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Assessing the replacement of lead in solders: effects on resource use and human health

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ABSTRACT

Human health and environmental concerns are not usually considered at the same time. Tin-lead solders are still widely used in several countries, including Brazil, by manufacturers of electronic assemblies. One of the options to reduce or eliminate lead from the manufacturing environment is its replacement with lead-free alloys. This paper applies emergy synthesis and the DALY indicator (Disability Adjusted Life Years) to assess the impact of manufacturing soft solder using tin, lead and other metals on the environment and on human health. The results are presented together with the company's financial results and the results calculated from the Brazilian statistical value of life. The calculation of emergy per unit showed that more resources are used to produce one ton of lead-free solders than to produce one ton of tin-lead solders, with and without the use of consumer waste recovered through a reverse logistics system. The assessment of air emissions during solder production shows that the benefits of the lead-free solution are limited to the stages of manufacturing and assembling. The tin-lead solder appears as the best option in terms of resource use efficiency and with respect to emissions into the atmosphere when the mining stage is included. A discussion on the influence of the system's boundaries on the decision-making process for materials substitution is presented.

1. Introduction

Lead-based solder, as well as its substitutes, is the principal method for attaching components to a printed circuit board during the manufacturing of electronic assemblies, while eutectic tin-lead solder has long been the basic choice for assembling electronics due to its low melting point and reflow properties and the ductility of the formed solder joints (Garcia et al., 2009). Lead, however, has come under increasing regulatory review due to its high toxicity to human health and the environment. In this context, lead-free solders have been presented as a reasonable solution to avoid the use of lead.

The replacement of lead-based solder began in the early 2000s, mainly in Europe and Japan (Turbini et al., 2000). Although the European community and some Asian countries are using lead-free solders on a large scale, the lead-free solders are not, as yet, widely used in Brazil, not only because of the lower cost of lead but also because of its wettability and its physicochemical properties, which guarantee a high reliability for electronic equipment. In many Brazilian small- and medium-sized enterprises, the production of lead-free solders occurs mainly due to pressures from foreign customers, and the alloys with the greatest potential for use by Brazilian industries are from the Sn–Ag–Cu family.

Several studies in the literature dealing with the replacement of tin-lead solder refer to aspects related to its physical properties and the problems arising in electronic assembling (Laurila et al., 2007; Ročak et al., 2007; Xia and Xie, 2008; Gao et al., 2009; Zou et al., 2010). Most studies indicate increased energy consumption and decreased soldering quality due to the use of lead-free solders. There are also several studies defending the lead-free option that consider the effects of the exposure to lead fumes in the working environment (Abdel Hameed and Khoder, 2000; Dartey et al., 2010; Yu et al., 2011). Armenti et al. (2011) propose combining cleaner production–pollution prevention and toxics use reduction to assess the ability to shift environmental and worker health and safety strategies so that exposure prevention is a priority over exposure control. This study examines interventions of environmental programs on worker health and safety, and shows that the integration of cleaner production–pollution prevention and toxics use reduction attenuates exposure to toxic substances in the working environment.

Turbini et al. (2000) reflect on the importance of assessing the environmental impact of lead-free electronic products throughout

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the entire lifecycle of the electronic device, which includes factors such as metal availability, considerations of manufacturing, energy use, and groundwater contamination. Fujino and Suga (2003), using a simplified lifecycle assessment (LCA), reported that lead toxicity and the value of energy consumption are the key factors to consider when selecting the most appropriate solder. Following this idea, Zhou and Schoenung (2007) reported that the overall environmental impact of both solders is similar when the entire lifecycle is taken into account. They argue that the replacement of tin-lead solders by lead-free solders decreases toxicity, but increases energy consumption. However, electricity consumption can diminish as technological developments (e.g., advancements in recovery furnaces and manufacture of electronic boards) lead to more effective use of lead-free solders.

There are also some broader evaluations that assess the lifecycle and environmental impacts of tin-lead and lead-free solders (Segerberg and Hedemalm, 1996; Socolof and Geibig, 2005; Andrae et al., 2008; Andrae, 2009). Socolof and Geibig (2005) presented the results of a LCA performed for both solders and show that tin-lead solders have a higher impact on four human health categories (occupational cancer, occupational diseases, chronic noncancerous illnesses, public health and chronic non-cancer diseases among the public). Conversely, lead-free solders have a higher impact on twelve categories associated with non-renewable and renewable resources, such as the use of electricity and liquefied petroleum gas (LPG), use of landfill space, global warming, ozone layer depletion, photochemical smog, acidification, air particulates, water quality and public contamination.

Because of the toxicity of lead, the replacement of tin-lead alloys has been studied by several researchers. Itsubo et al. (2003) assessed the damage of these alloys to human health and emphasizes the need to establish a damage factor to improve the quality of assessment and calculates that 0.6 g of lead per kilogram of solder produced are emitted into the atmosphere from mining to manufacturing. Ku et al. (2003) recommend the replacement of lead-containing alloys after contrasting several metals in terms of toxicity, availability and supply. Okamoto et al. (2005) evaluate the substitution of lead with antimony, bismuth, silver, copper, indium and zinc and recommend the use of lead-free solders as the best solution.

The literature review shows that there is still controversy regarding the replacement of tin-lead alloys, and the focus of industry research is on performance-based issues. Some researchers emphasize lead toxicity and its damage to human health during manufacturing and assembling (Itsubo et al., 2003; Ku et al., 2003; Okamoto et al., 2005; Armenti et al., 2011). Others note the disadvantages associated with the replacement of tin-lead alloys such as the increase in energy consumption and use of nonrenewable resources (Segerberg and Hedemalm, 1996; Socolof and Geibig, 2005; Zhou and Schoenung, 2007; Andrae et al., 2008; Andrae, 2009).

In developing countries, the electronic assembly community is striving to accommodate the replacement of lead-containing solders with lead-free solders due to environmental regulations and market pressures. Of the lead-free choices, a family of solder alloys based on the Sn–Ag–Cu composition has emerged with the greatest potential for broad use across the industry.

Recent studies on the emergy evaluation of production processes, mining and metals production (Ingwersen, 2011; Cherubini et al., 2008) and systemic tradeoffs (Chen and Chen, 2012) show that, compared to embodied energy metrics, emergy synthesis, considering the flows to support the human-dominated production system, is a promising metric for evaluating the ecological cost, which is difficult to evaluate in the economic market.

In this study, emergy synthesis and the DALY indicator are used to evaluate a manufacturer of soft solders. The DALY indicator, originally developed for the World Health Organization (WHO, 2010), aggregates the effects due to exposure to a particular pollutant on human health and the reduction in life expectancy. Emergy was chosen because it avoids the difficulty one would experience in normalizing and aggregating variables having different units (Almeida et al., 2007). This method gives transparency in evaluating systems as weighting factors, which are value judgments and can be prone to errors, are not employed. Moreover, emergy synthesis can also account, directly or indirectly, for the information and the free ecological services and their contribution to systems operations.

The substitution of tin-lead solders by lead-free solders was executed in the production of Sn–Pb (63%, 37%, respectively) and Sn–Ag–Cu (96.5%, 3%, 0.5%, respectively) solders to achieve the following:

(i) determine the effect on resource use with and without the reuse of customers' residues by means of a reverse logistics process;
(ii) determine the effect on human health with the use of the DALY (Disability Adjusted Life Years) indicator; and
(iii) evaluate both cases in terms of currency.

The importance of the comprehensiveness of the assessment is discussed herein.

2. Materials and methods

2.1. System description and data collection

The Brazilian company, certified by the International Standard ISO9001, has been in operation since 1999. The company manufactures solders in anodes, bars, rods, wires, and solid wires in various shapes, sizes and diameters. The solder production in weight is divided into approximately 90% w/w for tin-lead and 10% w/w for lead-free solders, which are produced according to the demand of the domestic market. The emergy evaluation procedure was performed by means of data collected from the purchase documents in the years 2006 and 2007.

For each alloy, the quantities of electricity, liquefied petroleum gas (LPG), and lubricating oil consumed for production and the paper and cardboard used for packaging were calculated using the average consumption in 2006 and 2007. The amount of acid used in the chemical laboratory was calculated from purchase invoices for the same years. Water consumption was calculated from monthly bills, and material quantities used for the amortized facility construction were accounted for by considering their useful life.

The specific gravity of the standard lead-based alloys is approximately 8.4^- g/cm^3, while the specific gravity of the lead-free alloys, being mostly tin, is approximately 7.3^- g/cm^3; thus, the same volume of lead-free solder weighed approximately 15% less. This difference was taken into consideration in our calculations.

2.2. Emergy synthesis

Emergy synthesis was used to evaluate the production of two solders as it provides a strong scientific basis and indicators that are functional for evaluating the effectiveness of resource use.

Emergy is the available energy previously used directly and indirectly to perform a service or develop a product (Odum, 1996). In contrast to other analyses based on energy (Brown and Herendeen, 1996), exergy (Sciubba and Ulgiati, 2005), or thermoeconomy (Lazzaretto, 2009), emergy synthesis has a logic of memorization rather than a logic of conservation. The definition of emergy stimulated a new mathematical approach to differential calculus (Giannantoni, 2006; Giannantoni and Zoli, 2010), and because it accounts for the energy quality (transformity), some special algebraic rules needed to be considered (Brown and Herendeen, 1996) and a special mathematical formulation was required (Giannantoni, 2002).

Unit emergy values (UEVs) are used to “transform” a given form of energy into emergy by multiplying the given energy by its corresponding UEV (Brown and McClanahan, 1996). Emergy synthesis permits the conversion of all contributions received by the production system (metals, energy, oil, money and information) to a single base of measurement: the solar energy joule (sej). To convert energy inputs and other flows into their solar equivalent, UEVs expressed in sej/unit are used.

It is important to note that UEVs are not weighting factors, but they are physical quantities that represent the emergy required to make a unit of a product or service. UEVs can be used to indicate the efficiency of a system (Brown and Ulgiati, 2004; Almeida et al., 2010a), and they are a measure of the global productivity regarding resource use (Almeida et al., 2010b; Bonilla et al., 2010).

UEVs, which are defined on the basis of non-conservative emergy algebra (Brown and Herendeen, 1996), lead to the definition of the total emergy. See (Eq. (1)):

$$\text{Emergy} = \text{Energy quality(UEV)} \times \text{Available energy} \tag{1}$$

Services were calculated considering the indirect labor and the energy embodied in human-derived services inferred from the price of tin, lead and scrap (Cuadra and Rydberg, 2006; Dong et al., 2008). Management and consulting services were assessed according to the amount of money paid for each service (Brandt-Williams, 2002).

2.3. The disability-adjusted life years indicator

To aggregate the effects of lead emissions in the production of both solders, the DALY indicator was used. To estimate the number of lost years caused by a fatal disease, the indicator combines data on the probability of death with data from dose-response and exposure-response for each pollutant, that is, YLL (years of life lost). The indicator also includes the health effects that do not lead to immediate death but that cause a decrease in the quality of life caused by pain or suffering, that is, YLD (years lived with disability). See Eq. (2) (WHO, 2010).

$$\text{DALY} = \text{YLL} + \text{YLD} \tag{2}$$

In general, pollutants contribute to DALY through both effects as exposure to certain pollutants not only causes mortality but also a period of pain and suffering prior to the occurrence of death. Based on the calculated concentrations, it is possible to determine the quantity of a substance to which people, plants or other life forms are exposed and to calculate how many years of life are lost because of a disability or a premature death. The emission of lead into the atmosphere was taken from Itsubo et al. (2003) and equals 0.6 g of lead per kilogram of solder produced. The emissions of CO_2, SO_x and particulate matter (PM) were derived from Socolof and Geibig (2005). The analysis of the damage is expressed as a unit of damage, in this case, the DALY indicator (Hofstetter and Hammitt, 2002). The values of DALY per kilogram for each pollutant (lead, CO_2, SO_x and PM) were obtained from Itsubo et al. (2003).

The statistical value of life was used to express the years lost in currency (Miraglia and Saldiva, 2005). The statistical value of a human life is defined as the economic value associated to an incremental modification of the death risk or disease risk for a non-identified member of a huge group (Reis, 2001). This value is usually used for life insurance calculations and work security assessments, and accordingly, it uses contingent valuation, which directly verifies the willingness to pay for reducing risks of premature disease. The Brazilian annual value of a statistical life is US$ 7700 as calculated by Seroa da Motta et al. (1998) after adapting European values based on per capita income, life expectancy, health expenses and income-elasticity data.

3. Results and discussion

3.1. Emergy synthesis

For the company assessment, process flows were established with the mass balances for the production of both solders. Fig. 1 shows the mass balance for the tin-lead alloy.

For the production of 946 t of the tin-lead solder, 237 t of consumer waste returns from customers and 124 t of scrap were captured on the market. The internal recovery process has an average yield of 55% by weight and recovers the customers' consumer waste and scrap for a total of 198 t. The remaining 45% w/w is sent for external treatment and generates a return of 114 t of the tin-lead alloy.

Fig. 2 shows the energy system diagram for the production of both solders, drawn to organize data collection. Each flow corresponds to a line in the emergy table, where flows of energy, materials and services already calculated in terms of their conventional units are converted into emergy flows when multiplied by their corresponding UEV (sej/unit). The evaluation for the tin-lead solder is shown in Table 1. Footnotes to the table describe the data sources and calculation procedure.

In Table 1, items 1 to 6 refer to the inputs needed for the company infrastructure, while items 7 to 22 refer to the actual operational data for the manufacture of tin-lead solder. For the construction phase, the main inputs for the building construction, such as concrete, metal roof and labor as well as machinery and tools, were accounted for. For this company, price fluctuations justify the use of a reverse logistics system (Table 1, item 2), which requires metal boxes for recovering the consumer waste.

In the production phase, tin contributes 71.7% of the total emergy, lead supplies contribute 11.9% and the scrap bought from scrap-dealers contributes the remaining 16.4%. The total emergy to produce 946 t of this type of solder is 9.47×10^{20} sej/year.

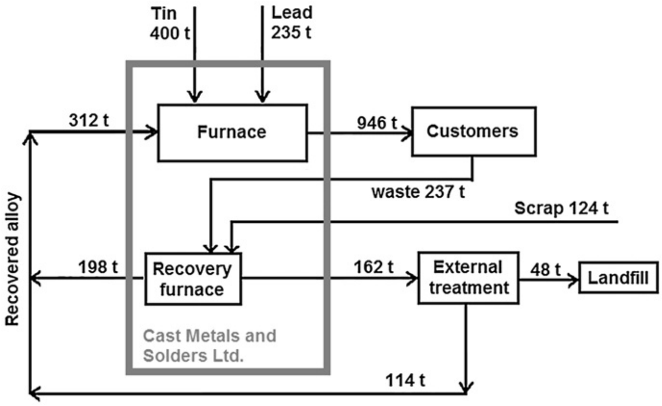

Fig. 1. Mass balance for the tin-lead solders production at Cast Metals and Solders Ltd. Average values for 2006/2007.

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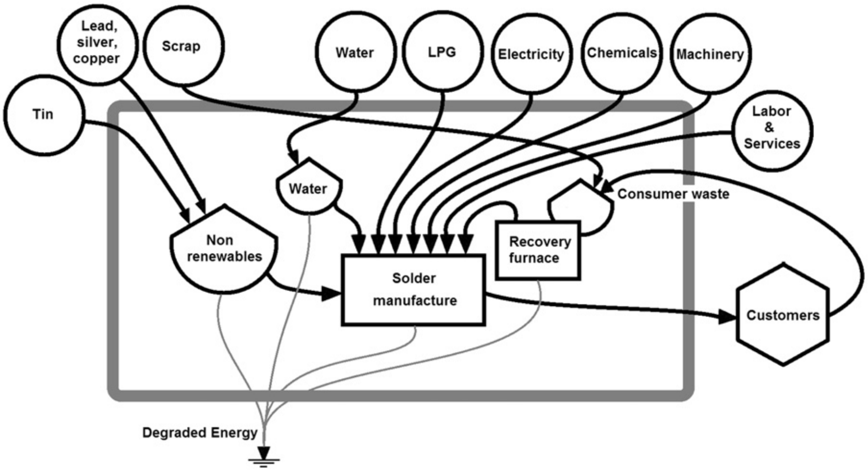

Fig. 2. Energy system diagram for the production of tin-based solders.

The set of calculation procedures leading to results for the lead-free solder is not shown in this paper; however, they are available on request. The company produces 13.7 t of the lead-free solder with a total emergy of 1.68×10^{19} sej/year (without services), and tin accounts for more than 90% of the total emergy. The emergy invested in the production processes is far greater than that required for the construction and maintenance of the company's infrastructure. Tin and lead, as virgin or recovered materials, have the highest UEVs and correspond to more than 90% of all emergy inputs. Services increase the total emergy by approximately 4% for both solders.

Both of these analyses are dominated by the high transformities for tin and lead. These values obscure the emergy investment and operational emergy required for the output. For evaluating the relative efficiency of the production process and for optimizing or improving the values, it may be instructive to run the analysis without the metal fluxes. This analysis shows that approximately 58% of the process emergy is due to labor and 33% is due to the construction and maintenance of the building.

3.1.1. The effects of the reverse logistics for consumer waste recovery on resource use

The growth of tin consumption due to the increasing demand of the Chinese market aggravated the fluctuation of prices for tin and other metals. These price fluctuations stimulated the recovery of solder consumer waste through the use of a reverse logistics system (Fig. 1). The consumer waste collection from customers improves the company's environmental performance, preventing the use of natural resources and landfilling, while also generating economic benefits (Table 2).

The maximum acceptable amount of consumer waste to be returned by customers was established considering the actual quantities returned: 25% w/w for the tin-lead solder and 30% w/w for lead-free alloy. An increase in these quantities would be an indication of poorly regulated equipment during the soldering operation. As the company cannot expect that their customers will produce more consumer waste, the maximum environmental and economic gain due to the reverse logistics system implemented for consumer waste collection is represented in Table 2. For the tin-lead solder, the consumer waste quantity recovered generates a cost reduction of approximately 5% (US$ 310,000 per year), corresponding to 0.32 US$/kg of solder produced. The reduction in the total emergy is 16%. For the lead-free solder, costs decreased by US$ 11,200 per year or US$ 0.86 per kilogram of solder produced. The total emergy was reduced by approximately 26%.

3.1.2. The effects of the scrap bought from scrap-dealers on resource use

The amount of scrap purchased from third parties (Fig. 1) of each alloy was recorded to evaluate the role of scrap uptake in the economic and environmental performance of the company. The effect of increasing the use of scrap along with the corresponding financial gains is shown in Table 3. As expected, the increase in the quantity of scrap used lowers the total cost of raw materials. However, this cost reduction is accompanied by a small increase in the total emergy (7%), which is due to the environmental costs relative to the recovery of the scrap. Only 86.5% w/w of the scrap bought is converted into raw material for the company (Fig. 1). For the lead-free solder, there is a cost reduction of 27% if the current amount of scrap used is doubled and 49% if this amount is tripled. Economic gains are larger for the lead-free solder because of the price of silver.

3.1.3. The effect of the total replacement of tin-lead solder on resource use

To simulate the condition of complete replacement of tin-lead solder, we considered a hypothetical production of lead-free solders equal to the 67Sn–37Pb currently produced (Table 4). The company's total emergy increases by approximately 23%, indicating that more resources are required to produce one ton of lead-free solder than to produce the lead-containing solder. It is interesting to note that the increase in emergy is due to the increase in the quantity of tin in the alloy composition.

3.2. The effect on human health of the adoption of lead-free solders

The DALY indicator was calculated admitting equal quantities for both solders. The company uses equipment for collective and individual protection (CPE and IPE, respectively) that have 80% efficiency. Table 5 shows the DALY values obtained and the annual costs associated with the statistical value of a life. Due to the exposure of the workers to toxins in the company's work environment, the production of tin-lead solders causes a loss of 2.9 years of life, whereas the full replacement by lead–free solder would result in only 0.4 years of life lost. Considering the value of US$ 7700 for a statistical human life (Miraglia and Saldiva, 2005), the costs can be calculated as US$ 22,425/year for manufacturing tin-lead solders, and US$ 3154/year for lead-free solders. When the DALY values are converted into currency, the production of lead-free solders results in a savings of US$ 19,271/year, which could be interpreted as a reduction of approximately 85% in

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Table 1
Evaluation of the annual production of the tin-lead solders using emergy synthesis.

Item	Description	Quant.	Unit	UEV[a]/ (sej/unit)	Emergy/ (sej/year)	%[d]
Company's infrastructure						
1	Machinery and equipments	1.26×10^4	g	4.10×10^9	1.22×10^{15}	<0.1
2	Metal boxes	3.99×10^3	g	2.77×10^9	1.43×10^{14}	<0.1
3	Crucibles	5.04×10^4	g	3.06×10^9	1.54×10^{14}	<0.1
4	Metal roofs	2.98×10^7	g	2.77×10^9	8.25×10^{16}	<0.1
5	Concrete	2.12×10^6	g	1.54×10^9	3.26×10^{15}	<0.1
6	Labor	6.56×10^9	g	4.49×10^6	2.95×10^{16}	<0.1
Solder production phase						
7	Tin	4.00×10^8	g	1.70×10^{12}	6.79×10^{20}	71.7
8	Lead	2.35×10^8	g	4.80×10^{11}	1.13×10^{20}	11.9
9	Scrap	1.24×10^8	g	1.25×10^{12}	1.55×10^{20}	16.4
10	Consumer waste	2.37×10^8	g	1.25×10^{12}	2.95×10^{20}	n.a.[b]
11	Electricity	6.07×10^9	J	2.69×10^5	1.95×10^{12}	<0.1
12	LPG	1.05×10^{11}	J	4.80×10^4	5.03×10^{15}	<0.1
13	Cardboard	1.24×10^6	g	3.90×10^9	4.83×10^{15}	<0.1
14	Lubricant	1.84×10^9	J	1.11×10^5	2.04×10^{14}	<0.1
15	Labor	9.80×10^{10}	J	4.49×10^6	1.38×10^{17}	0.1
16	Plastic	1.90×10^7	g	3.80×10^8	7.21×10^{15}	<0.1
17	Cleaning cloth	2.04×10^3	g	3.88×10^{10}	7.91×10^{13}	<0.1
18	Hydrochloric acid	8.91×10^4	g	1.68×10^9	1.50×10^{14}	<0.1
19	Sulfuric acid	3.47×10^4	g	1.68×10^9	5.83×10^{13}	<0.1
20	Nitric acid	1.59×10^4	g	1.58×10^9	2.67×10^{13}	<0.1
21	Hydrofluoric acid	5.85×10^3	g	1.68×10^9	9.83×10^{12}	<0.1
22	Water	8.09×10^7	g	6.64×10^5	7.02×10^{14}	<0.1
	Tin-lead solder	1.96×10^8	g			
	UEV and emergy without services			4.61×10^{12}	9.47×10^{20}	
Services[c]						
23	Management and consulting	1.90×10^5	$	5.20×10^{12}	9.88×10^{17}	
24	Tin	5.38×10^6	$	5.20×10^{12}	2.80×10^{19}	
25	Lead	4.87×10^5	$	5.20×10^{12}	2.53×10^{18}	
26	Scrap	6.20×10^5	$	5.20×10^{12}	3.22×10^{18}	
	Tin-lead solder	1.96×10^8	g			
	UEV and emergy with services			4.83×10^{12}	9.47×10^{20}	

[a] Values of specific emergy are relative to the 15.83×10^{24} sej/year baseline (Odum et al., 2000), with references as follows: tin, lead, silver, copper, dross and scrap (Cohen et al., 2006); electricity (Odum, 1996); liquefied petroleum gas (Wang et al., 2005); cardboard (Ulgiati et al., 2002); lubricating oil (Odum, 1996); labor in Brazil (Bonilla et al., 2010); plastic (Ulgiati et al., 2002); cleaning cloths, hydrochloric acid, sulfuric acid, nitric acid and hydrofluoric acid (Odum, 1996); water (Caruso et al., 2001); machinery and equipment, metal boxes, crucibles, metal roofs, and concrete of the industrial building (Brown and Buranakarn, 2003).

[b] Not considered, to avoid double counting.

[c] Services of the annual production of tin-lead solders with the Brazilian EMR = 5.20×10^{12}sej/$, for the year 2007 (Demétrio, 2011).

[d] Without services.

hospitalization costs caused by emissions relative to the company's total annual production. This result indicates that, although the company does not pay this cost directly, it would be preferable to produce lead-free solders.

Fig. 3 shows the values of DALY relative to the annual production of the company discriminating against the contributions of lead emissions, CO_2, SO_x and PM. Lead emissions contribute 75% of the years lost, and CO_2 emissions account for 22% of the calculated damage of tin-lead solders.

At this point, the local assessment performed at the company's work site presents two distinct results. The DALY values indicate lead-free solders as the best option, while the emergy synthesis indicates that their production would require 23% more resources than the lead-based solders (Table 3). If the relative UEVs for alloy formation are used, the differences may not be as great, but the overall conclusion is still the same. The emissions into the atmosphere evaluated in this local assessment also contradict the results of an attributional LCA performed by Ekvall and Andrae (2006). The LCA indicated that the lead-free option contributes 10% more to the global warming potential than the tin-lead option. The LCA published by Socolof and Geibig (2005) also indicated that lead-free solders have higher impact indicators relative to global warming, ozone layer depletion, photochemical smog, acidification, and air particulates. In this paper, the total quantity of lead emissions from extraction to manufacture (0.6 g of lead emitted/kg of solder) was entirely attributed to the manufacturing stage. Therefore, it is reasonable to infer that higher CO_2, SO_x and PM emissions may occur at another lifecycle stage of the lead-free solder production. For this reason, a more detailed evaluation, including other lifecycle stages of solder manufacturing, was performed.

3.2.1. *The effect on human health of the adoption of lead-free solders in the whole life-cycle*

The report of Socolof and Geibig (2005) shows the amounts of CO_2, SO_x and PM released into the atmosphere per kilogram of solder for the entire lifecycle of both types of solder. As LCA does not account for the local conditions of the receiving environment, values reported for the United States (even though they may underestimate emissions for a developing country) can be used to give an idea of the distribution of emissions over the entire lifecycle.

The results were calculated assuming that collective and individual protection equipment (CPE and IPE) were used during the whole lifecycle with 80% efficiency. The DALY value for CO_2 emissions in the extraction/processing stage of lead-free solders is approximately two times greater than that calculated for lead emissions in manufacturing. Likewise, there are approximately 7.6 years lost through disability or premature death due to the emission of particulate matter in the lead-free solder extraction/processing phase in contrast to 4.8 years lost by the emission of lead fumes in the manufacture and use stages of tin-lead solders.

Fig. 4 shows the comparison between the DALY values for each lifecycle stage considering the total emissions associated with the production of 946 tons of each solder. The lower limit of the bars considers the use of collective and individual protection equipment, and the upper limit simulates circumstances in which collective and individual protection equipment are not used.

Table 2
Evaluation of the maximum gains due to consumer waste recovery with the use reverse logistics.

	Raw materials					Cost/(US$/year)	Emergy[a]/ ($10^{20} \times$ sej/year)
	Sn/(t)	Pb/(t)	Ag/(t)	Cu/(t)	Dross/(t)		
Sn–Pb (63%, 37%)							
No consumer waste	530	310				6,179,729	12.0
25% w/w consumer waste	400	240			240	5,866,785	9.5
Sn–Ag–Cu (96.5%, 3%, 0.5%)							
No consumer waste	12.9		0.40	0.067		164.611	0.22
30% w/w consumer waste	9.44		0.29	0.049	4.11	153.410	0.17

[a] Without services.

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Table 3
Simulation of the scrap increase in the solders production process.

	Raw materials					Cost/ (US$/year)	Emergy / (10^{19} × sej/yr)
	Sn/(t)	Pb/(t)	Ag/(t)	Cu/(t)	Scrap/(t)		
Sn–Pb (63%, 37%)							
No scrap	470	260			–	5,454,246	**9.26**
Actual	400	250			120	5,301,785	**9.47**
Scrap × 2	270	1606			250	5,125,825	**9.68**
Scrap × 3	140	80			370	4,949,865	**9.89**
Sn–Ag–Cu (96.5%, 3%, 0.5%)							
No scrap	12.9		0.40	0.67	–	164,611	**16.8**
Actual	9.4		0.29	0.49	0.42	123,850	**16.9**
Scrap × 2	6.0		0.19	0.31	1.66	90,007	**17.2**
Scrap × 3	2.6		0.08	0.13	3.75	62,939	**17.6**

For the tin-lead solder, the years lost due to lead emissions into the atmosphere are most significant in the manufacturing and soldering stages. During extraction/processing stages, the years lost due to CO_2, SO_x and PM emissions are similar to those associated with lead in the later stages. For the lifecycle of lead-free solders, the DALY values associated with CO_2, SO_x and PM emissions during extraction/processing are approximately four times greater than the DALY's value associated with lead emissions in the manufacturing/soldering stages. Without the use of collective and individual protection equipment, the total years lost in the lifecycle of tin-lead solder may total 54.4 years. In contrast, the manufacture of lead-free solders may reach 92.4 years lost, from which 40 years correspond to CO_2 and 42 years correspond to particulate matter emissions.

Table 5 shows the calculated costs using the Brazilian statistical value of human life for each stage of the lifecycle. In the company's working environment, the loss of human capital and the costs of hospitalizations associated with the production of tin-lead solder can range from US$ 22,000.00 to US$ 112,000.00 per year, depending on the use and effectiveness of CPEs and IPEs. For the same stage of the lead-free solder lifecycle, these costs range from US$ 3000.00 to US$ 16,000.00 per year. According to this partial assessment, the replacement of lead would result in a reduction of over 80% of the possible health costs and hospitalizations caused by emissions into the atmosphere during solder production. The same occurs at the use stage, in which health expenditures are reduced by approximately 37%. The decision, based on this partial analysis, would lead to the complete replacement of lead alloys if the worker's health was more important than the consumption of natural reserves. However, for the entire lifecycle, spending on human health can exceed US$ 700,000.00 if totally replaced, which corresponds to 1.7 times the estimated expenditure for the tin-lead solder lifecycle.

Table 4
Simulating the full substitution of tin-lead solders by led-free ones.

	Quantity	Unit	UEV/(sej/unit)	Emergy/ (sej/year)
63Sn–37Pb				
Tin	4.00×10^{8}	g	1.70×10^{12}	6.80×10^{20}
Lead	2.35×10^{8}	g	4.80×10^{11}	1.13×10^{20}
Scrap	1.24×10^{8}	g	1.25×10^{12}	1.55×10^{20}
			Total emergy	9.47×10^{20}
Sn96.5–Ag3–Cu0.5				
Tin	6.76×10^{8}	g	1.70×10^{12}	1.15×10^{21}
Silver	2.10×10^{7}	g	4.50×10^{11}	9.45×10^{18}
Copper	3.50×10^{6}	g	9.80×10^{10}	3.43×10^{17}
Scrap	4.15×10^{5}	g	1.65×10^{12}	6.87×10^{17}
			Total emergy	1.16×10^{21}

4. Local assessment versus global assessment

The replacement of potentially toxic materials by materials that appear less problematic is a common approach. This apparently acceptable action can occasionally be troublesome, however, if it results in the rapid depletion of a potentially scarce resource or the increased extraction of other environmentally problematic materials, or if it raises new toxicity issues that are potentially more severe than those related to the conventional material.

The literature review shows that considerable disagreement remains as to whether the environment would benefit more from the use of lead-free solders or from enhanced recovery and recycling of the present formulations (Turbini, 2006(). In this context, some questions are relevant:

- Does the replacement of tin-lead solders make sense from a resource supply perspective?

The results of the local assessment have shown that the total replacement of tin-lead solders would cause an approximately 20% increase in emergy units. This means that additional resources are used to support lead-free manufacture, thus preventing their possible use for other activities, which is in agreement with the resource availability parameters for metals in electronic solders published by Graedel (2002). The projected depletion time for the universal adoption of lead-free solders showed that tin reserves would last 50 years if tin-lead solders remain in use, but this time would be only 36 years in the case of lead-free solder adoption (Graedel, 2002). For silver, if the substitution was fully

Table 5
Estimated monetary values of lives lost considering the use of collective and individual protection equipments (lower limit) and in their absence (higher limit).

Life cycle stage	US$/year	US$/year
	Lower limit	Higher limit
Tin-lead		
Extraction/processing	33,110.00	165,588.50
Manufacture[a]	22,330.00	112,150.50
Use[a]	27,720.00	139,139.00
Disposal		1540.00
	83,930.00	418,418.00
Sn96.5–Ag3–Cu0.5		
Extraction/processing	120,890.00	604,527.00
Manufacture[a]	3080.00	15,785.00
Use[a]	17,710.00	89,551.00
Disposal		1809.50
	142,450.00	711,672.50

[a] Lead emissions to air and DALY units of damage were taken from Itsubo et al. (2003).

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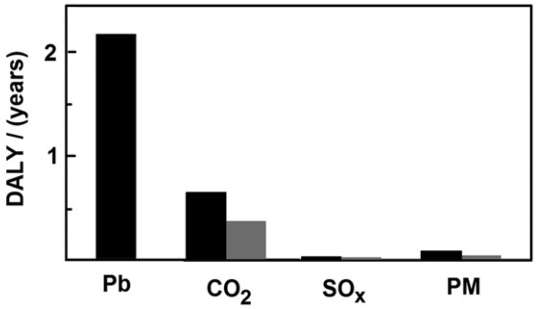

Fig. 3. DALY values associated with damage to the workers' health at the company's working environment for each pollutant considered. Black columns correspond to the tin-lead solder and gray columns the lead-free one.

implemented, the depletion time would be lowered to eight years, and this action would significantly change the overall use rate of silver, possibly causing supply problems for its potential substitute.

The environment has an ability to provide resources (emergy) to support human activities, but when these resources are used for a particular procedure, they are not available for other purposes. Thus, when the solder manufacturers use direct or indirect resources to mitigate local damages to human health posed by their emissions, other processes are prevented from using these resources. The emergy associated with the damage to human health caused by the emission of pollutants into the atmosphere during the lifecycle of lead-free solders can reach 1.42×10^{18} sej/year corresponding, for example, to the emergy required to maintain 200 acres for the production of coffee for one year (Giannetti et al., 2011) or approximately 1700 ha per year for the production of bamboo (Bonilla et al., 2010).

- Could recycling satisfy the total anticipated magnitude of use and the rate of increase in the use of the potential substitute?

The benefits of consumer waste recovery were evaluated, but a maximum acceptable amount of consumer waste to be returned by customers limits the environmental gains due to reverse logistics. The increased uptake of scrap also results in environmental and economic benefits, but the environmental performance of the manufacturer falls below the desirable level as emergy increases by approximately 7%.

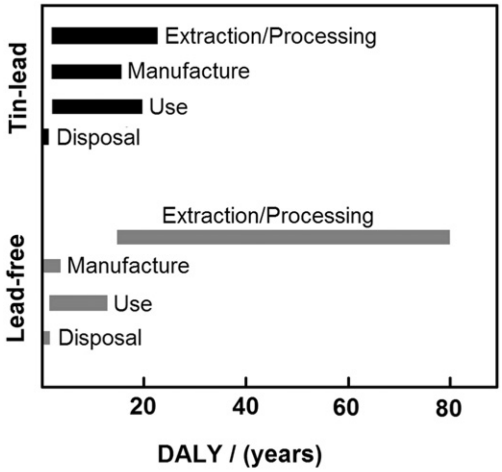

Fig. 4. DALY values by lifecycle stage. The vertical bars show the range of values when considering the use of CPEs and IPEs with 80% efficiency (lower limit) and their absence (upper limit). DALY values were taken from Itsubo et al. (2003).

While it is clear that when resources are recycled after use the demand on virgin resources decreases, in an expanding world economy requiring more and more resources, recycling can only reduce the need for primary resources, it cannot eliminate the need (Graedel, 2002).

- Does the potential substitute raise new toxicity issues potentially more severe than those related to the present material?

Values of DALY in manufacturing, including the results for CO_2, SO_x and PM for both types of solder, indicate that lead emissions contribute 75% of the damage associated with the production process. However, this assessment also has established that the damage associated with the emissions during extraction/processing is approximately four times greater than that corresponding to lead emissions during the manufacturing/soldering stages. This analysis only considers emissions in the atmosphere, and further studies regarding emissions to water and soil in the disposal stage would, thus, complement the evaluation.

The discussion of the results of this case study makes it clear that the substitution of other materials for lead should not be conducted on the basis of local assessments.

5. Concluding remarks

The emergy synthesis and the DALY indicator were used to assess efficacy of the replacement of tin-lead solders by lead-free solders. The effects of consumer waste recovery, scrap use, and damages to human health were evaluated allowing for the recognition of some key factors:

- The intensive use of natural resources: tin is the major contributor to the total emergy for both solders, and the entire substitution of the tin-lead solder by lead-free solders increases the use of natural resources by approximately 20%.
- Reverse logistics results in economic benefits, and savings were calculated for both solders (5% for the tin-lead solder, and 1% for the lead-free solders).
- Reverse logistics may promote a maximum resource savings of 16% for tin-lead solders and 26% for the lead-free option. Thus, to enhance the manufacturer's environmental performance, it is necessary to increase the amount of scrap collected.
- For the years lost due to emissions into the atmosphere, the calculation of DALYs shows opposite results depending on the boundaries considered for each evaluation.

The results of this work reveal that the total replacement of tin-lead solders may lead to an increase in resource use and to an increase of hazardous emissions during the extraction/processing stage. An increase in resource use was found after performing the analysis at the local level, and an argument in favor of lead substitution would rely on the consideration that human health is more important than resource depletion. However, when the assessment is performed over the entire lifecycle, the results favor the continued use of tin-lead solders.

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