$ for each polluting process) and $L_{\exp}$ (which is the effective L value calculated based on the number and intensity of the polluting processes occurring in each sector). Areas characterized by processes with high hazard potential ($L_{\exp}$ close $L_{\max}$) require urgent action on the productive layout.

Table 2: Matrix of process pollutants for sector A.

	Air	Water	Soil	Acoustic	. . .	. . .
Material 1	$Y_{A/1/\text{air}}$	$Y_{A/1/\text{water}}$	$Y_{A/1/\text{soil}}$	$Y_{A/1/\text{acoustic}}$	$Y_{A/1/\ldots}$	. . .
Material 2	$Y_{A/2/\text{air}}$	$Y_{A/2/\text{water}}$	$Y_{A/2/\text{soil}}$	$Y_{A/2/\text{acoustic}}$	$Y_{A/2/\ldots}$	. . .
Material 3	$Y_{A/3/\text{air}}$	$Y_{A/3/\text{water}}$	. . .	. . .	. . .	. . .
Material 4	. . .	. . .	$Y_{A/4/\text{soil}}$	$Y_{A/4/\text{acoustic}}$	. . .	. . .
. . .	. . .	. . .	. . .	. . .	. . .	. . .
Sector A	$\Sigma Y_{A/i/\text{air}}$ $=Y_{L/A/\text{air}}$	$\Sigma Y_{A/i/\text{water}}$ $=Y_{L/A/\text{water}}$	$\Sigma Y_{A/i/\text{soil}}$ $=Y_{L/A/\text{soil}}$	$\Sigma Y_{A/i/\text{acoustic}}$ $=Y_{L/A/\text{acoustic}}$	$\Sigma Y_{A/i/\ldots}$ $=Y_{L/A/\ldots}$	$\Sigma Y_{A/i/\ldots}$ $=Y_{L/A/\ldots}$

Table 3: Matrix of polluting processes considering all the homogeneous sectors.

	Air	Water	Soil	Acoustic	. . .
Sector A	. . .	$Y_{L/\text{A/water}}$	$Y_{L/\text{A/soil}}$	$Y_{L/\text{A/acoustic}}$	$Y_{L/A/\ldots}$
Sector B	$Y_{L/\text{B/air}}$	$Y_{L/\text{B/water}}$	$Y_{L/\text{B/soil}}$	$Y_{L/\text{B/acoustic}}$	$Y_{L/B/\ldots}$
Sector C	$Y_{L/\text{C/air}}$	$Y_{L/\text{C/water}}$	. . .	. . .	. . .
Sector D	. . .	. . .	$Y_{L/\text{D/soil}}$	$Y_{L/\text{D/acoustic}}$	. . .
. . .	. . .	. . .	. . .	. . .	. . .

The sum by column of the elements of the matrix of the polluting processes gives, for each column, an index R which represents the amount of pollutant for each type of pollution (Tables 3 and 7).

The sum by row of the different values of L_{exp} gives a resulting value called 'index of environmental protection':

$$\sum_{i=\text{sector A}}^{\text{sector N}} L_i = \text{Ep}_{\text{exp}}.$$

The sum of the different values of L_{max} gives a resulting value called maximum index, Ep_{max}.

The ratio $\text{Ep}_{\text{ratio}} = \text{Ep}_{\text{exp}}/\text{Ep}_{\text{max}}$ indicates the sustainability of the whole productive cycle by means of the relation:

$$0 \leq \text{Ep}_{\text{ratio}} \leq 1,$$

where 0 refers to a totally sustainable process and 1 means that the process is totally unsustainable.

As a consequence of the values obtained and the immediate identification of the most polluted sectors and operations, companies can decide whether and how to intervene so as to improve the environmental performance, as described in Fig. 2. A reiterative application of the method gives an evaluation of the efficiency of the chosen remedy.

There are considerable differences between the behaviour of the smallest and the largest particles within our range of interest, roughly from molecular sizes up to 103 μm. The smaller particles closely follow the motion of the surrounding gas and may remain airborne almost indefinitely, while the larger particles have an appreciable acceleration under gravity and are relatively easy to precipitate.

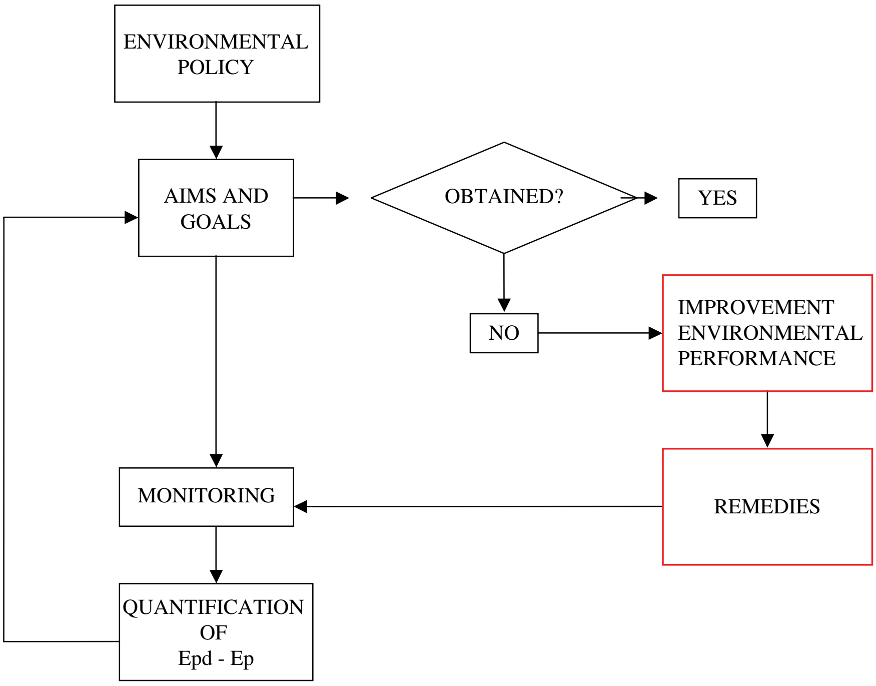

Figure 2: Scheme of the company environmental performance.

Nevertheless, large grains of dust are transported for many miles under favourable atmospheric conditions.

2.2 Construction of the 'matrix of polluting processes'

For each sector, several types of pollution (air pollution, acoustic pollution, dust production, solid waste production, chemical discharge in sewage, vibrations, thermal pollution, gas production) were considered as reported below.

Sector A (Foundry): The operations involved in this sector are described below and the results obtained are reported in Table 4.

- *Raw materials and scraps collection and stockage:* The operation involves two types of pollution: air pollution and solid waste production. The stocking area is full 24 h a day ($t = 1$), produces very low quantities of dust and solid particles in the atmosphere ($P = 0.1$) consequently with limited and controlled air pollution ($G = 0.1$).
- *Volume reduction:* The raw materials are ground by means of a mechanical device to a size of 30 cm. The duration of the operation is 18 h ($t = 0.66$) and the main types of pollution are dust, acoustic pollution and vibrations in remarkable but controlled production (P and $G = 0.5$).
- *Melting operation:* The ground aluminium chips are transported by a conveyor belt to an oven heated at a temperature of 720–740°C by a combination of electric power and methane combustion. After cooling, the aluminium bars are cut to the required size. The duration of the operation is 18 h ($t = 0.66$) and the consequent types of pollution are: remarkable but controlled gas production

Table 4: Calculation of the pollution indices Y_L for sector A (foundry).

Operation	Pollution	t	G	P	Y_A	Y_i	Pollution	Y_L
Raw materials and scraps collection	Air pollution	1	0.1	0.1	0.01	0.01	Air pollution	0.175
	Solid waste		0.1	0.1	0.01	0.01	Gas production	0.18
Volume reduction	Dust production	0.66	0.5	0.5	0.25	0.165	Acoustic pollution	0.165
	Acoustic		0.5	0.5	0.25	0.165	Thermal pollution	0.07
	Vibrations		0.5	0.5	0.25	0.165	Dust production	0.165
Melting	Gas production	0.66	0.5	0.5	0.25	0.165	Solid waste	0.05
	Air pollution		0.5	0.5	0.25	0.165	production	0.165
	Thermal pollution		0.1	0.75	0.075	0.049	Vibrations	
Homogenizing	Solid waste	0.66	0.25	0.25	0.0625	0.04		
	Gas production		0.25	0.1	0.025	0.0165		
	Thermal pollution		0.1	0.25	0.025	0.0165		

(CO_x, NO_x) and air pollution (P and $G = 0.5$), high but without consequence thermal pollution ($P = 0.75, G = 0.1$) and low solid waste production (P and $G = 0.25$).

- *Homogenizing:* Before the extrusion process, the aluminium bars require a homogenizing treatment (heated at 530°C for 12 h in a secondary oven). This operation produces gas and low quantity of thermal pollution.

Sector B (Extrusion process): The operations are described below.

- *Extrusion:* The aluminium bars are pre-heated at the temperature of 450°C, cut into smaller pieces and transported to the extruder where the material passes through a press. During this operation thermal pollution, acoustic pollution and vibrations occur.
- *Cutting:* The extruded bar is cut to the required dimensions by a squaring shear creating dust production and acoustic pollution.
- *Ageing and cooling*: The extruded bars obtained are transported to another oven where an ageing treatment, in order to improve the mechanical properties, is carried out. Vibrations, thermal pollution and acoustic pollution occur.

P, G, t and Y_L values relative to all the operations involved in this sector are reported in Table 5.

Sector C (Coating and packing):

- *Washing:* This operation is required to perfectly clean the surface of the aluminium bars in order to obtain a good coating. Different chemical solutions are used following the sequence: (1) sodium hydroxide, (2) water, (3) acidic solutions, (4) water, (5) nitric acid and chromic acid solutions, (6) water. During the washing operation, high concentrations of chemicals, with controlled pollution, are discharged.
- *Coating:* After drying, the bars are coated by the electrostatic method which involves the induced deposition of very fine solid particles of enamel (previously electrically positive charged) on the aluminium bars (previously negative charged). After the deposition, the bars are heated in an oven at 180°C. Vibrations, air pollution, acoustic pollution and dust production occur.

Table 5: Calculation of the pollution indices Y_L for sector B (extrusion process).

Operation	Pollutant	t	G	P	Y_B	Y_i	Pollution	Y_L
Extrusion	Thermal pollution	1	0.1	0.1	0.01	0.01	Acoustic pollution	0.375
	Acoustic pollution		0.5	0.25	0.125	0.125	Thermal pollution	0.015
	Vibrations		0.5	0.5	0.25	0.25	Dust production	0.25
Cutting	Dust production	1	0.5	0.5	0.25	0.25	Vibrations	0.3125
	Acoustic pollution		0.5	0.25	0.125	0.125		
Ageing and cooling	Vibrations	0.5	0.5	0.25	0.125	0.0625		
	Thermal pollution		0.1	0.1	0.01	0.005		
	Acoustic pollution		0.5	0.5	0.25	0.125		

Table 6: Calculation of the pollution indices Y_L for sector C (coating and packing).

Operation	Pollutant	t	G	P	Y_C	Y_i	Pollution	Y_L
Washing	Air pollution	1	0.25	0.5	0.125	0.125	Air pollution	0.3125
	Chemical discharge in sewage		0.5	0.75	0.375	0.375	Acoustic pollution Dust production	0.125 0.25
Coating	Air pollution	1	0.25	0.75	0.1875	0.1875	Solid waste production	0.025
	Acoustic pollution		0.5	0.25	0.125	0.125		
	Dust production		0.5	0.5	0.25	0.25	Chemical discharge in sewage	0.375
Packing	Solid waste production	1	0.25	0.1	0.025	0.025		

- *Packing and solid waste production:* This is the last operation of the process. The coated bars are packed using paper sheets and stored. Solid wastes are produced.

The results obtained for sector C (t, P, G and Y_L) are reported in Table 6.

The contribution of each type of pollution for each sector is reported in the matrix of the polluting processes in Table 7.

The comparison between the various indices is useful because even though the whole process seems to be sustainable ($\mathrm{Ep_{max}} = 17$; $\mathrm{Ep_{exp}} = 3.12$; $\mathrm{Ep_{ratio}} = 0.18$), there are some operations, such as extrusion, coating, washing, packing, that involve pollutant production: during the coating operation there is a remarkable production of dust ($Y_{\mathrm{C/dust\ production}} = 0.25$, Table 6); during the washing operation chemicals are discharged in sewage ($Y_{\mathrm{C/chem.\ disch.}} = 0.375$, Table 6); during the extrusion operation vibrations occur $Y_{\mathrm{B/vibration}} = 0.25$, Table 5).

Table 7 allows the immediate identification of the most significant pollutants for each sector. If we compare the L_i values for sectors A and B (0.95 and 0.98, respectively), we can see that in sector A there are more pollutants which influence to a lesser degree because of the smaller values of ($Y_L = 0.17, 0.18, 0.16, 0.07, 0.16, 0.0,; 0.16$), while in sector B the Y_L values are higher ($Y_L = 0.375$, 0.25, 0.3125). Specifically, the value $Y_L = 0.375$, which is significantly high, could influence the company in its decision on what action to take to improve the environmental efficiency and thereby obtain the environmental quality certification.

Table 7: Matrix of polluting processes. The ratio $\mathrm{Ep}_{\mathrm{exp}}/\mathrm{Ep}_{\mathrm{max}} = (3.12/17) = 0.18$.

	Air pollution	Gas production	Acoustic pollution	Thermal pollution	Dust production	Solid waste	Chemical discharge in sewage	Vibrations		$L_i = \Sigma Y_{L(\mathrm{row})}$	$L_i = \Sigma Y_{L(\max)}$
Sector 1: Foundry	0.17	0.18	0.16	0.07	0.16	0.05	0	0.16		0.95	7
Sector 2: Extrusion	0	0	0.37	0.04	0.25	0	0	0.31		0.98	4
Sector 3: Coating and packing	0.31	0	0.12	0	0.25	0.02	0.37	0.12		1.19	6
										$\mathrm{Ep}_{\mathrm{exp}}$	$\mathrm{Ep}_{\mathrm{max}}$
Global pollution value	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_s	3.12	17
$R_n = \Sigma Y_{L(\mathrm{column})}$	0.48	0.18	**0.65**	0.11	**0.66**	0.07	0.37	**0.60**			

The values in bold indicate the most significant pollutants for each sector.

3 ECOLOGICAL INDICATOR: EMERGY ANALYSIS

3.1 Evaluation of the emergy flows

Emergy is an expression of all the energy (and resources) used in the work processes that generate a product or service and is expressed as units of one type of energy [8]. In the most general sense, the total emergy driving a process is a measure of the activities required and converged to make that process possible. It is a measure of work (in both the past and the present) necessary to provide a given resource or service [9, 10]. To evaluate the quality of the energy flows, transformities can be calculated and compared with other energy forms. The solar transformity of services and products generated by the system under study is obtained by dividing the total emergy input required by the energy of the product or service. Figure 3 shows a diagram of emergy flows involved in the whole process. Renewable and non-renewable resources are supposed to act in the system where they enter from the left in the diagram, transformations occur inside and products are obtained on the right. Tables 8–10 report the emergy values for the foundry, the extrusion process and the coating process, respectively. The transformities used for the calculations are mainly found in the literature as reported in Appendix A. The calculation procedure adopted for the foundry process is given in Appendix B; for the other two processes similar relations were used.

3.2 Emergy results

Results of emergy analysis are reported in Tables 8–10. Column 1 is the name of the item involved in the process; column 2 is the raw data in joules, grams or euros, usually evaluated as flux per year;

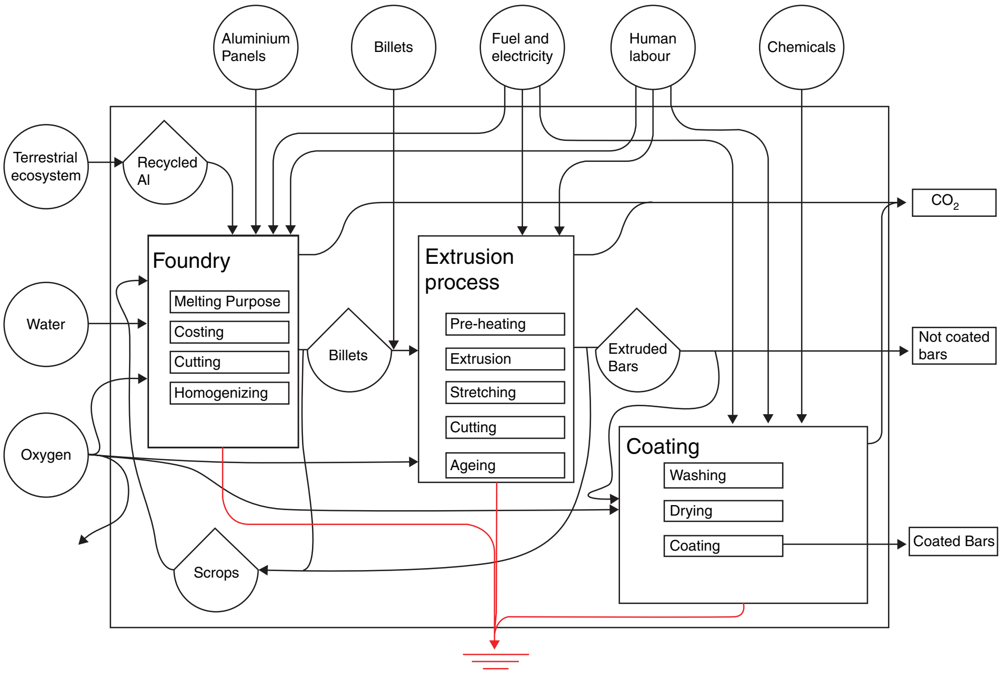

Figure 3: Diagram of emergy flows.

Table 8: Evaluation of the emergy flows for the foundry.

1 Item	2 Quantity per year (J, g, €)	3 Emergy per unit (sej/unit)	4 Emergy flow (sej/year)
Electricity	1.89E12 J	1.43E5 sej/J	2.70E17 sej
Human labour	2.80E10 J	7.38E6 sej/J	2.07E17 sej
Methane	3.55E13 J	4.80E4 sej/J	1.70E18 sej
Recycled aluminium	3.58E9 g	12.53E9 sej/g	4.48E19 sej
Aluminium panels	2.49E9 g	12.53E9 sej/g	3.12E19 sej
Aluminium scraps from billets	1.16E9 g	12.53E9 sej/g	1.45E19 sej
Aluminium scraps from draw pieces	0.30E9 g	12.53E9 sej/g	3.75E18 sej
Other materials*	2.30E7 g (42,735 €)	1.4E12 sej/€	5.98E16 sej
Water	3.23E9 g	3.40E5 sej/g	1.09E15 sej
Oxygen	2.56E9 g	5.16E7 sej/g	1.32E17 sej
Maintenance cost	9.50E3 €	1.4E12 sej/€	1.33E16 sej
Plant construction cost	2.15E5 €	1.4E12 sej/€	3.02E17 sej
Total emergy for billets production	7.14E9 g	1.35E10 sej/g	9.68E19 sej

*Other materials:
Magnesium consumed = 1.15E7 g/year; Mg cost = 0.0015 €/g; Mg total cost = 17325 €/year.
Silicon consumed = 1.15E7 g/year; Si cost = 0.0022 €/g; Si total cost = 25410 €/year.
Total cost = 42735 €/year for 2.30E7 g of materials.

Table 9: Evaluation of the emergy flows for the extrusion process.

1 Item	2 Quantity per year (J, g, €)	3 Emergy per unit (sej/unit)	4 Emergy flow (sej/year)
Electricity	1.01E13 J	1.43E5 sej/J	1.44E18 sej
Human labour	9.16E10 J	7.38E6 sej/J	6.76E17 sej
Methane	1.82E13 J	4.80E4 sej/J	8.73E17 sej
Billets	5.97E9 g	1.35E10 sej/g	8.06E19 sej
Billets from others	1.66E9 g	1.35E10 sej/g	2.24E19 sej
Oxygen	1.31E9 g	5.16E7 sej/g	6.75E16 sej
Maintenance cost	9.50E3 €	1.4E12 sej/€	1.33E16 sej
Plant construction cost	2.74E5 €	1.4E12 sej/€	3.84E17 sej
Sodium aluminate*	2.0E7 g	1.4E12 sej/€	1.96E16 sej
Total emergy for extrusion products	7.64E9 g	1.39E10 sej/g	10.63E19 sej

*Sodium aluminate treatment cost = 1.4E4 €/year for 2.0E7 g of material per year.

Table 10: Evaluation of the emergy flows for the coating sector.

1 Item	2 Quantity per year (J, g, €)	3 Emergy per unit (sej/unit)	4 Emergy flow (sej/year)
Electricity	1.87E12 J	1.43E5 sej/J	2.67E17 sej
Human labour	4.33E10 J	7.38E6 sej/J	3.19E17 sej
Methane	5.70E12 J	4.80E4 sej/J	2.73E17 sej
Extruded bars	2.39E9 g	1.39E10 sej/g	3.32E19 sej
Oxygen	0.41E9 g	5.16E7 sej/g	2.11E16 sej
Maintenance cost	1.10E4 €	1.4E12 sej/€	1.54E16 sej
Plant construction cost*	1.25E5 €	1.4E12 sej/€	1.54E16 sej
Total emergy for coated products	2.39E9 g	1.43 sej/g	3.42E19 sej

*Plant construction cost: in order to obtain the cost per year, it was assumed that the plant life is 20 years. The total cost for plant construction, 2.5E6, was then divided by 20 years (2.5E6/20 = 1.25E5 €).

column 3 is the transformity used for calculations, expressed in solar emergy joule per joule or other appropriate units (sej/€, sej/g); column 4 is the solar emergy of a given flow, calculated as the input times the transformity (column 2 × column 3). The sum of all the solar emergy values in column 4 gives the total emergy flow for each process. On dividing this value by the quantity reported in column 2, a new transformity is obtained (i.e. on dividing the total emergy flow of the foundry, 9.68E19 sej, by the quantity of billets produced, 7.14E9 g, the transformity of the billet is obtained). For each table (Tables 8, 9 and 10), a new transformity was obtained for the manufactured aluminium. It is possible to compare the transformity of raw aluminium (12.5E9 sej/g) with the transformity of the aluminium billets (1.35E10 sej/g, Table 8) coming out from the foundry, the transformity of the extrusion product (1.39 E10 sej/g, Table 9) and the transformity of the coated aluminium bars (1.43 sej/g, Table 10). As expected, the transformity value increases due to the energy flows involved in each process, as described in Fig. 3 (renewable and non-renewable resources such as electricity, fuel, materials, human labour, water, oxygen, etc.). The most remarkable emergy flows are mainly associated with electricity and methane consumption and to the use of aluminium panels, due to the high solar emergy content of raw aluminium.

4 CONCLUSION

The application of the matrix method permits the company to evaluate the environmental protection indices (Ep, Y_L, L_i) but does not provide information on the environmental cost of the whole industrial process, in terms of use of resources (fuel, electricity, water, etc.). For this purpose, we recommend the application of emergy analysis as a complementary index for the global evaluation of sustainability. The integrated results of the two methodologies applied suggests that an effort towards the practice of energy recovery and the use of renewable resources can lead to socioeconomic savings and a more sustainable way of living.

APPENDIX A: LIST OF REFERENCES FOR THE TRANSFORMITIES USED

Electricity = 1.43E5 sej/J [11]
Human labour = 7.38E6 sej/J [12]
Methane = 4.80E4 sej/J [8]
Oxygen = 5.16E7 sej/g [13]
Money = 1.4E12 sej/€ [14]
Water = 3.40E5 sej/g [15]
Aluminium panels = 12.53E9 sej/g [10]

APPENDIX B: PROCEDURE FOR EMERGY CALCULATIONS IN TABLE 8

1. **Electricity consumption** = 526680 kW h = 1.89E12 J per year
   The transformity is 1.43E5 sej/J [11, p. 72].
2. **Human labour** = 2.8E10 J per year
   22 employees working 8 h per day correspond to 2628 persons/year × 2500 kcal/person × 4186 J/kcal = 2.8E10 J. The transformity is 7.38E6 sej/J [12].
3. **Methane consumption** = 891,660 m^3 per year
   Multiplied by the heating capacity: 891,660 m_n^3 × 39,830 kJ/m_n^3 = 3.5E10 kJ. The transformity is 4.8E4 sej/J [8].
4. **Recycled aluminium** = 3580 t/year
   Transformity = 12.53E9 sej/g [10].
5. **Aluminium panels** = 2494.8 t/year
   Transformity = 12.53E9 sej/g [10].
6. **Aluminium scraps from billets** = 1462.08 t/year
   Transformity = 12.53E9 sej/g [10].
7. **Other materials:**
   Magnesium consumed = 1.15E7 g/year; Mg cost = 0.0015 €/g; Mg total cost = 17,325 €/year.
   Silicon consumed = 1.15E7 g/year; Si cost = 0.0022 €/g; Si total cost = 25,410 €/year.
   Total cost = 42,735 €/year for 2.30E7 g of materials.
8. **Water consumption** = 3.2E6 kg/year
   Transformity = 3.4E5 sej/g [15].
9. **Oxygen consumption** = 2,557,280 kg/year
   Transformity = 5.16E7 sej/g [13]
10. **Maintenance costs** = 9500 € per year
    The transformity is 1.4E12 sej/€, according to Tiezzi's evaluation [14]: 7.26E8 sej/£ × 1.93627E3 £/€ (1€ = 1.93627 £).
11. **Plant building price** = € 4,312,410/20 = 2.15E5€
    The yearly cost was evaluated by dividing the total cost by 20 years (the average efficiency of the plant is estimated to be 20 years).

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