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An emergy-based evaluation of a reverse logistics network for steel recycling

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ABSTRACT

Efficient implementation of recycling networks requires appropriate logistical structures for managing the reverse flow of materials from users to producers. The steel sheet distributor studied had established a protocol for scrap recovery with the steel plant and its customers. The company invested in producing containers, hiring a specialized labor force and in purchasing trucks for container transportation to implement the logistics network for recycling. That network interconnected the company with two kinds of customers: the ones returning scrap and the ones who preferred to continue business-as-usual. The logistical network was analyzed using emergy synthesis, and the data obtained were used to evaluate and compare the system's environmental costs and benefits from the perspective of the distributor and the steel plant operator. The use of emergy ternary diagrams provided a way to assess recycle strategies to compare the relative economic and environmental benefits of the logistical network implemented. The minimum quantity of scrap that the distributor must recover to improve environmental benefits was determined allowing decision on whether it is worth keeping the system running. The new assessment method proposed also may help policy-makers to create strategies to reward or incentive users of reverse logistics, and help to establish regulations, by decreasing taxes or stimulating innovation, for effectively implement the National Policy on Solid Waste.

1. Introduction

The supply and demand of limited resources are among the critical factors in dealing with sustainable development. Proper resource management of natural and manufactured products is key challenges for modern society. Environmental programs must use resources properly in order to operate their systems within sustainable limits locally and globally.

In several countries, steel recycling is a well-established supply chain of collection programs, ferrous scrap processors, mills and fabricators, with multiple markets for recycled steel (Steel Recycling Institute, 2006). In Brazil, the production of steel from recycled steel was only about 24% w/w of the total steel produced in 2008 (Relatório de Sustentabilidade – Sustainability Report, 2009).

A smoothly functioning logistics network focusing upon material's recovery is essential to improve the competitive advantage and also to reduce net energy and material usage (Gungor and Gupta, 1999). The network configuration is strategic as it involves decisions on the number, location and capacities of facilities and the flows of materials among them. There are several case studies, which address the systematic design of logistics networks.

For example, in developing a theory of reverse logistics, six operational factors were identified by Dowlatshahi (2005) for classification purposes: transportation, warehousing, supply management, cost/benefit analysis, remanufacturing/recycling, and packaging. Dethloff (2001) developed an algorithm to determine favorable material's flows of re-usable packaging, goods to be recycled or remanufactured, and transport to all actors in the system. Realff et al. (2000) emphasized the need for collection centers in a reverse production system to assist in maximizing the collection of returned products. Lu and Bostel (2007) presented a two-level facility location model for the reverse logistics systems that include remanufacturing activities, in which both direct and reverse flows are considered simultaneously. Several researchers such as have studied the cost-effectiveness of reverse logistics network design, highlighting the overall cost of recovery as a key factor (Fleischmann et al., 1997). Jahre (1995) stated that, for recycling of returned products, logistics costs account for a large share of the total costs. Nagel and Meyer (1999) also concluded that reverse logistics requires large investments. In 2004, Beullens presented a generic model for evaluating the costs of a single

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product flow between facilities and reprocessing as a product-recovery option. Transportation of used products was highlighted as one of the biggest challenges of reverse logistics (Fleischmann et al., 1997, 2001; Krumwiede and Sheu, 2002) because the small quantities of used products returned to the producer increase the transportation costs (Ferrer and Whybark, 2000; Tibben-Lembke, 2002). Biehl et al. (2007) emphasized that collection centers are essential elements in reverse logistics production systems for increasing the collection of returned materials, and for decreasing transport costs.

Savaskan et al. (2004), and Savaskan and van Wassenhove (2009) proposed a product-recovery strategy depending on who collects the used products, be it the producer; the retailer; or a designated third-party. Fig. 1 illustrates typical collection methods used for recycling. According to Savaskan and van Wassenhove (2009), the manufacturer usually does collection when the quantities to be returned are large, and especially when transportation costs are low (Fig. 1A), but in many cases, collection centers are required to maximize recovery of products or materials. Third-party collectors (Fig. 1B) or distributors (Fig. 1C) may serve as collection centers when the number of customers is large, or the quantities, to be collected from each customer, are small.

Several networks have been proposed for diverse products and materials, such as the recycling of polluted sand (Barros et al., 1998), carpet wastes (Louwers et al., 1999; Realff et al., 2004), and batteries (Zhou et al., 2007). These different reverse logistic networks evaluate locations, their capacities, and transportation costs, and were done to determine the optimal number of collection centers, their proper locations and their collection capacities. These studies show that the cost of transport determines the network design. Spengler et al. (1997) developed a model for the recycling of industrial by-products in the German steel industry in order to reduce the negative environmental impacts and to avoid disposal costs.

The availability of a quantitative measure of the efficiency and effectivity of the system may provide the foundation for evaluating the environmental performance of reverse logistics networks over time, by determining optimal potentials, assessing and seeking to establish and monitor the environmental improvement targets, identifying market opportunities, and communicating results. Among the techniques proposed to assess the economic and environmental efficiency of reverse logistics systems, emergy synthesis has been used effectively as an environmental science-based methodology. As with other resource accounting methodologies for materials and/or energy, it does not evaluate the effects of toxic and hazardous substances, but it may be useful to investigate reverse logistics networks to determine the resource savings and the corresponding environmental and economic benefits.

In this paper, emergy synthesis was used to evaluate a reverse logistics network for steel recycling. Interpretation of the results was done with the aid of emergy ternary diagrams providing a new and practical way to help in decision-making in reverse logistics networks.

2. Environmental benefits and costs of logistic networks from an emergy perspective

'Emergy is the available energy (measured in solar energy joule, seJ) once used up directly and indirectly to make a service or product' (Odum, 1996). Each flow that enters a system is expressed in energy units, and corresponds to a measure of resource and energy use. The transformity (total emergy per joule of product or service, seJ/J) and the emergy per mass (total emergy per mass of product or service, seJ/kg) are measures of efficiency. The system, which uses less emergy to produce a given amount of product, is more efficient, and emergy per mass can be used to determine when materials can be economically reused, reprocessed or beneficially recycled (Odum, 2001).

Ecosystems are based on their capability to, continually, recycle resources via multiple paths to ensure optimal resource use. Such system-wide strategies can also be applied to human systems, wherein materials are effectively recycled via effective reverse logistics systems that can result in increased efficiency and lower adverse emissions.

Materials cycles in nature and human societies pass from dilute background levels to successive centers of concentration at different hierarchic structural levels before being dispersed. In nature, these materials are processed and recycled in a closed cycle. In human systems, if not collected and reused or recycled, become pollution (Fig. 2) and logistics networks resemble ecosystems'

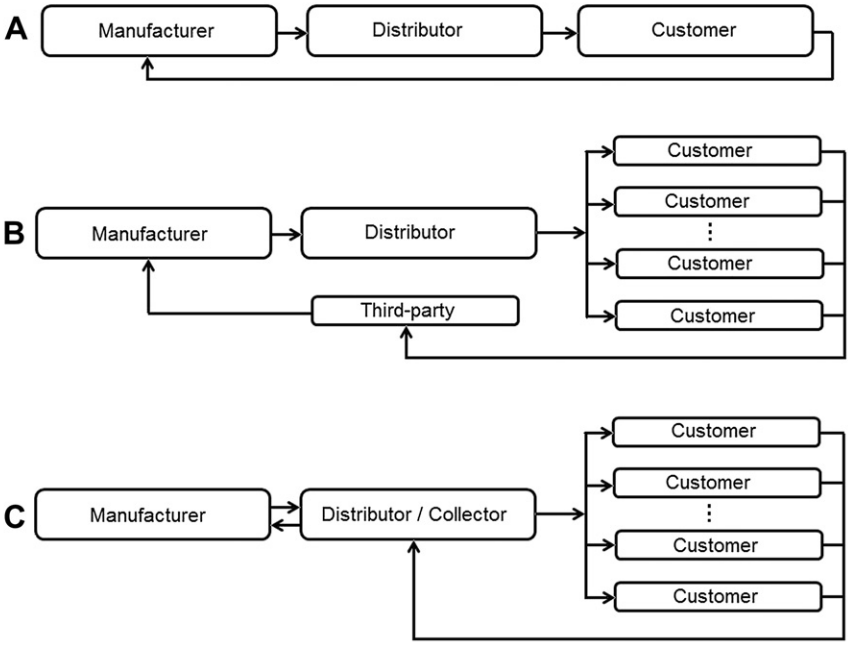

Fig. 1. Collection methods: (A) the manufacturer collects directly from customers; (B) a third-party collects from customers; and (C) the distributor acts as a collection center.

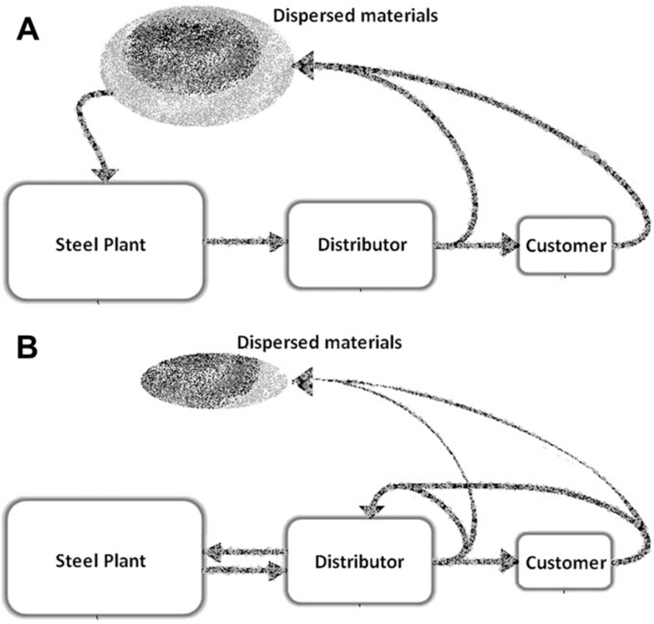

Fig. 2. Material flows with hierarchy structural units of different scales. (A) Material's circulation using third-party collectors, and (B) material's circulation when the distributor acts as a collection center.

mechanisms in several ways. Fig. 2A shows the circulation of matter in a system similar to that shown in Fig. 1B. After leaving the steel plant, steel is cut and shaped without losing its identity as a material. The steel plant's outflows are transferred to the distributor's customers, emergy per mass increases along the production chain. After the production processes, the steel scrap flows may be collected by scrap dealers or third-party collectors.

Fig. 2B shows the reverse logistics network created for this system similar to that shown in Fig. 1C. The distributor uses energy to collect the dispersed materials. Work must be done to lower entropy to insert order within the system. In this case, the scrap outflows from the steel buyers are collected by the distributor, decreasing the amount of dispersed material and thereby helping to ensure an inflow of high quality material to the steel plant. With the use of emergy synthesis, the quantity of energy for concentrating the scrap outflows from the distributor's clients can be documented, and the environmental costs and benefits due to the implementation of the reverse logistical network for recycling can be quantified. This quantitative information can be used to make improvements in the efficiency and effectiveness of all elements of the system.

Emergy was applied as an environmental science-based measure in an array fields such as cleaner production practices in medium size companies (Giannetti et al., 2008), the estimation of negative externalities in a coffee farm (Giannetti et al., 2011); the sustainability assessment of a bamboo plantation (Bonilla et al., 2010); the selection of materials for beverage packages (Almeida et al., 2010a) and the assessment of water management systems (Almeida et al., 2010b). Few authors evaluate benefits and costs of recycling employing emergy synthesis. Bakshi (2002) evaluated industrial systems including the waste treatment. Considering that emissions and wastes require energy to make them harmless to the environment, reuse and recycling were evaluated in order to assess how the use of these practices results in prolongation of the materials cycles and a reduction of energy expended to deal with emissions and wastes. Yang et al. (2003), based on Bakshi's findings, proposed a new sustainability index that includes wastes reclaimed by recycling. According to their results, a system including material feedbacks can increase the yield, and reduce the environmental load (Yang et al., 2003). Brown and Buranakarn (2003) concluded that the emergy to recycle building materials was only beneficial for materials with high emergy content. Bargigli and Ulgiati (2001) studied the industrial production of steel in three cases: primary steel (produced 100% from iron ores), secondary steel (produced from 100% recycled steel scrap) and a weighted mix of both types. The secondary steel and the steel mix were documented as having a better environmental performance than that of primary steel, because both have lower values of emergy per mass.

3. Methods

3.1. Case study

The steel sheet distributor selected for this case study has been in operation since 1995 and is located in São Paulo metropolitan area. The company buys steel directly from steel plant and resells it to various processing companies, which transform the sheets into consumer products. After political and economic changes in the domestic and international markets, the steel plant operator decided to export most of its production to foreign buyers. The distributor started collecting scrap and proposed a deal to the steel plant operators to ensure the steel supply to its SME customers. It is essential to note that the agreement was conceived and designed based on operational costs. For its customers, the distributor offered a system for buying and collecting their trimmings, based upon the scrap prices practiced by the scrap dealers in the open market. The price is equivalent to one-fourth the price of the steel sheet. For steel plant operators, the distributor offered a collection service of high quality trimmings at a price equivalent to half the price of the steel sheet.

Fig. 3 shows the mass balance data from the case study that includes the steel plant, the distributor and its customers, and the reverse logistics network established with the customers (C2). Customers, in this context, are clients who buy steel sheets from the distributor, and return trimmings of those sheets to the reverse logistics network. The scrap returned by these customers has higher quality than that captured by third-party collectors, because it is not contaminated with other materials. The distributor had to

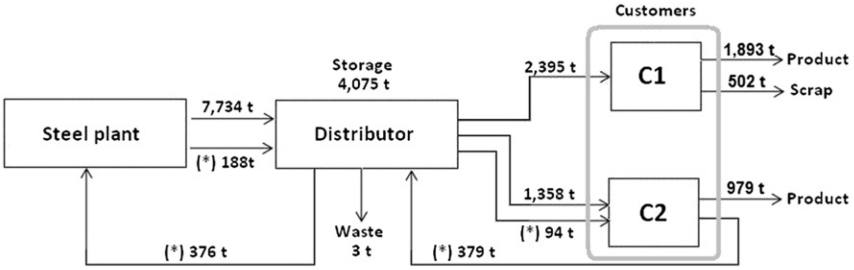

Fig. 3. Mass balance of the steel/scrap distribution system (data corresponding to one year's operation). C1 – customer without scrap exchange, C2 – customer with scrap exchange. Values marked with (*) are referred to material exchange. Steel sheets comprise all fluxes towards the right direction and all the fluxes towards the left are referred to steel scrap.

develop an infrastructure comprised of containers, a specialized labor force and trucks to install the network for scrap recovery, as well as to collect and transfer the scrap back to the steel plant. The system size was planned with the intention to serve all customers (C1 and C2, Fig. 3). Part of the customers adhered immediately to the new system, but others (C1) preferred to rely on the market prices for scrap.

The mass balance (Fig. 3) shows the materials exchanged in the first year of the reverse logistics network operation. The distributor collected 379 t of trimmings from its customers (C2), and after selection and separation, it was possible to return 376 t of trimmings to the steel plant. In this year, the distributor received 188 t of steel sheets as payment for the collection service provided to the steel plant and paid the equivalent to 94 t to customers C2 for their trimmings.

Among the strategies for dealing with the metal trimmings, some humans perceive them to be valuable outputs from processes, while other materials are dealt with as wastes and pollutants. This changes when a commercial benefit is found for the wastes, such as in the case of the business-as-usual strategy that does not account for the quality of waste (customer C1, who prefers to sell its trimmings to third-parties). If processes were not designed to recover these materials and their embedded energy, then the amount to be handled externally would be larger, as would the price of products. Moreover, if this strategy is followed, high entropy wastes, in particular, require considerable energy inputs to reconstitute or recycle them so that recycling of low-quality waste streams may increase overall environmental burdens (Seager and Theis, 2004).

The general questions of quality, concentration, availability, transport, and all related costs were addressed in this case. Resources and energy were invested (outside the firm's boundaries), and disorder was created as a result of the investment. The hope is that the disorder due to this strategy is less than the disorder than would have been caused by releasing the steel trimmings to the environment, and by going into the mines to obtain and process the iron ore into virgin steel.

3.1.1. *Emergy synthesis*

The evaluation procedure was performed by means of data collected through the distributor's formal documents from the following steps:

- Definition of the system under study including its limits for investigation;
- Construction of energy flows diagrams;
- Construction of the emergy tables based upon the data collected;
- Discussion based on the emergy ternary diagram.

Ternary diagrams were developed to depict information and improve the decision-making processes (Gasparatos et al., 2008). This is because the ternary diagrams can be used to compare different development paths or arrangements.

The total solar emergy of a resource flow, such as fuels or labor, can be calculated using one the following equations:

$$\text{solar emergy flow (seJ/yr)} = \text{solar transformity (seJ/J)} \times \text{energy flow (J/yr)} \quad (1)$$

$$\text{solar emergy flow (seJ/yr)} = \text{emergy per mass (seJ/kg)} \times \text{mass flow (kg/yr)} \quad (2)$$

In regard to the steel emergy per mass, the emergy method builds on geological studies about the time needed for land in the geo-biosphere to self-organize into a hierarchy of components and cycles on many scales. The emergy of the geo-biospheric driving forces converges materials to build rock against the flows of dispersal and recycle. The contributions of geologic work to human–environment systems by the concentration and transformation of minerals are expressed in emergy units assuming that transformities and concentration are linearly related (Odum, 1996). Each element, at its background crustal concentration, is part of the global earth cycle. Elements in ores, at higher concentration than their average crustal concentration, represent biological, geological, hydrological and chemical work. The transformity for such materials and minerals scales linearly with their enrichment factor. Values of the emergy per unit used in this text are taken from the literature (Table 1).

3.1.2. *Emergy-based currency equivalent (Em$)*

The emergy-based currency equivalent integrating economic and ecological assessments may be used for comparative purposes providing familiar units to the public. In practice, to obtain the emergy-based currency equivalent value of an emergy flow, the emergy is divided by the emergy money ratio (EMR) for a national economy (Brown and McClanahan, 1996). The EMR is a measure of the monetary value generated within" an economy as the result of an emergy input flow. In this article, the EMR and Em$ were calculated using American dollars to facilitate comparison with other values in the literature (NEAD, 2009). For Brazil, the Em$ was obtained by dividing the emergy per mass by the EMR of the country (1.17×10^{13} seJ/US$, NEAD, 2009).

3.1.3. *Emergy ternary diagrams*

The emergy triangular diagram is comprised of three variables associated with percentages (Giannetti et al., 2006; Almeida et al., 2007). The constant sum constraint allowed us to represent three variables in two dimensions within a triangle. With the aid of diagrams, it is possible to evaluate the performance of production systems (Almeida et al., 2007) and their interactions with the environment (Giannetti et al., 2011). For this case study (Fig. 4), the upper apex of the diagram represents the saved emergy associated with the recovered steel and the apexes represent the emergy invested in goods and services (right), and the emergy invested in fuel (left). The emergy saved by using scrap or trimmings was determined and compared to that needed to produce the same amount of material from virgin ores, making possible for

Table 1
Values of transformities and emergy per unit used in this study.

Item	Unit	Emergy/unit* (seJ/unit)	References
Diesel	J	1.11×10^5	(Odum, 1996)
Electricity [(a)]	J	2.77×10^5	(Brown and Buranakarn, 2003)
Electrode and welding wire [(b)]	kg	2.99×10^{12}	(Ulgiati and Brown, 2002)
Labor (non-qualified)	J	4.30×10^6	(Brown and Ulgiati, 2002)
Mechanical and transportation equipment	kg	1.13×10^{13}	(Brown and Ulgiati, 2002)
Oxygen	kg	5.16×10^{10}	(Ulgiati and Brown, 2002)
Propane [(c)]	J	8.06×10^4	(Ulgiati and Brown, 2002)
Steel sheets	kg	5.35×10^{12}	(Brown and Buranakarn, 2003)
Synthetic paint	kg	1.50×10^{12}	(Brown and Buranakarn, 2003)
Thinner [(d)]	kg	3.80×10^{11}	(Brown and Buranakarn, 2003)
Water [(e)]	J	1.39×10^5	(Buenfil, 2001)

*Values of the transformities used in this text are mostly taken from the literature, and are referred to the 15.8 × 10^{24} seJ/year biosphere emergy baseline (Odum et al., 2000): (a) hydroelectric (Tucurui, Brazil), (b) iron and steel products, (c) natural gas, (d) chemicals, (e) drinking water (distribution not included).

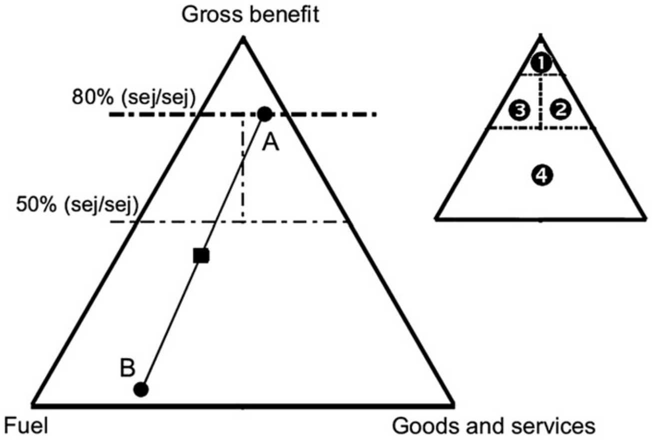

Fig. 4. Emergy ternary diagrams where (∎) represents the combination of points A and B. The diagram shows four regions adopted by the authors, where: area ① excellent, areas ② and ③ indicate good performance, but in ③ fuel consumption is higher than in ②, and area ④ indicates that there is no net benefit.

researchers to assess the contribution of the new distributing system to the environment, regarding material savings. The saved emergy is called "gross benefit". When two different ternary compositions are mixed, a point, identified by the black square (∎) in Fig. 4, denotes the resulting set, which is used to determine the characteristics of the combination of two or more products or processes.

The line, which crosses the diagram horizontally at 50%, shows the situation where the gross benefits obtained are equal to the resources use (fuel, goods and services). When the resources invested to recover the scrap are lower than the saved emergy, a point above this line the net benefit equal that is equal to the difference between the gross benefit and the resources used to recover scrap and trimmings (Eq. (3)).

$$\text{Net benefit} = \text{Emergy saved} - \text{Emergy invested} \qquad (3)$$

Fig. 4 shows a classification according to the location within the diagram. Area one indicates a situation in which the gross benefit is above 80%; area two indicates gross benefit with higher use of goods and services and lower fuel consumption; area three indicates a condition in which there is a high gross benefit, and fuel consumption is higher than the investment in goods and services; and area four indicates that there is no net emergy benefit: the use of fuel, goods and services to recover the scrap is higher than the material recovery.

3.1.4. *Data collection and analysis*

Fig. 3 shows the steel and the scrap mass quantities for the first year of the system's operation.

Electricity flows were allocated according to the weight of the steel sheets bought by each customer (38% of the electricity corresponds to energy of the reverse logistics network and 62% of electricity is due to customers without scrap exchange). Direct labor was accounted for by considering the number of working-hours in each case. The useful life was estimated to be 25 years for the containers, 10 years for the machines and four years for the trucks.

Services were defined as the indirect labor associated to a purchased item, and can be considered as the work done outside of the investigated process, to make the inputs that are used within the process. Thus, each purchased item is characterized by its raw emergy (the raw materials emergy "content" directly and indirectly used to make it) and labor and services emergy (respectively the emergy associated to the direct and indirect human contribution to the process). Due to the difficulty to go back to such indirect labor, services are accounted for based on the price of inputs, since money pays for human labor, not for raw materials provided for free by nature. According to Brown and Ulgiati (2002), the values calculated without services are associated to the physical and technological characteristics of the system investigated, while the fraction depending on indirect labor and services is affected by the economic level of a given country and will vary accordingly. In this way, the total emergy is presented with and without services to assist the understanding of the influence of the economic level of the country in the systems operation.

Managing services were accounted according to the money paid for each service (Brandt-Williams, 2002). The energy embodied in financial resources from human-derived services was also inferred from the price of imported items (Cuadra and Rydberg, 2006; Dong et al., 2008; Giannetti et al., 2011).

4. Results

A simplified system diagram of the main driving energies and internal processes of the conventional system and the logistic network for recycling implemented is given in Fig. 5. The diagrams show the main fluxes that enter the distribution process (fuel, goods and services).

After the construction of the diagrams, it is possible to identify the system's inflows in an evaluation table. Table 2 shows the resources used during the implementation and operation phases of the conventional system (Fig. 5A). The acquisition of a truck to distribute the steel sheets corresponds to 42% of the total emergy, and the spent fuel to 43%. Fuel represents 85% of the emergy used for the operational phase. The emergy-based currency equivalent estimated to deliver the steel sheets to the customers C1

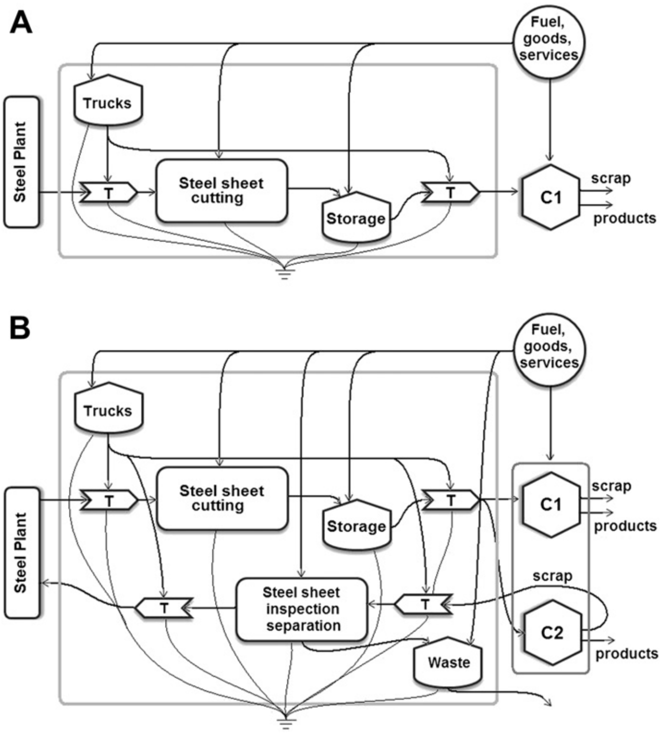

Fig. 5. Energy diagrams of (A) conventional system and (B) new system. C1 – customer without scrap exchange, C2 – customer with scrap exchange and T – steel sheet and scrap transportation.

Table 2
Emergy investment for the conventional system.

Item	Description	Unit	Value	Emergy per unit/(seJ/unit)	Emergy/(seJ/year)
Implementation phase					
1	Wagon truck	kg	4.00×10^3	1.13×10^{13}	4.52×10^{16}
Operation phase					
2	Electricity	J	6.43×10^9	2.77×10^5	1.78×10^{15}
3	Labor	J	2.43×10^9	4.30×10^6	1.04×10^{16}
4	Fuel	J	4.17×10^{11}	1.11×10^5	4.63×10^{16}
5	Oxygen	kg	9.82×10^3	5.16×10^{10}	5.07×10^{14}
6	Propane	J	3.13×10^{10}	8.06×10^4	2.52×10^{15}
Total emergy without services		seJ/year			**1.07×10^{17}**
Emergy-based currency equivalent without services		Em$/year			**9145**
Services					
7	Managing costs	$	12,800	1.17×10^{13} [a]	1.50×10^{17}
8	Variable costs	$	4679	1.17×10^{13} [a]	5.47×10^{16}
9	Fixed costs	$	5534	1.17×10^{13} [a]	6.47×10^{16}
Total emergy with services					**3.76×10^{17}**

[a] Brazil's EMR was taken from NEAD (2009) and equals 1.17×10^{13} seJ/$.

corresponds to Em$ 9145 (Table 2). The emergy that supported human services was inferred from the price of imported items multiplied by the EMR of the economy in which the system is inserted.

Variable costs (item 2) refer to the sum of the prices of electricity, fuel, oxygen and propane. Fixed costs (item 3) refer to the cost per year of the wagon truck. When the services and indirect labor emergies are included, the total emergy increases by 3.5 times

Table 3
Emergy investment for the system including the reverse logistics network.

Item	Description	Unit	Value	Emergy per unit/(seJ/unit)	Emergy/(seJ/year)
Implementation phase					
1	Steel sheets	kg	2.77×10^3	5.35×10^{12}	1.14×10^{16}
2	Electrode	kg	9.66×10^1	2.99×10^{12}	2.89×10^{14}
3	Welding iron	kg	5.44×10^1	2.99×10^{12}	1.63×10^{14}
4	Machinery	kg	3.44×10^1	1.13×10^{13}	3.89×10^{14}
5	Propane	J	7.63×10^8	8.06×10^4	6.15×10^{13}
6	Oxygen	kg	2.75×10^2	5.16×10^{10}	1.42×10^{13}
7	Thinner	kg	3.08×10^0	3.80×10^{11}	1.17×10^{12}
8	Synthetic paint	kg	6.16×10^0	1.50×10^{12}	9.24×10^{12}
9	Electricity	J	2.30×10^8	2.77×10^5	6.37×10^{13}
10	Water	J	1.48×10^9	1.39×10^5	2.06×10^{14}
11	*Labor*	J	2.26×10^8	4.30×10^6	9.72×10^{14}
12	Temporary labor	J	9.72×10^7	4.30×10^6	4.18×10^{14}
13	Fuel	J	1.06×10^9	1.15×10^5	1.22×10^{14}
14	Fixed container truck	kg	4.05×10^3	1.13×10^{13}	4.58×10^{16}
15	Wagon truck	kg	4.00×10^3	1.13×10^{13}	4.52×10^{16}
16	Dump truck	kg	2.65×10^3	1.13×10^{13}	2.99×10^{16}
Maintenance phase					
17	Steel sheets	kg	6.93×10^2	5.35×10^{12}	3.71×10^{15}
18	Electrode	kg	2.42×10^1	2.99×10^{12}	7.24×10^{13}
19	Welding iron	kg	1.36×10^1	2.99×10^{12}	4.07×10^{13}
20	Propane	J	4.08×10^0	8.06×10^4	3.29×10^5
21	Oxygen	kg	6.87×10^1	5.16×10^{10}	3.54×10^{12}
22	Thinner	kg	2.57×10^1	3.80×10^{11}	9.77×10^{12}
23	Synthetic paint	kg	5.13×101	1.50×10^{12}	7.70×10^{13}
24	Labor	J	8.09×10^8	4.30×10^6	3.48×10^{15}
25	Electricity	J	5.76×10^7	2.77×10^5	1.60×10^{13}
26	Water	J	3.71×10^8	1.39×10^5	5.16×10^{13}
Operation phase					
27	Electricity	J	3.94×10^9	2.77×10^5	1.09×10^{15}
28	Labor	J	4.86×10^9	4.30×10^6	2.09×10^{16}
29	Fuel	J	5.53×10^{11}	1.15×10^5	6.36×10^{16}
30	Oxygen	kg	6.02×10^3	5.16×10^{10}	3.11×10^{14}
31	Propane	J	1.92×10^{10}	8.06×10^4	1.55×10^{15}
Total emergy without services					**2.29×10^{17}**
Emergy-based currency equivalent without services		Em$/year			**19,572**
Emergy-based currency equivalent per kilogram without services [a]		Em$/kg			**0.10**
Services					
32	Managing costs	$	12,800	1.17×10^{13} [b]	1.50×10^{17}
33	Variable costs	$	6220	1.17×10^{13} [b]	7.28×10^{16}
34	Fixed costs	$	16,602	1.17×10^{13} [b]	1.94×10^{17}
Total emergy with services					**6.43×10^{17}**

[a] The distributor recovers 188 t per year of steel, at the cost of Em$ 19,572.
[b] Brazil's EMR was taken from NEAD (2009) and equals 1.17×10^{13} seJ/$.

in this system. The emergy-based currency equivalent without services increases from Em$ 9145 to Em$ 33,274. However, it is essential to keep in mind that part of this value mainly that associated to the managing costs, returns to society as a benefit (employment). This value corresponds to 40% of the total emergy with services included. When a particular service is studied, it may be more accurate to use only the metabolic emergy of the human services (Odum, 1996), since an average seJ/$ ratio would be more appropriate for overall aggregate calculations, as the study of regions or nations. In this way, the comparison between systems (with and without scrap exchange) was performed using the emergy values without services. This procedure allows the comparison of the physical and technological characteristics of the system under investigation, independently of the economic level of the country in which the system operates (Brown and Ulgiati, 2002).

The resources employed during the new system implementation and operation (composed by the old system and the logistic network, Fig. 5B) are shown in Table 3, and includes the resources used for maintaining the containers constructed specifically for scrap storage and the trucks acquired for its transportation. The steel use for container construction contributes with 5% to the total emergy, and the main investment is due to the purchase of the trucks for scrap recovering, 53% seJ/seJ. The emergy balance made for the maintenance phase shows that steel sheets for containers repair represent 3% of the total emergy. In the operation phase, labor inputs correspond to 9% seJ/seJ, and fuel is the resource used in a higher proportion, 28% seJ/seJ.

The system emergy (Fig. 5B) is twice that calculated for the conventional system when the logistic network for recycling is included. However, this higher emergy investment permitted the recovery of 376 t/year of scrap (Fig. 3).

5. Discussion

5.1. The benefits and costs under the steel plant point of view

The steel plant receives material with specific emergy of 6.09×10^{11} seJ/kg from the distributor, and uses 10.1×10^{11} seJ/kg (Table 4) to produce steel sheets to sale (secondary steel production). The total emergy spent (16.2×10^{11} seJ/kg) is approximately 3 times lower than that needed to provide 1 kg of steel from virgin ores (53.5×10^{11} seJ/kg, Table 6). The emergy invested to save 1 kg of steel (6.09×10^{11} seJ/kg) is also 40% lower than that calculated to produce steel exclusively from recycled material (Bargigli and Ulgiati, 2001).

The steel plant benefits, in terms of emergy-based currency equivalents, can be calculated (Eq. (4)).

$$\text{Em\$}_S = \text{Em\$}_V - \text{Em\$}_R \tag{4}$$

Table 4
Comparison of the value of emergy per mass calculated in this work with values found in the literature.

	Emergy per mass [a] × 10^{11}/(seJ/kg)	References
Logistic network for recycling	6.1	This work
Primary Steel production	53.5	(Brown and Buranakarn, 2003)
Primary Steel production	61.9	(Bargigli and Ulgiati, 2001)
Secondary Steel production	10.1	(Bargigli and Ulgiati, 2001)

[a] Values of specific emergy are relative to the 15.83×10^{24} seJ/year baseline as defined in the literature cited (Odum et al., 2000).

Table 5
Summary of the savings obtained in the first year of the reverse logistics network.

	Emergy per mass × 10^{11}/(seJ/kg)	Currency per mass/(Em$/kg)	Currency per year/(Em$/year)
Steel plant			
Net savings	37	0.32	121,368
Distributor			
Total savings	30	0.26	48,880
Investment	6	0.05	19,573
Net savings	24	0.21	29,307

where $\text{Em\$}_S$ is the emergy-based currency equivalent relative to the difference between the emergy-based currency equivalent used to produce 1 kg of steel from virgin ores ($\text{Em\$}_V$) and $\text{Em\$}_R$, which corresponds to the emergy-based currency equivalent for producing 1 kg of steel from steel scrap. The steel plant saves Em$ 0.32 per kilogram of scrap used, and due to the distributor's investment of Em$ 19,573 per year, the steel plant saves approximately Em$ 120,000 per year.

5.2. The benefits and costs under the distributor point of view

The distributor, in its turn, has also environmental benefits receiving from the steel plant 188 t of steel sheets as payment for the services of collection of trimmings (Fig. 3). The points location in the ternary diagram (Fig. 6) shows the relationship between the investment in fuel, goods and services and the amount of steel recovered. The system represented by the black square (Fig. 6) resulting from the combination of both customers is located in region 2 suggesting that it is environmentally beneficial. The location of the system also indicates a situation in which fuel consumption is lower than the investment in goods and services.

The distributor benefit in terms of emergy-based currency equivalents can be calculated with the use of Eq. (5).

$$\text{Em\$}_{SD} = \text{Em\$}_V - \text{Em\$}_R - \text{Em\$}_I \tag{5}$$

where $\text{Em\$}_{SD}$ is the emergy-based currency equivalent relative to the distributor's savings. $\text{Em\$}_V$ is the emergy-based currency equivalent used to obtain 1 kg of steel made of virgin ores (0.46 Em$/kg) and $\text{Em\$}_R$, corresponds to the emergy-based currency equivalent value of 1 kg of recovered steel (0.10 Em$/kg). $\text{Em\$}_I$ is the distributor's investment to implement and administer the logistic network for recycling 1 kg of steel scrap (0.10 Em$/kg).

The distributor saves Em$ 0.26 per each kilogram of steel bought from the steel plant, or Em$ 48,880 in a year. This benefit is lower than that achieved by the steel plant but is still advantageous.

The emergy-based currency equivalent is not a real dollar, which can be accounted for in the company bookkeeping system, but it refers to advantages gained by society at the local, regional and global scales. Nevertheless, the total value saved per kilogram (Em$ 0.53, Table 5) calculated using the emergy-based currency

Table 6
Summary of the benefits obtained by the reverse logistics network, and the simulations for the system to reach area 2, area 1 and running at full capacity.

Trimmings collected	Figure	Quantity/(t)	Emergy savings × 10^{17}/(seJ/year)	Savings/(Em$/year)
Minimum to reach area 2	7	102	1.8	15,701
Actual	**6**	**376**	**14.2**	**121,368**
Minimum to reach area 1	8A	440	19.9	170,256
Full capacity	8B	800	39.2	334,872

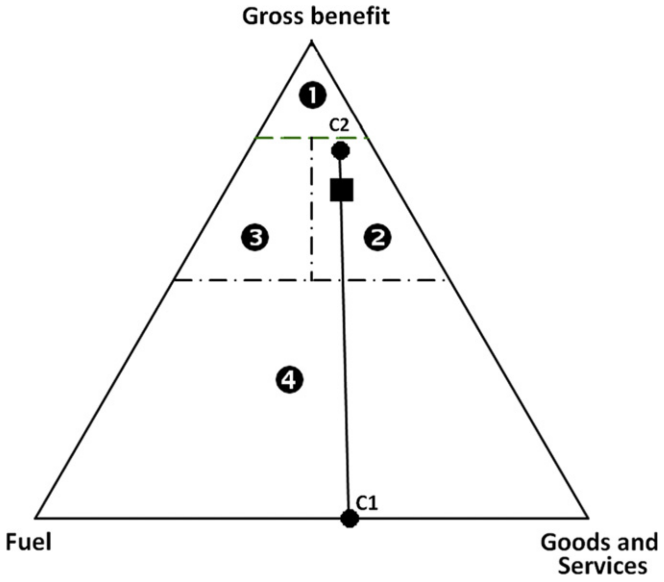

Fig. 6. Emergy ternary diagram of the whole distribution system: (C1) customer without scrap exchange, (C2) customer with scrap exchange and system (C1 + C2) representing the combination between (C1) and (C2). The diagram shows four regions adopted by the authors, where: area ① excellent, areas ② and ③ indicate good performance, but in ③ fuel consumption is higher than in ②, and area ④ indicates that there is no net benefit.

equivalent is consistent with the market values calculated by Calderoni (2003). This author estimated savings of US$0.30 to US$0.85 for the steel cans recycling in São Paulo, and savings from US$ 0.30 to US$ 1.80 for the whole country.

5.3. Improving the reverse logistics network

The use of emergy ternary diagrams allows simulating the conditions to monitor and improve the logistics network. Figs. 7 and 8 show two situations that may help decision-making in order to cover the environmental benefits in conjunction with the cost-effectiveness considerations.

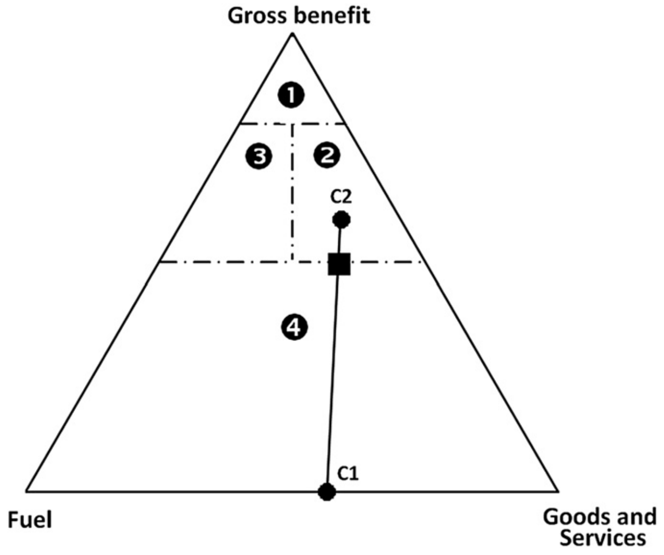

Fig. 7. Minimum quantity to be collected to achieve environmental benefits reaching area ② of the emergy ternary diagram. The diagram shows four regions adopted by the authors, where: area ① excellent, areas ② and ③ indicate good performance, but in ③ fuel consumption is higher than in ②, and area ④ indicates that there is no net benefit.

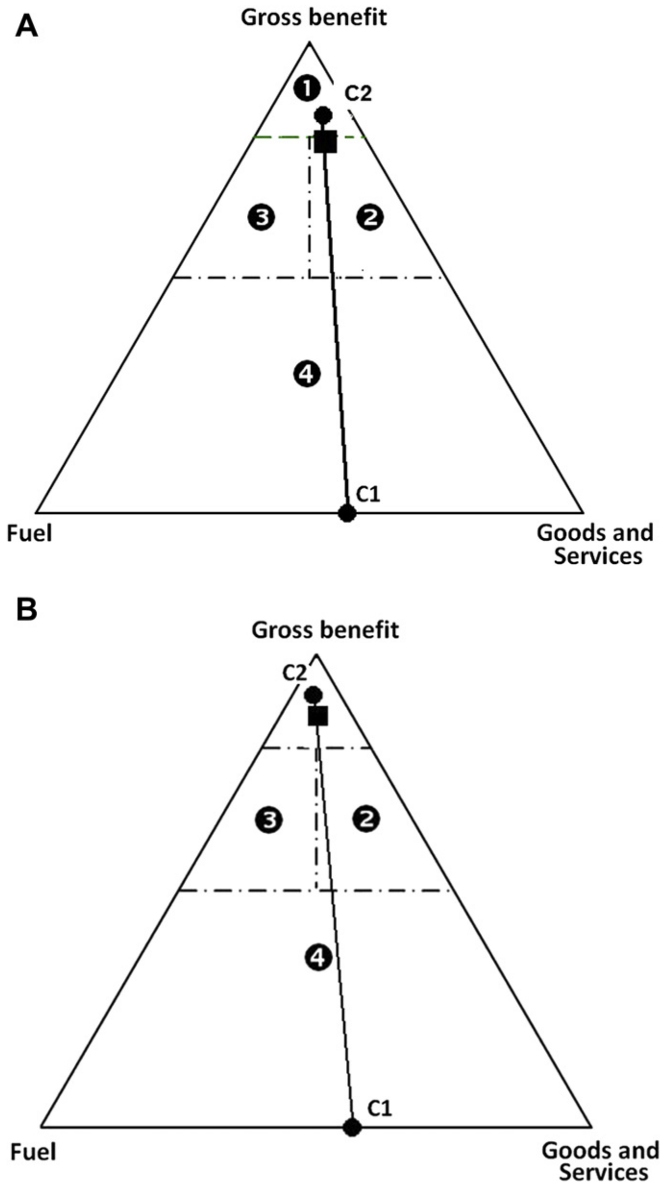

Fig. 8. Simulation of the quantity of trimmings to be collected to reach area ①. (A) Simulation for achieving area 1 and (B) simulation for the system running at full capacity. The diagrams show four regions adopted by the authors, where: area ① excellent, areas ② and ③ indicate good performance, but in ③ fuel consumption is higher than in ②, and area ④ indicates that there is no net benefit.

The minimum amount to be collected according to the infrastructure implemented was estimated (Fig. 7). The location of the black square on the line that crosses the diagram horizontally at 50% seJ/seJ shows the condition in which the emergy investment (fuel, goods and services) equals the emergy of the steel recovered. This situation results from the collection of 102 t of steel trimmings per year combining of both types of customers, and the location of the black square between regions 4 and 2 indicates that fuel consumption is less significant than the investment in goods and services.

Fig. 8A simulates the situation in which the distributor collects a quantity of trimmings that allow the whole system (black square) to be located in the line that separates regions 2 and 1. Fig. 8B simulates the system running at full capacity. Results summarized in Table 5, make it clear that, in the first year, the system operates with environmental benefits that can be measured by the emergy-based currency equivalent. With the recovery of 376 t (Fig. 6, Table 5), the reverse logistics network implemented saved about Em$ 120,000, without investment by the steel plant. The distributor, which has invested approximately Em$ 19,000, receives a payment of Em$ 48,880 for the separation and collection services provided to the steel plant. Customers C2 have guaranteed the sale of their scrap at market prices.

The simulation of the minimum amount to be collected to ensure the environmental benefit is useful for decision-making at the distributor level. It is known that the annual quantities of scrap may increase or decrease according to the market demand. This simulation determines a minimum value (102 t) to be collected that allows decision on whether it is worth keeping the system running. In this case, the benefit in emergy-based currency equivalents shows that with the collection of only 102 t is still possible to save about $ 15,000 in a year.

To achieve an excellent environmental performance (Fig. 8A, Table 6), the distributor should increase the amount of scrap collected to 440 t, corresponding to an increase of only 17% w/w of the total collected in the first year.

Knowing that the reverse logistics network was designed to collect all the waste generated by their customers, decision makers can estimate the potential benefit for the recovery of 800 t (Fig. 8B) at around Em$ 330,000 (Table 6). In this situation the black square moves to the left side of the diagram, indicating that fuel consumption is more significant than the investment in goods and services.

6. Conclusion

Motivated by the growing importance of reverse logistics activities in an increasingly competitive global market, this study proposed a new method for assessing a selected reverse logistics network for steel recycling. The goal was to reintroduce materials and energy back into productive use with the minimum energy required and the least waste of material in the process. The new assessment method using the emergy ternary diagrams helped to:

- integrate economic and ecological assessments documenting the emergy invested for steel recovering,
- provide units more familiar to decision makers and the public using the emergy-based currency equivalent
- calculate the gross benefit resulting from implementation of the reverse logistics network
- show that the steel plant benefits more than the distributor, but both of them had win–win benefits.
- determine the minimum quantities of steel scrap to achieve environmental benefits
- determine the potential benefits of the reverse logistics network for recycling.

Less nonrenewable emergy and increased renewable emergy use are beneficial for the environment and provides benefits to society. Recognizing that the implementation of reverse logistics networks for recycling generates benefits to society and that they can be represented by a given amount of equivalent dollars, may call for policies that favor these processes and more reliable dealers. In Brazil, the environmental legislation is still limited, and it does not provide incentives to improve the degree of recycling of materials. The National Policy on Solid Waste was granted in 2010 (Law No. 12305 of August 2, 2010). However, this policy still depends on future regulations for its effective implementation. The evaluation proposed may help policy-makers to create strategies that reward the use of reverse logistics networks for recycling, by decreasing taxes or stimulating innovation. In this way, a share of the benefits that they generate to society will return to them as a reward and further motivation. With appropriate governmental policies and proper training and technical assistance, much more economic and environmental benefits can be obtained.

The strength of this new assessment method is that it can be used to help company decision makers to make key decisions considering not only the economic benefits but also the environmental and societal benefits. The use of logistic networks for recycling is an attractive model that may also be beneficial for other industrial sectors, and the model presented here may help to design and monitor new initiatives. Hopefully, these successful and profitable achievements will inspire other companies that value the win–win benefits of improving profitability and decreasing environmental burdens throughout their supply chain.

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