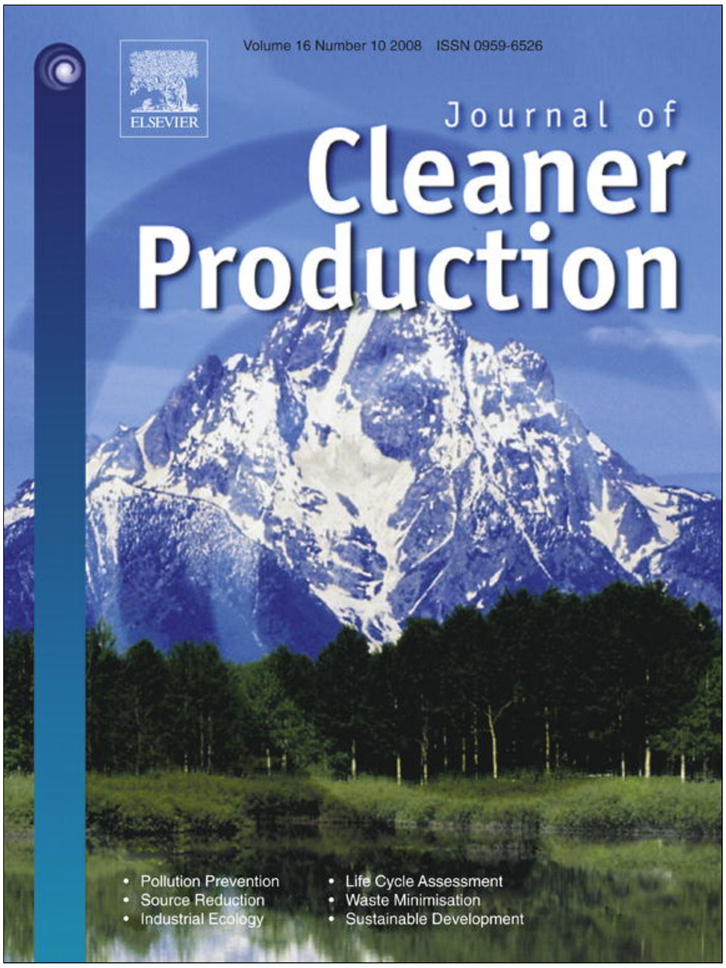
Volume 16 Number 10 2008 ISSN 0959-6526
ELSEVIER
Journal of
Cleaner
Production
• Pollution Prevention
• Source Reduction
• Industrial Ecology
• Life Cycle Assessment
• Waste Minimisation
• Sustainable Development

Available online at www.sciencedirect.com
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ELSEVIER
Journal of Cleaner Production 16 (2008) 1106–1117
Journal of Cleaner Production
www.elsevier.com/locate/jclepro

Cleaner production practices in a medium size gold-plated jewelry company in Brazil: when little changes make the difference

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Received 12 December 2006; received in revised form 23 May 2007
Available online 4 September 2007

Abstract

The paper reports the experiences of a medium size gold-plated jewelry company, located in São Paulo – Brazil, in order to reduce waste and pollution. Actions taken for this purpose are described, as well as the key factors affecting progress, the changes that have been introduced, their cost-effectiveness and the additional benefits accomplished. A waste minimization project was carried out to obtain environmental and economic benefits. The first cleaner production (CP) interventions targeting the improvement of the company's environmental performance are also described and related to economic benefits. Local scale performance indicators were employed to evidence the economic and the material savings by kilogram of piece produced. Additionally, savings achieved included 86% reduction in volume of degreasing solution and 36% reduction in electricity consumption. The results are complemented with the use of global scale performance indicators (Material intensity, MIs, and Emergy accounting), which look at upstream impacts and evaluate the environmental performance of the system on the biosphere scale, respectively. Material savings (MIs) account for each matter flow to and from a chain of processes from raw material to the final products, and were calculated in order to estimate the changes avoided in material flows and cycles due to the reduced use of inputs by the company. The total emergy of the savings is used as a quantitative measure of the total environmental support to the flows of energy and matter involved in the process, and is calculated to assess the work of nature spared by the reduced use of materials and energy by the company. Emergy values were converted to currency. Global scale performance indicators have shown that little changes within the company reduce upstream impacts and that benefits to the environment are greater than that observed in the companies neighborhood.

Keywords: Waste minimization; Gold-plated jewelry; Cleaner production; Environmental-economic indicators; Material intensity; Emergy

1. Introduction

Metal finishing operations are recognized as a major source of environmental pollution [1–3]. Finishing operations such as electroplating are coming under increasing scrutiny and regulations worldwide. This can increase their costs of operations and their commercial risks [4]. While this has the effect of reducing environmental pollutants, it leaves plating companies with the difficult problem of finding reasonable, cost-effective alternatives [5]. However, despite the documented linkages between environmental-economic improvements, the acceptance of cleaner production and waste reduction initiatives has been slow [6–9].

Environmental-economic improvement is a very general term that can cover reductions in raw material and energy use, improvements in workers health and safety, decreases in discharges to air, water and land, including solid waste for landfill disposal, and the environmental impact of products during use and at disposal [10]. For these reasons, there are several approaches for finding ways to simultaneously make economic and environmental improvements. One tool to accomplish this is to perform an impact assessment to evaluate the most environmentally benign system among design alternatives [11,12]. A second approach is based on process integration methodologies for final comparative assessment [13–17]. For every

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doi:10.1016/j.jclepro.2007.06.002

approach, a detailed waste audit must be performed to ascertain, in specific detail for the individual company, the waste quantity and quality, and the cost to deal with this waste. The waste audit process helps decision makers to find economically and environmentally sound alternative practices, procedures and technologies to make improvements and to reduce their wastages and risks. For this, the use of performance indicators can help to monitor and compare, systematically the environmental-economic improvements, as a first step towards a more complex evaluation. Local scale performance indicators could be particularly attractive for medium size industry in developing countries.

Research in Brazil indicated that cleaner production practices could generate promising results in reducing pollution at low costs [18]. The medium size industries are, however, constrained in implementing those practices by various attitudinal, organizational, technical and economic barriers. In São Paulo, Brazil, educational initiatives to show the environmental and financial benefits of cleaner production are encouraged by the *Companhia de Tecnologia de Saneamento Ambiental* (CETESB), the state environmental agency, which monitors cleaner production projects within companies and displays the data to show the benefits to other companies [18]. Such projects, monitored by CETESB, have a good chance of success, as companies volunteering to participate are motivated to improve their environmental performance, are wishing for innovation, and have access to the CETESB's advisors.

Another initiative is supported by the *Mesa Redonda Paulista de Produção Mais Limpa* (Paulista Cleaner Production Round Table) [19], a non-profit forum, with volunteer participation of academic and industrial sectors. The round table promotes courses and meetings to teach the cleaner production concepts, tools and approaches. However, several initiatives are still taken without this kind of support for the companies, resulting in poorly documented improvements, which are not enough to motivate the companies to incorporate elements of cleaner production into their routine. On the other hand, most large-scale industries report remain unpublished due to confidentiality.

Most of the initiatives in Brazil regarding cleaner production are still dependent upon academic groups that work to spread the CP concepts to their community. The group at *Universidade Paulista* developed a series of thesis [20–29] and articles [9,30,31] on environmental concerns. The purpose of this paper is therefore, designed to present the experiences of a medium size company that implemented a program to minimize wastes and pollution in a joint action with the researchers of *Universidade Paulista*. By providing this information we hope to inspire manufactures to include cleaner production approaches to help them make improvements in environmental and economic performance as equal aspects in their production of products and services. Thereby they can also save substantial time and effort in their improvement journey.

In this paper, the experiences of a medium size gold-plated jewelry production facility located in São Paulo are described and discussed. The company started the improvement of its environmental performance with a waste minimization project suggested by one of its employees, who was getting her Masters degree at the *Universidade Paulista*. Her suggestions led to innovations in the production processes of the company. Local scale performance indicators were employed to clarify and document the economic and the material savings per kilogram of jewelry pieces produced. The process of improvement was complemented with the use of global scale performance indicators. These indicators were used to assess the environmental performance of the system on the biosphere scale (Emergy accounting, [32]) and to evaluate upstream impacts (MIs methodology, [33]). After the company description, a detailed report of the improvements is presented to show how little changes resulted in environmental and financial benefits.

2. Company description

The gold-plated jewelry industry is spread all over the country, but São Paulo, Minas Gerais and Rio Grande do Sul are states in which most of the producers are located. Among the 560 Brazilian jewelry making companies approximately 200 are located in São Paulo. Approximately 64% of them are small companies with less than 20 employees and 26% are of medium size with fewer than 100 employees [34]. In 2006, the sector exported US$ 92 million, which was a 26% increase over the export of 2005 [34].

The company studied is located in São Paulo, Brazil, and is producing gold-plated jewelry since 1986. It employs about 100 people and has the goal of becoming a company which looks carefully at improving efficiency, reducing wastes and environmental impacts.

The company produces about 600 kg of products per month. About 70% is exported to Chile, Bolivia, Venezuela, Argentina, Honduras, Nicaragua, Mexico, Portugal, France, Switzerland and South Africa. The company has always been in compliance with environmental regulations, maintaining an effluent treatment unit and gas emission control system.

Simple ideas led the staff to become more involved with environmental concerns and in developing solutions to problems. The innovations the company has implemented in one year were triggered by this waste minimization program and by the recognition of the potential savings.

Fig. 1 shows the flux of work pieces through the company. Raw pieces, such as earrings, pendants, pins, rings, necklaces, collars and bracelets, without surface treatment are designed and manufactured by suppliers. These pieces are classified as gold-plated jewelry as the layer of precious metal applied varies from 1.5 μm to 6 μm, while knick-knacks always have less than 1.5 μm metal layer. The company is the first Brazilian and Latin American firm to obtain gold-plated jewelry certification, achieving "category a – international standard – ISO 10713" certification, ensuring its clients and distributors of high-quality products in the market.

As pieces without surface finishing enter the company (sector 1), they are visually inspected, separated by type, and identified with a code number. In second sector, the pieces are separated in lots according to clients' requests. The surface treatment with precious metals (mainly gold, but also silver and rhodium) is carried out in the third sector, which has

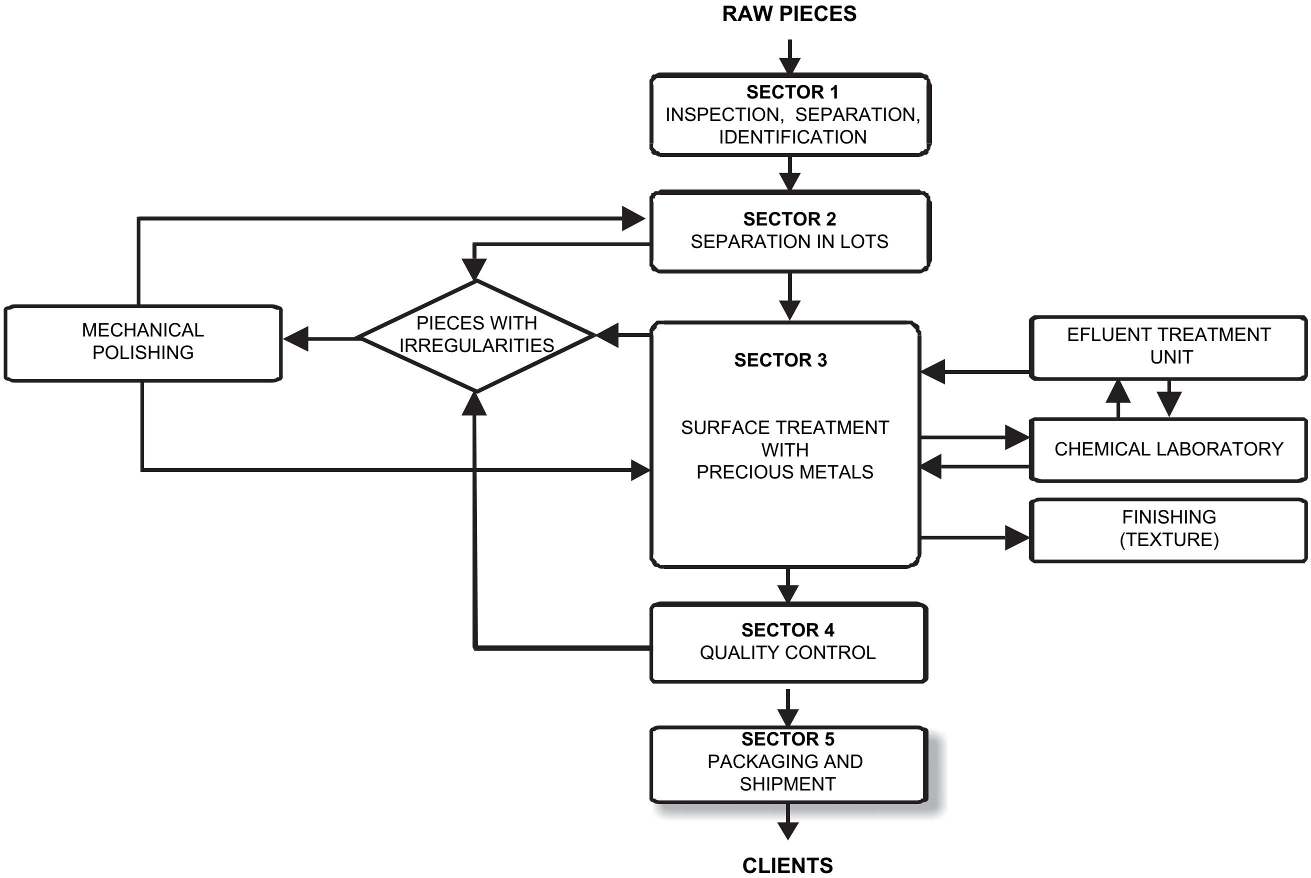

Fig. 1. The production sectors and the pathway of pieces through the company.

four sub-sectors: (i) mechanical polishing, where irregularities on pieces surfaces are corrected; (ii) chemical laboratory that controls baths composition and metal deposit thickness; (iii) finishing, where some of the pieces receive texture and/or stones are mounted (mainly Brazilian stones, zirconium and crystals), accordingly to design specifications; and (iv) effluent treatment unit, based on cyanide oxidation and metal complexation. In the fourth sector, pieces are examined for their technical and decorative quality, and then are sent to fifth sector for packaging and shipment.

3. Methodology

A basic knowledge of the waste stream is essential to create an effective waste management program. This knowledge was developed through a waste minimization audit, which involved the identification of waste generation by sector and the determination of the waste composition and characteristics. This step took a period of one year.

In this first year, the data received through this audit provided a baseline to estimate the potential for waste reduction, reuse and recycling. It was possible to review the waste stream(s) for each sector of the company, document waste reduction practices, and to conduct a field waste sorting and weighing program to provide a waste characterization report. The results provided valuable insight into problem areas.

In the second year, after the waste identification and classification, a performance analysis was carried out in order to evaluate the benefits of the selected interventions. Economic and environmental benefits were assessed in local and global scales, with the aid of performance indicators. The aim is to have suitable indicators for evaluating the real costs of production from a sustainability (and not a purely economic) viewpoint and to perform a cost-benefit analysis comparing the actual output obtained to these production costs.

3.1. Local scale performance indicators

The local scale performance indicators are those that deal with information within the company. Economic and material indicators were chosen, representing money savings per kilogram of pieces produced (kg_{pp}) and material savings per kilogram of pieces produced (kg_{pp}) [35,36], as recommended by CETESB [18].

Material and economic savings are referred to inputs, that is, to the economy of resources purchased by the company. In addition, other inputs of the facility were also analyzed with local performance indicators: the water use (L_{water}/kg_{pp}), degreasing solution use ($kg_{degreasing\ solution}/kg_{pp}$), effluent volume of baths' replacement ($L_{electrolyte}/kg_{pp}$) and electric energy consumption (kWh/kg_{pp}).

3.2. Global scale performance indicators

To provide a consistent evaluation of the benefits achieved from the savings, the following methods were employed.

3.2.1. Material intensity evaluation

This method, developed at the Wuppertal Institute [33], can evaluate the environmental harm associated with the extraction or diversion of resources from their natural ecosystemic pathways. Material intensity factors (g/unit) are multiplied by each saving (material or energy), respectively, accounting for the total amount of abiotic matter, water, air and biotic matter no longer required in order to provide that material to the company. Table 1 shows the values of material intensities (MIs) of the selected individual savings achieved by CP interventions.

3.2.2. Emergy accounting

This method, developed by Howard T. Odum [32], evaluates resources and services in both ecological and economic systems on a common energy basis, the solar energy joules (sej). It quantifies the direct and indirect environmental work for generating a resource or a service or the environmental work used to obtain a product or energy flow in a given process [32]. The greater the total emergy driving a process, the greater its environmental cost. The emergy accounting method is used as a quantitative measure of the total environmental support to the flows of energy and matter involved in a process. It is a measure of the work of nature necessary for providing a given resource. In other words, part of past and present work of ecosystems, geochemical cycles, and tidal momentum are required to make a resource available, be it the present oxygen stock in the atmosphere or the present stock of gold or oil deep in the planet.

Emergy investigation complements the results from material intensity accounting of processes, identifying patterns characterized by different demands for environmental support and different balance of renewable and non-renewable input resources. The amount of emergy required to provide one unit of each input is referred to as its emergy intensity (sej/unit), a 'quality' factor that measures the support provided by the biosphere to the input. Emergy intensity factors or specific emergies (sej/unit) are multiplied by each saving (material or energy), respectively, accounting for the total amount of emergy that would be no longer required to provide that material to the company. Table 2 shows the values of emergy intensities of the selected individual savings achieved by CP interventions.

Emergy evaluation also offers the possibility to integrate economical and ecological assessments by calculating the emprice (Em$). It expresses the emergy one receives in the material for each dollar paid for the material. It was introduced by Odum [32] in order to estimate the monetary value of the emergy content of a good or service. In this case, the emergy that one saves with the CP interventions was converted in currency (Em$). The use of Em$ instead of US$ is only a way to differentiate the methodology used to calculate monetary values.

To convert emergy values to Em$ values one can divide the total emergy by the emergy money ratio (EMR, expressed in emergy per currency, sej/US$), which is the ratio of the total emergy of the nation or region and the GDP (Gross Domestic Product). The GDP includes market dynamics and, in this way, when EMR is used as a conversion factor to calculate the emprice of a commodity or service, the market partially affects the emergy content of some flows.

In this work, the emprice was obtained by dividing the emergy savings by the emergy money ratio value equals 3.70×10^{12} sej/US$ [42]. This procedure restricts the analysis to the country where the product is commercialized or

Table 1
Material intensity factors of materials and energy sources taken from [33,37]

	Material intensities			
	Abiotic matter	Biotic matter	Water	Air
Paper/(g/g)[a]	1.86	0.75	93.6	0.325
Plastic/(g/g)[b]	2.49		122.2	1.617
Metal scraps/(g/g_{steel})[c]	8.14		63.7	0.444
Degreasing solution/ (g/g_{NaOH})[d]	2.76		90.3	1.064
Rinsing water/(g/g)[e]	0.01		1.3	0.001
Final-color electrolyte/ (g/g_{gold})[f]	540,000.00			
Electricity/(g/kWh)[g]	1550.00		66,700.0	535.000

[a] Corrugated cardboard paper, European data.
[b] Low density polyethylene, European data.
[c] Wire rod steel, world data.
[d] Sodium hydroxide, European data; degreasing solution composition content equals 26% in weight was used in calculations.
[e] Drinking water, German data.
[f] Gold, world data; final-color electrolyte content equals 0.5 g/L of gold was used in calculations.
[g] Electrical power, world data.

Table 2
Emergy intensity factors of materials and energy sources

	Unit	Emergy intensity/ (sej/unit)	Reference	Comments
Paper	g	3.88×10^{9}	[38]	
Plastic	g	5.85×10^{9}	[39]	Plastic packages
Steel	g	4.13×10^{9}	[39]	Metal scraps
Chemicals	g	1.00×10^{9}	[32]	Sodium hydroxide present in degreasing solution composition (26% in weight) was used in the calculations
Water	g	9.23×10^{5}	[40]	Potable water (river water source)
Gold	g	3.00×10^{13}	[41]	Gold content of the final-color electrolyte (0.5 g/L) was used in the calculations
Electricity	kWh	5.94×10^{11}	[32]	Hydroelectric plant in Tucurui, Brazil

produced, but it is useful to guide decision making. The emprice obtained may be compared to the actual money savings achieved by the company, that is, to the market price of the savings. If the emprice is lower than the market price, there is a buyer advantage. The buyer receives more emergy (energy and resources) than is being paid for. If the emprice is higher than the market price, a company may be selling more emergy than is being paid for.

Both accounting methods employed are extended back in time to include resource use or the environmental work needed for inputs formation. In this way, an estimation of the avoided cumulative environmental burden was performed in order to quantify the environmental benefits of material and energy savings by the company.

4. Results and discussion

4.1. Waste minimization program

The waste minimization audit (WMA) was performed in the first year and the ratio of the weight of inert solid wastes generated by the company by the weight of pieces produced, is shown in Table 3. The results obtained in the second year after the interventions are also shown.

The quantity of corrugated cardboard sold to recyclers in the second year diminished to less than a half of the value reported in the first year. The decrease was due to the reuse of cardboard boxes in several parts of the company. Other materials, such as mixed and white paper, increased in quantity sold to recyclers, due to an improvement in the collection process. The profit provided by waste sales is shown in Table 3.

4.1.1. Paper

The ratio of waste paper generation to the mass of pieces produced diminished approximately 47% in weight (Table 3). The main reduction was due to the reuse of cardboard boxes, as the use of suppliers boxes to deliver products to clients. This reduction diminished the sales to external recycles. Money savings due to the lower consumption of paper were not accounted. A reduction in the amount of new packaging materials that had to be purchased by the company also occurred, but unfortunately it was not tabulated.

4.1.2. Plastic packages

During waste auditing, it was noted that plastic packages used within the company to transport pieces were badly used and sent to recyclers in great quantities. The audit indicated that four types of plastic packages were used: transparent ones (with and without code labels) and yellow ones (with and without code labels). The reduction of package waste was performed by substituting the transparent ones without label by rigid plastic cups, which can be reused several times. The plastic packages with code labels could also be reused twice without decrease in the production flux. The ratio of the plastic packages quantity by the mass of pieces produced is shown in Table 4 for the second year, with the reduction/reuse program fully working. The money savings due to the reduce/reuse program avoiding the purchase of new packages for pieces transport within the company resulted in a considerable value (Table 4). The investment of the company to run this reduce/reuse program was US$ 18.00 due to the acquisition of cardboard boxes to keep the packages for reuse.

The use of plastic garbage bags was also diminished (not shown in Table 4). The use of disposable cups for coffee and teacups decreased the volume of the total garbage. The ratio $g_{plastic\ bags}/kg_{pp}$ decreased from 710 to 20 and the money savings in the bags acquisition reached US$ 225.80.

4.1.3. Metal scraps

The ratio of metal scrap waste to the mass of pieces produced diminished to 42% in weight in relation to the first year (Table 3). This reduction was due to the reuse of metallic materials within the company. Unfortunately, some of the

Table 3
Quantities of inert solid wastes sold to external recyclers by the company in relation to the quantity of pieces produced in two years with the correspondent profit due to the sales

	g_{waste}/kg_{pp}	Sales to external recyclers/ (US$/year)	g_{waste}/kg_{pp}	Sales to external recyclers/ (US$/year)
Waste	1st year		2nd year	
Paper				
Cardboard	620	288.60	220	96.10
Mixed	60	18.60	90	27.10
White	110	48.00	110	49.30
Subtotal	790	355.20	420	172.50
Metal				
Scraps	120	35.60	70	20.90
Plastic				
Packages	230	70.20	101	31.30
Total		461.00		224.70

Table 4
Quantities of plastic package and safety pins waste generated in the company in relation to the mass of pieces produced in the second year with the corresponding money savings due to the reduce/reuse program

Package type	g_{waste}/kg_{pp}	Money savings by reduction/ (US$/year)	Money savings by reuse/ (US$/year)
Plastic			
Transparent			
with code label	50	None	2,095.20
without code label	40	34.40	1,602.00
Yellow			
with code label	10	None	468.50
without code label	1	44.30	65.30
Implementation cost			(−) 18.00
Safety pins			
Internal reuse	20		1,886.40
Reuse by supplier	4		493.20
Implementation cost			(−) 19.30
Total		78.70	6,573.30

actions were taken without control and are noticed only by the reduction of materials sold to recyclers.

Within the metal scrap category, safety pins are used to separate and transport necklaces, collars and bracelets. These safety pins were used once, discarded regardless of their condition and sold to recyclers included in the metal scrap category along with other materials. The safety pin reuse was launched in the second year. Safety pins in good condition were reused internally to transport pieces after surface treatment, while oxidized pins were sent to suppliers to transport raw pieces. To reuse safety pins after surface treatment, a separation and cleaning sector was introduced. Damaged safety pins were sold to recyclers. The ratio of safety pins waste to the mass of pieces produced was 20 $g_{safety\ pins}/kg_{pp}$, corresponding to 2/5 of the total metal scrap reduction (Table 3). The total investment to reuse metal safety pins was US$ 19.30 spent on the acquisition of boxes to collect safety pins in the company sectors. Separation and cleaning was performed in the warehouse without cost. Table 4 shows the environmental benefits and the money savings due to pins reuse.

4.2. Improvements in the production process by cleaner production interventions

After the improvements achieved from the waste minimization project, the company followed with some innovations in production processes, by means of cleaner production (CP) interventions.

The electroplating line contains three chemical and seven electrochemical tanks (Fig. 2). The initial tanks are alkali bath (degreasing solution) to clean the metal surface and acid activation bath (10% v/v sulfuric acid) followed by rinsing tanks. Next, there are two electroplating tanks where the electrolytic solution is a mixture of copper salts, one alkaline, and the other acid. An electric current flowing from anode to cathode causes copper to pass from the anode to the cathode (rings, bracelets, etc.). Once the appropriate quantity of copper has been deposited on the surface of the pieces, they can go to silver/rhodium line or gold line. Organic compounds in the electrolytic solutions (brighteners) help the development of a smooth layer of metal on the pieces surface. After silver and rhodium baths, pieces are rinsed in hot water and dried. Rhodium bath improves hardness of silver-plated pieces. In the gold line, pieces still pass through the final-color bath, composed of gold, silver and copper, and are then rinsed in hot water and dried.

After each precious metal containing bath, there is a recovery tank implemented to capture the plating solution as the work pieces were taken out of the tank, before rinsing. These tanks, containing distilled water, are used as drag-out tanks before water rinsing. The solution is then evaporated, condensed and returned to replenish the plating bath.

As each stage is followed by a rinsing stage with water, there is a high volume of liquid effluents with different pollutants, mainly heavy metals and inorganic anions. Waste streams are generated in these stages related to the different chemicals used in the processes leading to hazardous wastes [2,3]. Then, the electroplating process creates a considerable amount of toxic wastewater containing heavy metals, which requires treatment. The most important toxic contaminants found in plating wastes are acids, cyanides and heavy metals such as copper. Alkaline cleaning agents, grease and oil are also found in these wastes [43].

Four steps of the electrodeposition process (Fig. 2) were considered for a CP intervention: the toxic wastewater stream of degreasing step, the fate of the liquid wastes due to final-color bath changes, the water consumption of the metal plating process and the energy consumption for heating baths.

4.2.1. Degreasing solution consumption

Alkaline cleaners are probably the most widely used in metal finishing. Cleaner formulations are antagonistic to good treatment of a metal finishing effluent because they are chemically formulated to keep dirt and oil in suspension. If their concentration in an effluent is high enough this same effect prevents efficient removal of the precipitated metals.

The raw pieces are first degreased in bath of caustic soda, cyanides and hypophosphite to remove the oil they come coated in to prevent corrosion (Fig. 2). They are then rinsed, soaked in an acid bath to pre-treat the surface and rinsed once more in water. The degreasing solution was replaced each 15 days and sent to the effluent treatment unit. This practice meant a loss of time and money. In a joint action with the degreasing solution supplier, the baths changes were tied up to the mass of pieces degreased, leading to a longer operating period of 2.5 months per change. Controlling the baths changes by the quantity of degreased pieces brought savings on chemical costs and reduced the company's quantities of toxic waste. Table 5 shows the results in money savings and the ratio of consumed degreasing solution to the mass of produced pieces.

There was a significant reduction (nearly 86% in weight) in the $g_{degreasing\ solution}/kg_{pp}$ ratio after the CP intervention, with savings of more than U$ 8,000.00 in a year. Moreover, the quantity of spent bath sent to the effluent treatment unit diminished about five times, reducing effluent treatment costs, and energy and chemicals consumption.

4.2.2. Rinsing water consumption

The surface finishing industry is a chemical-intensive industry. However, it is important to note that finishing operations also require equally disproportionate quantities of process water for parts cleaning and preparation, for bath make-up and maintenance and, especially, for rinsing. When the company started looking at its waste, water conservation was one of the main possibilities identified. The water use for rinsing pieces after each step of the electrodeposition process (Fig. 2) represented 64% of the water volume consumed by the entire company. Originally, the water flowing in all ten rinsing was treated as waste after use. Another simple CP intervention, targeting to reduce water use was performed. In this way, the registers of each rinsing tank were then controlled manually and only opened when the rinsing water showed a certain turbidity (empirical data) controlled by line staff. This procedure was adopted in a way to not compromise product quality or the composition

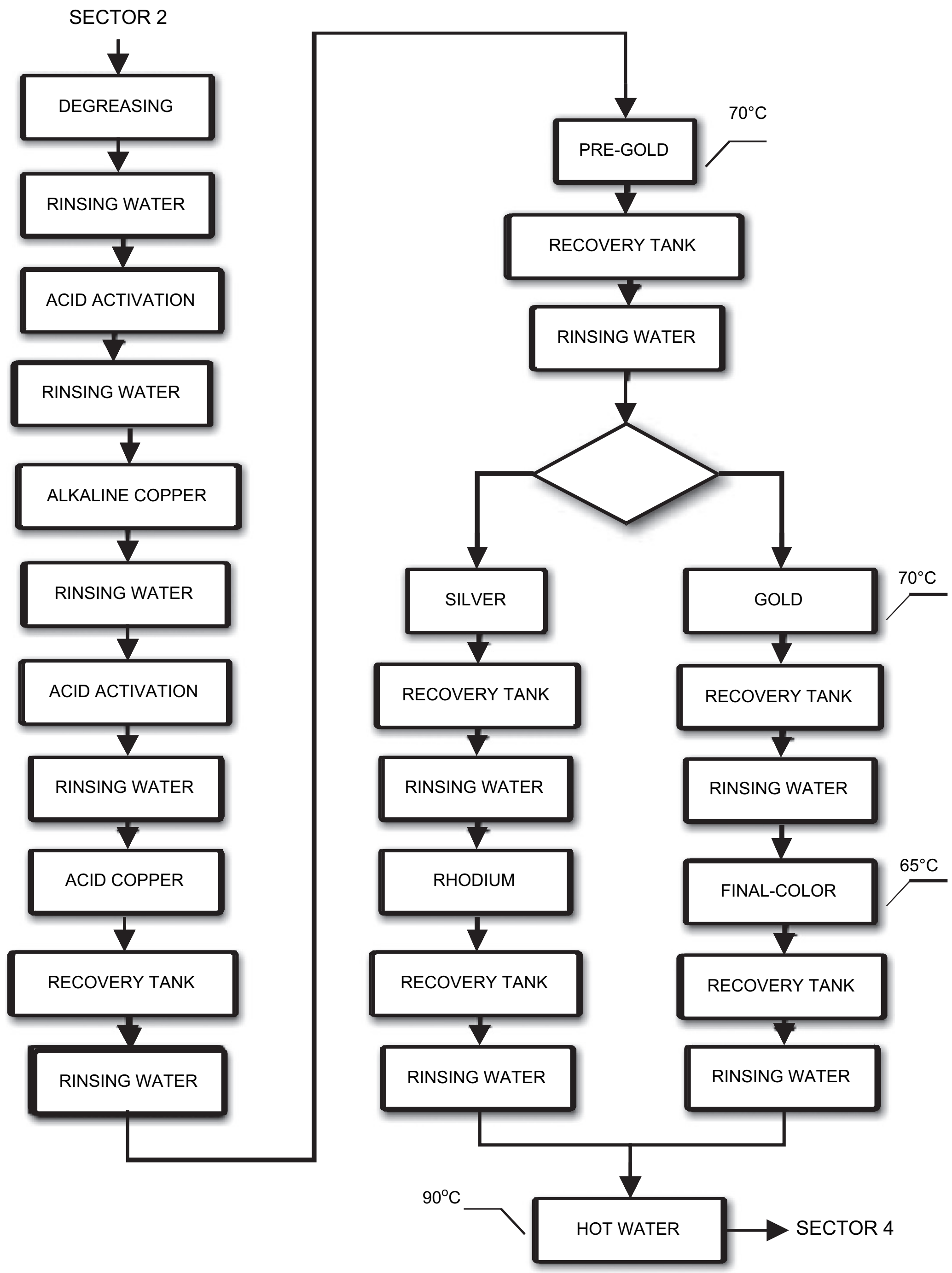

Fig. 2. Schematic representation of sector 3 (Fig. 1) of the electrodeposition process showing the working temperatures of heated baths. Recovery tanks use distilled water, which is collected after chemical analysis and evaporated to recuperate precious metals.

of next bath, which always performs an electrolytic process. Table 6 shows the ratio of water consumption, in volume, to the mass of pieces produced and the money savings due to the CP intervention. A reduction of 35% in water volume was achieved by this simple CP intervention.

4.2.3. The fate of the liquid wastes due to bath replacement

The process baths used in metal finishing are expendable and must be periodically discarded when their chemical activity is below a level acceptable for production purposes. Hence, another source of waste in surface finishing processes is the change of electrolytes.

The production of gold-plated jewelry operates with several electrolytes that have to be eventually changed. Among these electrolytes, that of final-color was chosen to undergo a CP intervention (Fig. 2). The final-color electrolyte was changed periodically, depending on the quantity of pieces processed. For a period the old mixture, still rich in precious metals, was simply returned to the supplier. Prices accounted in Table 7 are already discounted accordingly to the quantity of

Table 5
Ratio of consumed degreasing solution to the quantity of pieces produced with the associated money savings, before and after CP intervention

Period	$g_{degreasing\ solution}/kg_{pp}$	Cost/(US$/year)
Before CP intervention	360	9,309.60
After CP intervention	50	(−) 1,047.60
Money savings		8,262.00

electrolyte sent back to the supplier, before and after CP intervention. Monitoring of the chemical levels of this tank and the manufacturer's specifications, allowed establishing control charts with lower limits for efficient functioning of the process. Line staff was responsible for monitoring (with laboratory assistance) and keeping charts up to date. It was observed that the addition of 15% in volume of the initial composition of the final-color bath, after the quantity of processed pieces reached the limit value given by the supplier (empirical data) permitted to extend its useful life to about 60% in volume.

Table 7 shows the ratio of the volume of the final-color electrolyte consumed to the mass of pieces produced. The cost of the additional chemicals added to the bath and the money savings due to the CP intervention are also shown.

4.2.4. Reduction of electric energy use

Electric energy is a substantial component of the company's costs. The utilization of electricity for heating of water proved to be an important environmental 'hot spot'. Thus, it was interesting to determine if a new conceptual solution could provide an equivalent service but with lower overall environmental impacts.

The target was to manage energy demand across the factory to reduce overall demand and, in particular, to reduce costs per unit of production. There are four baths in the production process, operating 24 h a day, that work at temperatures between 65 °C and 90 °C (Fig. 2). A program to reduce the electrical energy consumption established that the electrical resistances could be turned off for 90 min three times a day, resulting in 18% reduction in electrical usage. This procedure does not compromise the operational temperature of the baths. The baths were also provided with polyvinyl chloride (PVC) balls to reduce evaporation and to reduce heat losses. This resulted in an additional 18% reduction in energy consumption. Table 8 shows the ratio of electrical energy consumed to the mass of pieces produced, before and after the CP intervention. A reduction of 36% in electrical energy, were confirmed by consumption measures *in situ*.

Table 6
Ratio of water consumption in relation to the mass of pieces produced with the correspondent money savings, before and after CP intervention

Period	L_{water}/kg_{pp}	Cost/(US$/year)
Before CP intervention	900	16,488.20
After CP intervention	580	(−) 11,546.40
Money savings		4,941.80

Table 7
Ratio of electrolyte consumption in relation to the mass of pieces produced with the accompanying money savings before and after CP intervention

Period	$L_{electrolyte}/kg_{pp}$	Cost/(US$/year)
Before CP intervention	3.0	126,212.40
After CP intervention	1.2	(−) 39,902.40
Cost for implementation		(−) 29.70
Money savings		86,280.30

4.3. Performance indicators

4.3.1. Local performance indicators

Table 9 summarizes the energy, material and money savings of CP interventions. The absolute quantities shown in Table 9 might be, at a first glance, considered small, but are proportionally significant. It is worthy of attention that the economic benefits of the CP interventions are considerable. Reductions in the consumption of material and energy brought major advantages to the company, especially the CP intervention carried out on the final-color electrolyte.

4.3.2. Global performance indicators

A considerable environmental benefit is related to the avoidance of environmental impact associated with the extraction or diversion of resources from their natural ecosystemic pathways. Table 10 summarizes the material savings in the four environmental compartments (abiotic and biotic matter, water and air). It can be observed that the relatively small quantities of materials saved within the company led to huge preservation of materials outside the company, in particular abiotic matter and water. The CP intervention on the final-color bath replacement accounts for practically all of the abiotic matter saved. In the water compartment, savings were due mainly to CP interventions on rinsing water tanks and electricity consumption, which contribute the principal fraction in the air compartment.

Emergy savings in natural and human systems were accounted, as this metric can provide quantitative insight into sustainability. These values represent a diminution of the environmental load caused by the company after running the waste minimization program and the CP interventions. The highest value corresponds to the final-color electrolyte savings, in agreement to the idea that gold is obtained after a great work of the natural systems and then concentrated further by human mining and industrial work.

All the savings achieved, local and global, are overpowered by those obtained with the CP intervention on the final-color electrolyte. Thus, despite the little quantity of gold recovered

Table 8
Ratio of electric energy consumption in relation to the quantity of pieces produced with the correspondent money savings, before and after CP intervention

Period	kWh/kg_{pp}	Cost/(US$/year)
Before CP intervention	118	26,420.40
After CP intervention	76	(−) 16,939.20
Money savings		9,481.20

Table 9
Annual material, energy and money savings due to CP interventions

	Action	Reduction/(%)	Energy, raw material and money savings/			
			(kWh/year)	(L/year)	(kg/year)	(US$/year)
Paper[a]	Reduction Substitution	47			2664	?
Plastic[a]	Reuse	52			929	4,273.70
Safety pins[a]	Reuse	80			360	2,398.90
Degreasing solution[b,c]	Reduction	86			2232	8,262.00
Rinsing water[b]	Reduction	35		2304		4,941.80
Final-color electrolyte[b,c]	Reduction	~100		13		86,280.30
Electricity[b]	Reduction	36	30			9,841.20
Total money saved						115,881.70

[a] Mass calculated from the difference between wastes sold to recyclers in the first and second years of program implementation (values from Table 3 multiplied by the annual production, 7200 kg/year); money savings from: plastic (US$ 4,291.70 + US$ 225.80) + safety pins (US$ 2,398.90); paper savings and other metal scraps not included.

[b] Data from Tables 5–8. Material and energy savings correspond to the difference of the values before and after CP interventions. Money savings from: degreasing solution (US$ 8,262.00) + rinsing water (US$ 4,941.80) + final-color bath (US$ 86,280.30) + electric energy (US$ 9,481.20).

[c] From the value of 2,232 kg/ano of degreasing solution, only 26% of NaOH were taken into account to calculate the global performance indicators, for final-color electrolyte (13 L/ano) was considered the concentration of 0.5 g/L.

within the company, the savings associated to the nature and human work previously done are considerable, which is consistent to the gold price in the market.

4.3.3. Confronting indicators' results

4.3.3.1. Emprice versus price. The money saved in the second year was US$ 115,881.70 (Table 9). From this value 6% is associated to the waste minimization program and 94% to the CP interventions in the production process. On the other hand, the nature and human work savings equals 2317×10^{11} sej/year (Table 10), being 7.5% due to the waste minimization program and 92.5% to CP interventions in the production process.

The emprice was calculated as Em$ 62,801.51, according to Brazilian economic figures for 1996. Thus, according to emergy accounting, savings related to the real wealth are less than that achieved via the economic accounting. This result shows that the company has a clear emergy disadvantage when it buys its inputs. But in order to stay in business every supplier will have to be paid more money for their products than they spend on fuels and raw materials. That is, their price must be higher than the value of the emergy content of their products. Despite the results that show that economic trades always use services from nature [32,44], there is a tendency for a decrease in the emergy advantage for the buyer as products undergo more processing. The more one advances up the supply chain, far away from the environment-economic interface, the more one will pay for the emergy received. This is in agreement with the macroeconomic observations performed by Ukidwe and Bakshi [45,46] who claim that the cumulative ecological emergy consumption (sej/US$), similar to emergy content, decreases along the economic supply chains.

Economic savings achieved are favored by the commercial trade performed by the company and its suppliers. Thus, in spite of saving Em$ 62,801.51, which was calculated considering only the work invested in emergy, the company economized US$ 115,881.70.

Another point to consider is that the company will no longer consume the stock of natural capital (Em$ 62,801.51), which will be available to further economic uses. This natural stock will certainly generate a higher value when injected in the market [45,46]. In this way, the total saving corresponds at least to the sum of the natural stock saved plus the manmade capital saved by the CP interventions (US$ 178,683.21), if the company production stays stable.

4.3.3.2. Savings signature. Two 'upstream' assessment methods were employed and each one was applied according to its own set of rules. Each method supplies a characteristic signature of the savings of each system, which shows the importance of each intervention depending on the set of rules. Both upstream methods were confronted with money accounting, the main method used in neoclassical economics, which deals with the 'market value' and is an example of a receiver-type value, in which items are valued according to the 'willingness to pay'. In contrast, both upstream methods (material intensity and emergy accounting) are donor-type value methods and provide a measure of what things were needed or disturbed

Table 10
Annual material and work in emergy savings due to CP interventions, using global performance indicators

	Material savings/(kg/year)				Emergy savings/ ($10^{11} \times$ sej/year)
	Abiotic matter	Biotic matter	Water	Air	
Paper	4955	1998	249,350	866	104
Plastic	2313	0	113,494	1502	54
Metal scraps	2930	0	22,932	160	15
Degreasing solution	1602	0	52,402	618	6
Rinsing water	23,040	0	2,995,200	2304	14
Final-color electrolyte	3,499,200	0	0	0	1944
Electricity	46,872	0	2,017,008	16,178	180
Total	3,580,952	1998	5,450,386	21,628	2317

to make an item or generate a service. The signature of each method was set up against each other to provide a comprehensive picture on the savings attained (Fig. 3).

Surprisingly, in the case presented here, emergy signature (donor-type) agreed totally with money signature (receiver-type), but some differences were observed in the material intensity evaluation results. As shown in Fig. 3, the main saving in the waste minimization program is attributed to paper savings in both evaluation methods, in spite of the lack of money savings data. It is interesting to note that all material savings are located mainly in the water compartment, even if all the saved materials are solid wastes.

The CP intervention in the final-color electrolyte corresponds to about 40% of the material, 90% of the emergy and 80% of the money saved (Fig. 3). This is the major saving according to all three-valuation methods, and the minor percentage found in material intensity evaluation may be seen as a contradiction. However, it must be pointed out that material intensity evaluation is strictly calculated on the time frame of the life cycle of the production process, and expresses the present ecosystem disturbance caused by the ore mining and processing phases. On the other hand, emergy accounting covers the 'memory' of the environmental resources that were used up in the past in order to provide the system with its inputs. In the case of gold, this memory goes back to the time of formation of the reserves, and is an indirect measure of global environmental support, and renewability. Thus, gold was found to be less impacting in its extraction and use (material intensity), but has required a larger environmental support for its formation (emergy). Money evaluation reflects gold scarcity, which in the present dominant school of economics means not having sufficient resources to produce enough to fulfill unlimited subjective wants.

Electricity savings take the second place in accordance with emergy accounting, but are in third when material disturbance is evaluated (Fig. 3). In this case, the difference may be attributed to the rules of emergy and material intensity accountings. As stated before, the first looks at the production process from the point of view that all the inputs have, at some time, required a certain amount of the ultimate energy resources that drive the earth cycles (sunlight, geothermal heat and gravitational potential), while the second is only concerned with the material resources that are necessary to support the process, and thus, represents the immediate environmental harm caused by the extraction, transportation and processing of the resources themselves.

There is also disagreement in the evaluation of the savings signature attained from the CP intervention of the degreasing solution (Fig. 3). In relation to the distribution of savings of other interventions, there are practically no savings corresponding to material disturbance evaluation, which may be explained by the low quantity of sodium hydroxide used per kilogram of jewelry pieces produced. When emergy and money accounting are performed, degreasing solution savings surpass the savings achieved by the CP intervention in rinsing water tanks. Emergy accounting includes human services and the exploitation of those energy resources that are not part of the mass flows, either because they have no mass (such as energy sources as sunlight and wind) or because they are no longer there, but were used up in the past in order to make

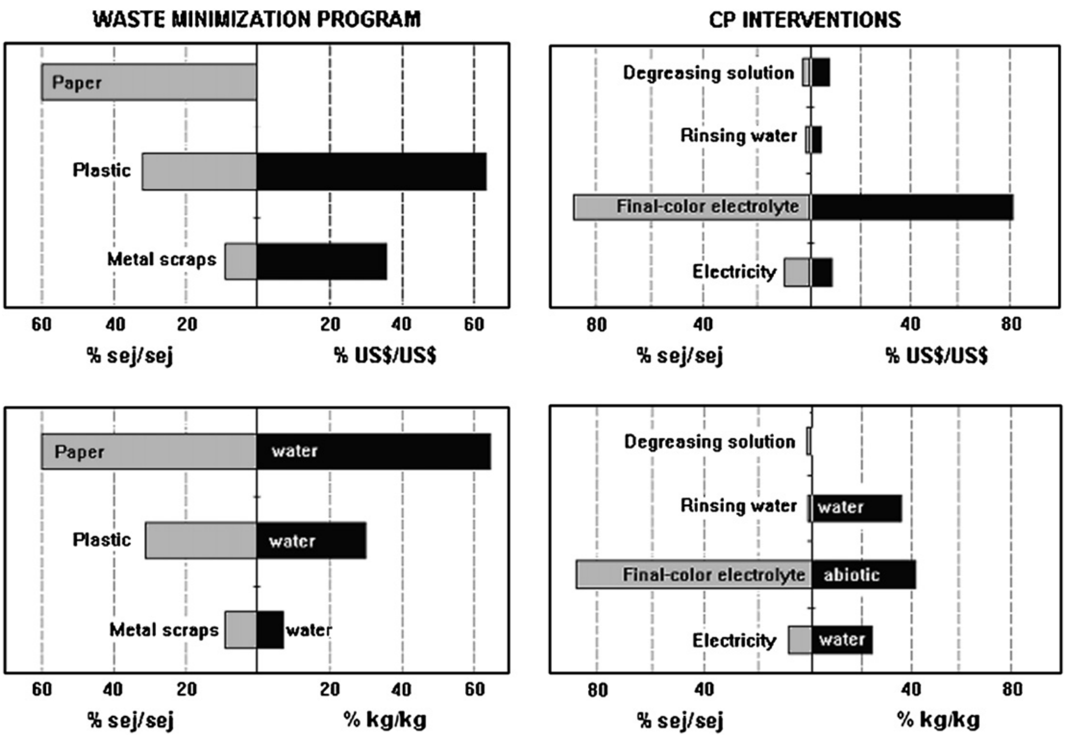

Fig. 3. Signature of the emergy savings achieved by the CP interventions compared with money savings (top) and material savings (bottom). Money savings of paper were not accounted. Material savings of final-color electrolyte are mainly related to the abiotic compartment, whereas for all the other items major savings are related to the water compartment.

a resource available. Thus, emergy will attribute more value to a more refined and manufactured product (degreasing solution) than to an environmental product (water) that is easy to extract, even if the water accounted here was taken as potable. Money accounting, in its turn, may also include risks of transport and handling, which are not accounted by the emergy intensity factors.

5. Final comments/conclusions

The company improved its environmental performance by being able to check its own processes with critical eyes and to make better use of its staff to develop cost-effective solutions. The waste minimization project was set in motion principally because of staff initiative. The financial benefits of the changes resulted in decreased raw materials, energy and waste disposal costs.

There were undeniable economic benefits from running the CP interventions, along with efficiency gains, benefits to workers and customers. Indeed, some initiatives required little or no investment. The replacement of plastic packages for plastic cups as part of the waste minimization project also brought efficiency gains in terms of pieces handling. It was important that benefits from the staff inputs were very significant because they could quantify the environmental improvements due to their interventions. Water consumption was decreased 35% in volume for the same output and there was a significant reduction in use of caustic degreasing solution and final-color bath. The reduction also led to raw material savings and reductions in hazards associated with bath's changes.

It is worthy to note that the implemented changes described in this paper represent only a first step towards more significant transformations. To make further improvements, the use of zero emissions concepts and approaches included in the special issue of the Journal of Cleaner Production [47] may help to identify fields for further actions, and a long list of actions for future work may be delivered in order to improve the company assessment and the production processes.

- The introduction of detailed records which document improvements on a daily basis to implement good housekeeping options.
- The adoption of analysis methods for determining concentrations of metals in all process solutions.
- To take care of impurities in the practical processes (organic materials, process chemicals, and metals).
- To test and further develop combinations of processes to enlarge the useful life of galvanic solutions.
- The analysis of the potential to use the spent process baths externally or internally to analyze drag out and rinse criteria.
- To install ion exchange or membrane technologies and evaporators to totally recycle the rinsing water.
- To implement electrolysis to recover precious metals instead of returning spent baths to the supplier.

Some of these actions, such as the use of membrane technologies, and evaporators, depend on economic investments. However, it was shown that actions with minimum investment also contribute to the economic-environmental performance of the company.

Despite the three valuation methods (currency, emergy and material) are not complementary as concepts, the use of the concepts may be complementary. Assuming the viewpoint concerning the economic utility, it was possible to detect achievements within the company, whereas the use of global performance indicators permitted to look at the savings from the 'natural' and biosphere viewpoint. In this way, suitable indicators were used for evaluating the real savings from a sustainability (and not a purely economic) perspective.

Emergy and material intensity evaluations provided global performance indicators that were used to assess the sustainability of systems. These indicators attempt to contemplate to Herman Daly's first principle of sustainability: resources should be used at a rate that allows their re-formation [48], which requires indicators based on thermodynamics of energy and material balances. The use of indicators for sustainability evaluation has been recognized as an important step towards operationalization of the concepts of sustainability and sustainable development. Indeed, the use of this kind of indicator creates awareness, and brings a new insight to the gains achieved with cleaner production practices.

With the experience described in this paper we hope to encourage company leaders to include cleaner production approaches to help them make improvements in environmental and economic performance. Results have shown that even little changes within companies can bring benefits to the environment that are not perceived with the use of local scale indicators.

Acknowledgments

The authors thank the owners of NG Group for data supplied and friendly cooperation. Special thanks are given for NG Group staff for keeping records of the key parameters which allow this paper to be written. This study had financial support from Vice-Reitoria de Pos-Gradução e Pesquisa da Universidade Paulista signatory of The International Declaration on Cleaner Production, a voluntary but public statement of commitment to the strategy and practice of cleaner production. Special thanks are addressed to Prof. Donald Huisingh. His critical remarks have significantly improved the manuscript, and after his comments we began to understand our own concepts much better than we did before.

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