Material flow accounting of the copper cycle in Brazil

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A B S T R A C T

This study is a quantitative description of Brazil's copper life cycle, comprising mining, refining, manufacturing, use and waste generation in the year 2005. A substance flow analysis is presented and the results are compared with existing values for other countries and economic regions (Europe, Asia, Latin America, and Africa).

The results show that Brazil is a net importer of copper both in concentrate and in the form of finished goods (total net weight 64 kt). Internal copper consumption is 1.44 kg per inhabitant per year and 0.52 kg/inhab/year is accumulated in the form of stock. Otherwise, the amount of waste generated (1.4 t/inhab/year) is close to that generated in Europe (1.9 t/inhab/year).

The copper distribution profile in waste flow is characterized by similar values for waste flow from construction and demolition (27.8%) and from electrical and electronic equipments (27.7%), whilst municipal solid waste and non-dangerous and industrial waste present 19.7% and 13.2%, respectively. Waste from electrical and electronic equipment and motor vehicles sent to scrap, in spite of representing just 1% of all waste in terms of mass, contain almost 38% of all residual copper (28% and 10%, respectively).

Brazil presents a secondary copper-recycling rate of around 25%, differing from that of other developing countries because it imports little scrap copper and releases 142 kt into the biosphere (0.75 kg/inhab).

We make the case that Brazil’s government can feasibly encourage reductions in demand for this metal while increasing copper recycling rates through a two-edged strategy based on education and public awareness on the one hand – making a case for the unsustainability of current copper production and consumption models – and on the other, implementing economic tools to transfer costs of post-use recovery to manufacturers and consumers.

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1. Introduction

For decades the unsustainability of metal production and consumption has been discussed in terms of intensity and forms of use. The capacity for exploitation of natural resources is constantly changing, not only as a result of technological advances, which allow it to take place at previously economically unfeasible levels of intensity, but also as a result of the discovery of new sites for exploitation, which in addition to the creation of new substitute materials, reduces the time limitations of exploitation and consumption. Meanwhile, growth in world population, particularly in China, India, and countries in the Southern Hemisphere, together with economic growth based on the current unsustainable growth models, will accelerate the depletion of these natural resources.

In this context, when natural resource cycles such as those involving copper cannot cope with increasing demand, it is essential to understand the working of the cycles that drive industrial metabolism. The importance of reducing consumption in preserving copper reserves cannot be overstated. In this context, new management tools for post-use of sub-products offer real prospects of meeting some portion of existing demand through effective reuse strategies. In this sense, substance flow analysis (SFA) has been used to identify new sources of copper replacement, presenting new manufacturing challenges as well as opportunities for reducing some of the demand on existing copper reserves.

The world’s 5th largest country in terms of land area, and rich in natural resources, Brazil’s economy is based upon the exploitation of both non-renewable and renewable resources. It is the world’s leading producer of niobium, and the second in iron, manganese, tantalite and aluminium, according to the National Department of Mineral Production (DNPM, 2006). It is the world’s top exporter of soybean, coffee, orange juice, sugar, alcohol, chicken meat and livestock, and the world’s second largest producer of soybean. It is also a major producer of paper and pulp, among others, and stands out as
a promising exporter of biomass for the substitution of crude oil as a source of energy. In 2005, the country’s total exports represented 13.4% of its GDP (DNPM, 2008).

In 2007, Brazilian copper reserves of 14.8 million t (DNPM, 2008) represented 1.5% of the world’s reserves, and its copper production totalled 218.4 kt, 1.3% of copper produced in the world. In the same year, Brazil’s industrial sector, including production of refined copper, electrical conductors and semi-manufactured copper products, had a turnover of US$ 5303 million, generating US$ 890 million in taxes, US$ 1650 million in exports and 18,000 jobs.

The aim of this study is to quantify the flow of copper in Brazil in 2005, throughout its life cycle, including stages of production, consumption and final disposal, using the methodology of the Global Stock and Flow project (STAF) (Lifset et al., 2002; Bertram et al., 2002; Spatari et al., 2002; Kapur et al., 2003; Vekler et al., 2004; van Beers et al., 2003). Similar work has been completed for copper and zinc at the global and continental level (Europe, Asia, Latin America, Africa, Oceania, Middle East). These studies have either used the SFA methodology (partial or total) for copper for nations as well as for urban centres. For example, SFA has been used to characterize copper metabolism for countries in the European Union and Asia (as part of the STAF project) and in other studies for China (Guo and Song, 2008; Wang et al., 2008) and Australia (van Beers and Graedel, 2007) or for cities such as Cape Town (van Beers and Graedel, 2003). This has resulted in numerous indicators for production and consumption.

Rather than applying those indicators for a country of continental size such as Brazil, this article aims at identifying and adopting local production figures (governmental databases, industrial associations), adjusting the methodology (bottom-up or top-down) in order to quantify the copper production chain at the regional level.

2. SFA methods

Methods for quantification of material flows can either be dynamic (top-down) or static (bottom-up). In the first case (top-down), incoming material in a certain geographical area is quantified and then divided between major sectors of consumption (automobiles, refrigerators, air conditioning, etc). In the second method (bottom-up), the dominant consumption sectors in the geographical area under study are identified and the copper within them is accounted for. In both approaches, each sector’s figure is weighted with its copper concentration, the total sum representing the inventory or stock during the period of analysis. Because it is often unfeasible to apply a single method due to time constraints and limited data availability, a combination of both techniques must be employed, and the balance between the inflow and disposal of the material within a given timeframe is used to estimate quantities of stock in use.

In this study, accounting for copper flows is based on primary data sources for the year 2005. Literature-based coefficients were not used as we felt they might introduce bias produced by social and economic conditions in a number of the countries providing the data. Where local parameters were unavailable, other figures were used, and referenced accordingly.

The study makes use of a technological model, as presented by Graedel et al. (2004) and Spatari et al. (2002), to describe and obtain data for some of the major processes (production, manufacturing, use and stock, and waste management) and flows (ore, processed, manufactured, in-use, waste, discarded) of copper life cycle stages.

2.1. Production

The main source of copper production information was the Brazilian Mineral Summary Report (DNPM, 2006) for the year 2005. Internal production reports from companies participating in the industry (Vale, Mineração Caráiba and Caráiba Metais) were also used, as well as current literature examining trends in the concentration of copper in manufacturing waste (Ayres et al., 2002). The mass balance for each production phase can be described using Eq. (1):

$$F_{Cu} = \sum_{i} n F_{prod, i, t} + \sum_{i} n F_{import, i, t} - \sum_{i} n F_{export, i, t} + \sum_{i} S_{i, t - 1} - \sum_{i} S_{i, t}$$

(1)

$F_{Cu}$ is the flow of copper contained in the different flows (copper mining, cathode, iron bar, residue) of copper mining and refining processes. $\sum_{i} F_{prod, i, t}$ is the production of copper for company $i$ in the year $t$; $\sum_{i} F_{import, i, t}$ is the import of copper in its different forms (concentrate, cathode or scrap) for company $i$, in year $t$; $\sum_{i} F_{export, i, t}$ is the export of copper in its different forms (concentrate, cathode or scrap) for company $i$, in year $t$; $\sum_{i} S_{i, t - 1}$ and $\sum_{i} S_{i, t}$ are the sum of the stock in the different forms within that company in the previous year and the year in question, respectively. This is the umbrella equation, which can be used to assess copper flow in each manufacturing company.

Since stock, final products and raw material figures are not presented in the reports assessed, they were not considered in the mass balance evaluations (Table 1).

2.2. Manufacturing

Copper flows were classified according to the Brazilian copper association, as semi-manufactured (compound for sheet, tube and connectors, bars and wire production); and manufactured (wires and cables used in electricity, enamelling, telecommunications, and others).

Figures for domestic consumption of copper-containing products were obtained from the mass balance, and take into account national copper production, import, export and recycling of primary scrap (returned to the production process through Caráiba Metais) and secondary scrap (consumed by manufactures of end products) (DNPM, 2006; SINDICEL, 2005).

2.3. Use and stock

The manufacturing stage produces copper-containing final products (electrical wires, plumbing pipes) or assembled products (cars, engines, electronic goods) used in a range of economic sectors: civil engineering, manufacturing, including the automobile industry and infrastructure (energy distribution network, telecommunications). Given the difficulty of obtaining information regarding the use of copper in these economic sectors, we estimated copper flow through these stages. Spatari et al. (2002) have classified the waste generated after use into seven categories:

- Municipal solid waste (MSW),
- Construction and demolition waste (C&D),
- Waste from electrical and electronic equipment (WEEE),
- Sludge and sewage waste (SS),
- End of life vehicle waste (ELV),
- Hazardous and industrial waste (HIW),
- Non-hazardous industrial waste (NH&IW).

1 Statistical Annual 2005 – electrical wires and semi-manufactured copper and copper alloy goods, a joint publication by the Brazilian Copper Association (ABC), and the Syndicate for the industry of Electrical Wires, Wire Drawing, Non-ferrous Metal Rolling for the State of São Paulo (SINDICEL).
Table 1: Copper flows in mining and refining, considerations and data sources.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Flow</th>
<th>Considerations</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mining</td>
<td>Copper ore</td>
<td>Estimated by mass balance</td>
<td>DNPM (2006)</td>
</tr>
<tr>
<td></td>
<td>Copper concentrated</td>
<td>Export dates obtained from summary of Brazilian minerals.</td>
<td>Cariba Metais (2006)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sales in internal market obtained from Cariba Metais relatory.</td>
<td>Cariba Metais (2006)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Copper concentration = 30%</td>
<td>DNPM (2006)</td>
</tr>
<tr>
<td>Refining</td>
<td>Tailings</td>
<td>Estimated by mass balance of output. Copper concentration from literature (0.05%)</td>
<td>Ayres et al. (2002)</td>
</tr>
<tr>
<td></td>
<td>Copper concentrated from Cariba</td>
<td>Import dates</td>
<td>DNPM (2006)</td>
</tr>
<tr>
<td></td>
<td>Purchasing dates from internal market</td>
<td></td>
<td>Cariba Metais (2006)</td>
</tr>
<tr>
<td></td>
<td>Copper wire (final product)</td>
<td>Import dates</td>
<td>Cariba Metais (2006)</td>
</tr>
<tr>
<td></td>
<td>Copper slag</td>
<td>Internal sales obtained from mass balance.</td>
<td>Cariba Metais (2006)</td>
</tr>
<tr>
<td></td>
<td>Copper waste (slag)</td>
<td>Sales from internal market obtained in Cariba Metais relatory.</td>
<td>Cariba Metais (2006)</td>
</tr>
<tr>
<td></td>
<td>Copper conc. in other flows</td>
<td>Gross production estimated in 100,000 t and copper concentration in 0.1%</td>
<td>Cariba Metais (2006)</td>
</tr>
</tbody>
</table>

The quantity of copper stock remaining in within a system for a certain period of time is estimated as the difference between the total quantity of copper present in consumer products and that exiting in copper waste in that time period.

Waste was quantified over a period of 1 year (2005), using Eq. (2):

$$ F_{Cu,i} = TG_{per \, \text{capita},i} \times P \times C_{Cu,i} \tag{2} $$

Where $F_{Cu,i}$ is the flow of copper contained in waste $i$; $TG$ is the rate of waste generation per capita for waste $i$; $P$ is the population in the period in question, and $C_{Cu,i}$ is the concentration of copper in waste $i$.

In order to estimate the flow of municipal solid waste, data were taken from the Multidimensional Statistics Bank at the Brazilian Institute of Geography and Statistics (IBGE, 2000b), considering not only the domestic and commercial waste collected, but also rubbish from the streets of 5475 Brazilian towns included in the survey. The value for population size was obtained from Brazilian censuses for 2000 (IBGE, 2000c) and 2005 (IBGE, 2005a). Copper concentration values used for the different waste flows were those employed by Bertram et al. (2002).

Estimates of waste generated by construction and demolition were based on information from John and Agopyan (2001) and corrected for the 1996 population as per IBGE (2000c). This correction was necessary because the values reported by the BME at the IBGE were significantly lower than those reported by Pinto (1999). Our waste estimates are consistent with analogous estimates for Europe.

Waste from electric and electronic equipment (WEEE) was divided into two categories: consumer goods and capital goods, taking up respectively 70% and 30%, of the copper in this category (Bertram et al., 2002). Consumer goods were estimated using a social indicator synthesis (IBGE, 2007), which indicates the percentage of Brazilian homes with a telephone, computer, refrigerator, freezer, TV, washing machine, mobile telephones and air conditioning. The mass quantity was obtained by applying an average weight coefficient (Kumar and Shrihari, 2007). The annual generation was obtained by considering the linear distribution throughout its usable lifetime (Jianxin et al., 2008). The concentration of copper estimated was the mean average of the concentration of consumer goods and capital goods (Bertram et al., 2002).

In order to estimate copper in scrapped vehicles (ELV), a curve for light vehicle scrap, listed by year of licensing was used (Meyer, 2001) (Fig. 1).

For heavy vehicles, useful life was considered to be 15 years (FENABRAVE, 2008). Thus, all 15-year-old heavy vehicles in 2005 were assumed to have left circulation in that year. The number of vehicles entering circulation per year was estimated based on the licensing data from the National Association of Automobile Vehicle Manufacturers (ANFAVEA, 2008).

The average concentration of copper in scrapped vehicles is estimated using Eq. (3):

$$ CM_{Cu,ELV} = \left( \frac{Q_{ELV} \times m_i \times C_{Cu,ELV} + Q_{ELV} \times m_p \times C_{Cu,ELV}}{Q_{ELV} \times m_i + Q_{ELV} \times m_p} \right) \tag{3} $$

Where $CM_{Cu,ELV}$ is the mean concentration of copper in the mass of scrapped vehicles, $Q_{ELV}$ is the number of light vehicles scrapped, $m_i$ is the mass of a light vehicle, $C_{Cu,ELV}$ is the concentration of copper in a light vehicle, $Q_{ELV,ELV}$ is the number of heavy vehicles scrapped, $m_h$ is the mass of a heavy vehicle, $C_{Cu,ELV}$ is the concentration of copper in a heavy vehicle.

The flow of solid sludge (SS) in domestic sewage treatment stations is also a source of copper. Machado (2001) used data from 275 domestic sewage treatment stations, representing the waste of 13 million inhabitants to depict the annual generation of sewage per capita (11.87 kg solids in dry base per year). In that same year, the concentration of copper was estimated to be 255 mg/kg of solid material, using samples from those stations.

The amount of hazardous industrial waste was based on state-wide inventories drawn up by the following states and representing 78% of the nation’s GDP: Acre, Amapá, Ceará, Goiás, Minas Gerais, Pernambuco, Rio Grande do Sul, Paraná, Rio de Janeiro and São Paulo. The generation of hazardous and non-hazardous industrial wastes is proportional to the GDP, and thus amounts of hazardous and non-hazardous industrial waste were obtained by extrapolation (Eq. (4)): 

$$ Q_{Cu,HW} = \left( \frac{\sum_{i=1}^{10} Q_{HW}}{\sum_{i=1}^{10} PIB/\sum_{i=1}^{27} PIB} \right) \times C_{Cu,HW} \tag{4} $$

[Image: Fig. 1. Percentiles of cars per year of licensing, which were scrapped in the year in study (adapted from Meyer, 2001).]
Where $Q_{CuHW}$ is the amount of copper contained in hazardous industrial waste; $Q_{LHW}$ is the total amount of hazardous industrial waste generated in the period in question; $\sum Q_{IHW}$ is the concentration of copper in the flow; $\sum PIB$ is the amount of waste generated by the 10 states for which the inventories were completed; $\sum PIB$ is the total GDP for the 19 and 27 states in Brazil (Table 2).

### 2.4. Waste management

To arrive at an estimate of residual copper flowing through a waste management cycle, Bertram et al. (2002) have suggested sampling at three points in the cycle: (i) collection and separation, (ii) incineration, and (iii) landfill. Accounting for copper flows for these points was accomplished using coefficients of copper re-use for each studied waste flow.

For the purposes of sampling at collection and separation, we considered that 1% of the solid waste collected by a given municipality is culled for recyclables (IBGE, 2000a,b). This same percentage was used to determine the amount of copper originating from waste from construction and demolition.

Of the copper contained in electrical and electronic equipment wastes, we assumed a recovery of 20%, based on the findings of Vexler et al. (2004); for copper recovered from scrapped vehicles, 80%; and from sewage waste, 15% was assumed to be reused as agricultural fertilizer (Machado, 2001). Hazardous industrial waste (21%) and non-hazardous and industrial waste (1%) are also partially re-used (Tanimoto, 2007).

Secondary scrap, generated after products are used by consumers, is estimated imprecisely in the Mineral Report published by the National Department of Mineral Research (DNPM, 2006). A further 80% was added to this value (Vexler et al., 2004) to correct for the informal economy, which dominates this sector. 25% of the secondary scrap resulted from waste generated by construction and demolition, and the remaining 55%, from electrical and electronic equipment waste.

To determine the copper flow at the point of incineration, we considered the amount of copper from municipal solid waste (IBGE, 2000a,b), and added an estimated 79% from hazardous industrial waste (Tanimoto, 2007).

Landfills were separated according to the types of waste they contain: domestic landfill sites, run by local councils, mainly receive domestic waste. Industrial landfill sites, which may or may not be located on company property, receive industrial waste. The following flows were taken into consideration for domestic landfill sites: 73% of municipal solid waste (IBGE, 2000a,b), for which the destination coefficient was also applied to construction and demolition waste. Estimates from previous studies were used to determine the fraction of waste from each source which is sent to landfills: 10% of electrical and electronic waste in Latin America (Vexler et al., 2004); 50% of sewage generated by treatment stations (Machado, 2001); and 3% of non-hazardous and industrial waste (Tanimoto, 2007). In addition to these waste flows, 90% of copper contained in incinerated waste was assumed to be destined for domestic landfill sites.

Industrial landfill sites were considered to be those controlled by waste-producing companies and businesses. This study assumes that 96% of the waste from industrial sites is non-hazardous, mainly tailing from mining (DNPM, 2006) and slag from refining (DNPM, 2006).

Finally, the difference between the waste flows and their final destination was considered to be lost to the biosphere. This includes the 70% of electrical and electronic waste (Vexler et al., 2004) which remain unused in homes and on the second hand market.

### 3. Results and discussion

The analysis of the copper cycle in Brazil in the mining and refining stage used, not only production data from relevant companies, but also data from recent literature sources (concentration of copper in residual currents – tailings and slag). In mining, Brazil produces concentrate at two companies, Mineração Carinha and Vale. Mineração Carinha produces only for the internal market, and as its mines are expected to be depleted in 2012, it is currently

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2 For hazardous industrial waste, and non-hazardous industrial waste, the statistics used were those for the disposal of a group of 11 companies at the Camaçari petro-chemical complex, taken as an ideal situation for representing Brazil, given that there was no statistic available at national level.
in search of alternative routes to continue its mining activity. Vale began its production in 2004, and it is estimated that in a few years Brazil will go from being a net importer to a net exporter of copper. Vale’s production of copper concentrate (141 kt/year) is primarily for the external market (84%) because its refinery plant is not expected to start up before 2011. To meet current national demand, Brazil imports concentrate (133 kt mainly from Chile (86%) (DNPM, 2006). Fig. 2 displays a flowchart that summarizes copper flow in Brazil.

In copper refining, there is only one company producing electrolyte copper – Caraíba Metais, responsible for 98.7% of cathodes and copper wires produced in Brazil. Two other companies produce copper as a by-product of metallurgical processes, and in small quantities (1.3%).

Demand for copper in Brazil’s manufacturing sector is also being met by imports of semi-manufactured products (172 kt, of which 93% was copper cathode) and to a lesser extent manufactured products (43 kt). Balanced against this, Brazil exports 135 kt copper in the form of manufactured and semi-manufactured products. Internal consumption of copper products and its metallic alloys is estimated here at 266 kt or the equivalent of 1.44 kg/inhab/year.

Lack of reliable statistical data prevented the estimation of the flow of copper at its use stage in Brazil’s various social segments – where indeed most copper products are consumed (buildings, machinery, vehicles and infrastructure. We were however able to arrive at an overall national figure for the quantity of copper in use over the course of a single year (94.9 kt) – or the equivalent of 36% of copper consumed nationally in 2005 – using our estimates of the quantities of copper present in post-use waste flows. The comparable figure for C&D and WEEE waste is 47 kt; for MSW waste, 33.6 kt; I&NHW waste, 22.4 kt; and ELV, 16.7 kt.

WEEE (0.2%) and ELV (0.6%) in terms of mass do not reach 1% of the total waste generated, yet together they contain almost 38% of copper released into the atmosphere (27.7% and 9.8%, respectively). This is due to the high concentrations of copper found in these flows (7.6% and 1.1%, respectively).

The relatively large value for our estimate of copper accumulated in C&D is due to the fact that the copper content in this type of waste in Brazil is not currently known; the figure is derived from homologous European estimates (670 mg/kg; Bertram et al., 2002) though we are aware that waste in Brazil for the type of construction in question would in all likelihood be lower.

Compared with data generated by the STAF project (Europe, Asia, Latin America and Africa) per capita annual waste generation in Brazil (1411 kg/inhab/year) is comparable with that of Europe (1856 kg/inhab/year), mainly in MSW, C&D and I&NHW. For other waste flows, lower relative values for Brazil’s waste production can be accounted for by the relatively lower purchasing power of its population and lower rate of technological development, as can be seen by comparing WEEE, ELV and I&HW. SS waste does not have a more appropriate destination, where it is estimated that only 15% is reused as fertilizer for agriculture.

Estimates for ELV, I&HW and I&NHW are very close to those obtained for Asia (2%, 16% and 18%, respectively). Figures for MSW and C&D are another matter, mainly due to differences in social and economic situations as well as data registration capacity where a wide range of figures are recorded – between 29 kg/inhab/year and
Table 3
Waste production and copper content in Brazil.

<table>
<thead>
<tr>
<th>Waste type</th>
<th>Generation</th>
<th>Cu conc. (mg/kg)</th>
<th>Copper flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg waste/inhab/year</td>
<td>%</td>
<td>kt Cu/year</td>
</tr>
<tr>
<td>Municipal solid waste (MSW)</td>
<td>365</td>
<td>25.9</td>
<td>500</td>
</tr>
<tr>
<td>Construction &amp; demolition (C&amp;D)</td>
<td>384</td>
<td>27.2</td>
<td>670</td>
</tr>
<tr>
<td>Waste of electro-electronic equipment (WEEE)</td>
<td>3.4</td>
<td>0.2</td>
<td>7.6%</td>
</tr>
<tr>
<td>End of life vehicles (ELV)</td>
<td>9</td>
<td>0.6</td>
<td>1.1%</td>
</tr>
<tr>
<td>Solid sludge (SS)</td>
<td>12</td>
<td>0.8</td>
<td>255</td>
</tr>
<tr>
<td>Industrial &amp; hazard waste (I&amp;HW)</td>
<td>27</td>
<td>1.9</td>
<td>500</td>
</tr>
<tr>
<td>Industrial &amp; non-hazard waste (I&amp;NHW)</td>
<td>611</td>
<td>43.3</td>
<td>200</td>
</tr>
<tr>
<td>Total</td>
<td>1411</td>
<td>100</td>
<td>170.6</td>
</tr>
</tbody>
</table>

860 kg/inhab/year (India and Hong Kong). Furthermore, the huge population of China (1300 million) generated just 43 kg/inhab/year, which has a strong influence on the final result.

Estimates derived for waste generation in Brazil differ from those in the rest of Latin America, despite Brazil's sizeable share of the region's population – 43%. This difference is attributable to the fact that regional statistics throughout Latin America are unreliable and thus, continental figures are inaccurate. The same is true of homologous data obtained for African countries.

The distribution profile of copper in Brazil presents different features when compared with the calculated profiles in comparable studies of other regions (Fig. 3). The significantly higher concentration of copper in WEEE flow in Latin America (83%), as compared with Africa (62%), Asia (45%) and Europe (41%) is one signal difference. Copper concentrations are more evenly distributed across the flows of C&D (27.8%), WEEE (27.7%), MSW (19.7%) and I&NHW (13.2%).

The high quantity of copper in WEEE flows falls into line not only with the adoption of the high coefficient of generation, but also with the high concentration of copper in its composition. For example, for Latin America, the figure used was 6.8 kg/inhab/year (Europe = 7 kg/inhab/year). The concentration of copper in WEEE flows for Asia is calculated as 13% (the same as for Europe), despite the fact that populations in these regions have a lower purchasing power than those in Europe, suggesting a lower level of generation and a correspondingly lower copper content in those flows.

Once the final destination of each of these flows were analysed, municipal landfill sites were identified as the point with greatest inflow, with 39% of the copper available after use which is similar to estimates by Lifset et al. (2002), of 42% for the United States. Landfill sites are notable for receiving a large part of waste flow from construction and demolition, the largest contributor with 34.7 kt, followed by municipal solid waste (24.6 kt) and electrical and electronic equipment waste 4.7 kt.

Industrial landfill sites, despite receiving comparatively less copper content (39.3 kt, including waste from mining and refining), deserve to be mentioned as they are fewer in number than municipal landfill sites, suggesting they may be potential sources for future copper production.

Brazil, unlike countries in developing Southeast Asian countries, does not fit the profile of a consumer of copper scrap as has imported 1.6 kt and exported 2.6 kt. Despite the positive mass balance (1.1 kt), copper prices are subject to the quality of the scrap being traded, resulting, in 2005 in an unfavourable commercial balance of 1.85 million US$.

The recycling system in Brazil is incipient in its statistics, as there is an informal economy dominating that sector. A copper recycling registry, mainly of secondary scrap obtained after the use of...
equipment containing copper, is practically non-existent. Furthermore, there is the fact that some kinds of wastes, mainly electrical wires and cables obtained illegally, are sources of scrap that finds its way back to the manufacturing process. As a result, the official figures for copper recycling are considerably lower than the actual figures. DNPM (2006) registered 26 kt, i.e. 14% of the copper potentially available for recycling, including industrial copper (tailings and slag). Vexler et al. (2004) estimated that the informal secondary copper recycling market in Latin America is around 80% of the formal one. Given this percentage, we would thus have a total of 46,800 t of copper recycled in 2005, representing 25% of the copper available for recycling. Compared with other regions, this falls below Japan (65%; Kapur et al., 2003), Europe (48%; Bertram et al., 2002) and even Africa (34%; van Beers et al., 2003). In a comparison at the country level, Brazil also has the lowest rate of recycling.

Efforts have been made in developed countries to encourage the recycling of copper post-use, as its production is increasingly unsustainable, and copper in use in society is becoming an alternative source for the manufacturing process. In order to do this, it is essential to map out how, in what way, and where copper is being deposited after use.

The final separation of copper for re-use could be made easier if equipment containing it was designed with its end of life in mind. Concepts such as Life Cycle Thinking and Ecodesign become important contributors to this process of optimizing the use of metal.

In a globalized world where copper is a commodity with its price is set by the market (London Metal Exchange (LME)), the internalisation of environmental costs in this production segment will be a decisive factor in the optimisation of recycling. Government policy can have significant positive influence here, specifically by: (i) sponsoring education and awareness programs that make the case for the unsustainability of current production and consumption models, and more specifically, the unsustainability of practices involving the discarding of copper-rich waste, (ii) developing economic instruments that provide financial incentives to participants in the recycling chain, (iii) defining the responsibility of producers regarding the destination of their products after use and finally, and (iv) promoting and sponsoring the development of technology that can increase the economic feasibility of recycling copper from electrical and electronic equipment.

The figures obtained for Brazil indicate that 39% of waste copper (66.9 kt) ends up in domestic landfill sites highlighting the importance of identifying and implementing procedures to concentrate and separate waste containing copper before it reaches landfill sites.

In Brazil, the annual loss of copper to the biosphere (including landfills) in 2005 was 141.5 kt, which translates into a per capita sum of 0.75 kg (Fig. 4). Compared with other parts of the world including Latin America, this is an intermediate figure. The comparative figures are 1.4 kg per capita in Europe (Spatari et al., 2002), and 0.23 kg per capita in Asia (Kapur et al., 2003) and Africa (van Beers et al., 2003). It should be noted that Asia leads the world copper scrap market and has a high rate of recycling (60–90%; Kapur et al., 2003) and Africa, in addition to having a recycling rate of 35%, also has a unit in Zambia which in 2005 reprocessed 47 kt of production waste (tailings).

Considering not the loss per capita but rather the loss per land area, Brazil occupies an intermediate position (16.3 kg/km²) together with Latin America (Fig. 4). Of all regions studied, Africa has the lowest rate of copper loss of copper per land area (6.58 kg/km²). The rate for Europe is notable – 159.5 kg/km² – four times greater than that of Asia (37.9 kg/km²). In comparison with the ten countries for which information is available (Spatari et al., 2002; Kapur et al., 2003; Vexler et al., 2004; van Beers et al., 2003; Lifset et al., 2002; Graedel et al., 2004; Wang et al., 2008), Brazil lies in eighth place for both of these variables (Fig. 5), above Zambia and Saudi Arabia.

Chile, the largest exporter of copper in the world, produces 14.3 kg per capita, four times greater than the rate of the United Sates.

When we compare the source and destination of copper consumed in Brazil (Fig. 6) it can be seen that Brazil is a copper importer (66% of requirements), 25% as concentrate and 41% in the form of products. In spite of this, it exports almost 55% of what it produces – 22% as concentrate and 33% as final products. A simplistic analysis would suggest that Brazil should direct its copper production towards internal consumption and thus economize in cash terms, as it would no longer import almost all of its copper concentrate, primarily from Chile. However, there are trading concerns that make this negotiation impracticable. Brazil’s main producer of copper concentrate will in a few years also be a producer of refined copper, thus competing on the national market with Carabina Metais.

It can also be seen that 53% (142 kt) of the copper consumed (266 kt) is lost to the biosphere. Landfills receive 106 kt, 37% of which is housed in industrial landfill sites, making them potential sources of copper in the future since they are fewer in number, and involve an operational structure that is well suited for exploitation (logistics, technological resources, utilities and the potential for private investment).

Due to the lack of records, 21% of copper in the waste management stage was considered as lost into the biosphere. This represents 35 kt, which in terms of environmental patterns is alarming as there is no possibility of determining of assessing environmental impacts.

In the European Union directives have already been issued to advise member states on handling some types of waste containing...
copper. Directive 2000/56, for example, determines the number of vehicles that may be withdrawn from the market after their useful life and Directive 2002/96, deals with the cost of waste management for electrical and electronic goods. In Brazil, the government has proposed a new law (1991/2007 – National Policy on Solid Waste), for managing solid waste, but no specific legislative instrument is expected regarding the reduction of copper in the waste flows discussed in this article.

4. Sensitivity analysis

The sensitivity of the copper data used was analysed in each of the seven waste flows individually, holding constant the flow data in the other streams. Values for statistical uncertainties and ranges for each stream were based on the work of Bertram et al. (2002). The base scenario of 170.6 kt of copper entering the waste management system was considered acceptable.

In our analysis of uncertainty introduced through incorrect assumptions with respect to waste generation, only C&D and WEEE flows presented significant variations (±11%), in relation to the total copper flow generated of 3.4 t/inhab/year (Fig. 7A). Other references – Rodrigues (2007) and Rocha (2009) – provide figures of 2.6 t/inhab/year and 3.4 t/inhab/year, respectively.

The analysis of copper concentration shows a possible upward variation in WEEE and NI&HW – +24% and +8%, respectively – and downward variations in C&D and NI&HW of 7% each (Fig. 7B). There is no measurement of copper concentration in Brazilian WEEE generated. Rocha (2009) uses a range between 4 and 12 (domestic and industrial equipments) based on EMPA (2009), whose figures are similar to copper concentration used in this article (Bertram et al., 2002).

In general, analysis of simple variables in uncertainty produces only a slight effect on the copper cycle, which affects the waste management system. An exception involves the variable with the greatest difference between the concentration used (7.56% Cu) and the maximum figure given in the literature (14% Cu) for WEEE, which would lead to an increase of 40 kt of copper destined for the landfill.

5. Conclusion

Brazil, a developing nation, still has a low per capita copper consumption rate of 1.44 kg/inhab/year. It can also be seen as a country with a potential for growth in copper consumption, once improvements are made in infrastructure, telecommunications and buildings.

Copper production from mining to refining is currently made by three companies. Mineração Caraíba is in the process of diversifying, reducing copper production and increasing its production of other metals. Vale invests heavily in mines in order to produce not only concentrate but also refined copper after 2011. Brazil will pass from importer to exporter of copper in the coming years, and this increase in national production will require more and more a business and governmental strategies which take into consideration environmental variations in addition to economic and social ones. Studies examining the environmental impacts of the copper
production chain will be required and an analysis of the flows of this metal will be an important tool in this regard.

The accounting of the copper cycle in Brazil can now be completed using the available data from governmental institutions and sector associations with relative precision, mainly for the early stages in the cycle (production, manufacturing, import, and export). Decision makers and institutions lack information for the post-use stages, particularly regarding the final destination of waste flows, which they require to develop and implement governmental policies.

In Brazil, according to world trends, waste flow for electrical and electronic equipment and scrapped vehicles are good prospects as future sources of usable copper. Despite representing less than 1% in mass, these waste flows contain almost 38% of the copper released into the biosphere. These are waste flows with a high added value and their recycling can be justified for the other metals they contain. A significant part of these flows is already part of an informal economy, encouraging a second-hand equipment market with less demanding specifications of parts and repairs.

Recycling information for these two flows are practically non-existing, adding difficulty to the process of reuse and recycling. With the exception of hazardous industrial waste, the other flows, in spite of the significant mass quantity (C&D (47 kt) and MSW (34 kt)), contain very dilute copper making the separation process economically unfeasible. Copper is not usually the problem in hazardous industrial waste and its separation adds no value to the waste, making the process economically unfeasible.

The secondary copper-recycling rate was estimated at 25%, well below the figures estimated for Europe (48%; Bertram et al., 2002), North America (60%; Lifset et al., 2002) and Africa (34%; van Beers et al., 2003). The low cost of copper has been cited as one of the reasons for this low rate.

Among the final destinations studied, industrial landfills present the best potential as future sources of copper, mainly because these sites are controlled, their composition is well-known, and they fall under the purview of private companies where business infrastructure is already in place – all of which stands to optimize the recovery of copper.

Copper which remains in use in society, counted in static form (2005) at 94.9 kt in this article, deserves a deeper analysis in terms of the dynamics of this process. The speed of concentration could lead governmental policy to restrict the disposal of equipment or types of waste that contain copper in order to optimize the recycling process.

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