The contemporary African copper cycle: One year stocks and flows

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Synopsis

This paper characterizes the copper cycle, that is, the flows of copper entering and leaving the African economy over a one-year period (1994). The major flows over the entire life-cycle of copper are examined; these include production (mining, milling and refining), fabrication of semi-products and manufacturing of finished products, use, and the waste management system.

The results reveal that substantial amounts of copper (of order 705 Gg/yr) are mined in Africa; of that amount, about 70 per cent is exported following processing, 18 per cent is utilized by African fabricators, and 12 per cent is discarded. The flows of copper products from African fabricators and product imports from other continents exceed product discards by large amounts. This difference, about 0.25 kg Cu/capita/yr on average, is added to in-use stock, largely as wire, plumbing tube, and in electronics.

Some 65 per cent of the copper in discard flows is contained in electrical and electronic products, where it is relatively easy to collect and process for reuse. About a third of the copper discard flows known is recycled. The actual percentage is almost certainly higher because of informal (and unrecorded) recycling. Much of the remaining discarded copper is diluted into the municipal waste stream, where recovery and recycling are probably not economically justified.

Keywords: material flow analysis, resource management, material budgets, copper, stocks and flows, systems analysis, Africa, developing country

Introduction

The characterization of material flows within and between countries and continents has the potential to inform analysis of resource availability, energy consumption, environmental degradation, and governmental policy. Quantification of flows (and the accompanying changes in resource stocks) has been accomplished for grouped resources largely for a small number of countries in Western Europe. Regularizing these approaches, directing them to specific industrial metals, and applying them to all the world's continents is the goal of the Stocks and Flows (STAF) project at Yale University, USA. In this paper, we treat the contemporary annual flows of copper on the African continent.

Copper has been selected as the first case study material being investigated by the STAF project, the reason being that copper has been widely used for several thousand years, is stored in several different chemical and physical forms and has an estimated depletion time of less than 80 years[1].

Material Flow Accounting (MFA) is the technique used for estimating and analysing flows of material within a geographic boundary[2]. Our copper-focused MFA goals are fourfold: the assessment of the magnitude of copper uses during the mid-90s, the estimation of the amount of copper leaving African economies in various waste streams, the determination of the amount of copper recovered, and the estimation of the amounts of copper accumulating in specific reservoirs.

A comprehensive approach was developed by Graedel *et al.*[3] for the evaluation of all relevant aspects of the copper cycle, especially stock build-up and draw-down and material flow magnitudes. If this approach is applied over an extended period, it has the potential to identify opportunities for resource strategies, assessment of associated environmental impacts, and policy developments. Spatari *et al.*[4] applied this comprehensive approach to compile a contemporary European copper cycle.

A static flow model represents a snapshot in time, and assesses the current (contemporary) epoch flows of materials. These flows result in changes of reservoir stocks over time unless inputs and outputs to the various reservoirs are in balance. If the results of a set of static models are integrated, a dynamic model is generated which includes an assessment of the total stocks in each reservoir and the inter-reservoir flow at any epoch within the time limits of the model. A dynamic model also assesses the age distribution for

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the material under investigation in each use. On average, any material older than the average service lifetime in a particular use will become available for re-use.

To our knowledge, this is the first copper MFA for the African continent. Much MFA work has been done using static flow models for copper and other metals at the national and global scales[5, 6]. In addition, many MFA and SFA case studies are published in the Conaccount literature[7, 8]. Zeltner *et al.*[9] and Ayres *et al.*[10] recently completed dynamic copper flow scenarios for the US and global systems.

This study of a contemporary flow model for Africa is a static flow model for a one-year period, and follows the framework used by Spatari *et al.*[4]. The study is part of the STAF project's aim to compile a comprehensive copper cycle on a global level. Some of the important terms and definitions are summarized in Table I.

Methodology

Scope and system boundaries

Selection of African countries

Africa is the world's second largest continent, with a land area of approximately 30 million km^2. The driest deserts, largest tropical rain forests, and highest equatorial mountains in the world can be found in Africa. The environment and natural resources in most African countries have been increasingly threatened by escalating and unsustainable pressures from fast-growing populations and 0cities, as well as expanding agricultural and industrial activities. Poverty is both a major cause and consequence of the environmental degradation and resource depletion that threaten present and future economic growth.

The African continent consists of 55 countries with a total population of about 825 million people[11] and a population density of 250 people per 1000 hectares, which is low compared to the world average of 442[12]. Because of low or negligible rates of copper extraction, processing, and/or use, frequently in combination with an absence of archival data, it is not possible nor important to characterize the copper flow magnitude of every country on the continent. As discussed in Graedel *et al.*[3], a pragmatic goal is to capture at least 80 per cent of the flow magnitude to and from six reservoirs: virgin orebodies (extraction), the mining and processing industries, the fabrication industries, the in-use reservoir, the waste management industries, and the environment (dissipation).

Figure 1 gives a visual presentation of the 22 African countries selected for this study, termed 'STAF-Africa'. Table II summarizes demographic and economic information relating to those countries. Copper mine production and Gross Domestic Product (GDP) for each African country were used as selection criteria for the STAF-African system boundary. The mining statistics were obtained from publications of the International Copper Study Group[13] and World Bureau of Metal Statistics[14]. The data on the GDP were taken from the World Fact Book[11].

We estimate that STAF-Africa, with 67 per cent of the African area and approximately 80 per cent of the African population, is responsible for almost 100 per cent of African copper production and 100 per cent of apparent refined copper consumption (at the level of approximation used in this study).

Selection of contemporary period

A time-period of one year was chosen as the temporal system boundary since most statistics are given on an annual basis. 1994 was selected as the year of investigation as this corresponds with the base year of the compiled contemporary European copper cycle mentioned above. Production, fabrication, and manufacturing data for 1994 was obtained from reports published by the International Copper Study Group[13] and World Bureau of Metal Statistics[14]. As data on waste management practices are more difficult to obtain, data closest to and within ± 3 years from 1994 were taken if data for 1994 were not available.

Table I

Summary of terms and definitions

Term or definition*	Explanation
Cycle	System of two or more connected reservoirs, where a large part of the material is transferred through the system in a cyclic fashion
Material	Stands for both substances and products (e.g. pure copper and brass plumbing fixtures respectively)
New scrap	Scrap that is produced during the manufacturing of finished products. This scrap does not enter the waste management system but is immediately recycled by the production facility
Old scrap	Scrap that enters the waste management system and is regarded as a post-consumer waste stream
Process	An operation for transforming materials
Product	Can be comprised of one or many substances, such as an alloy of copper and zinc
Reservoir	A compartment or group of like compartments that contain the material of interest
Secondary material	Material that is not made from virgin substances (non-virgin material)
Sub-process	A part of a process, which may again consist of several sub-processes
Substance	Consists of uniform units (atoms or molecules)
System	The investigated processes that are linked via flow of materials
System boundary	Is defined twofold: geographically (spatially) and temporally (period of time)

*Terms and definitions are listed in alphabetical order

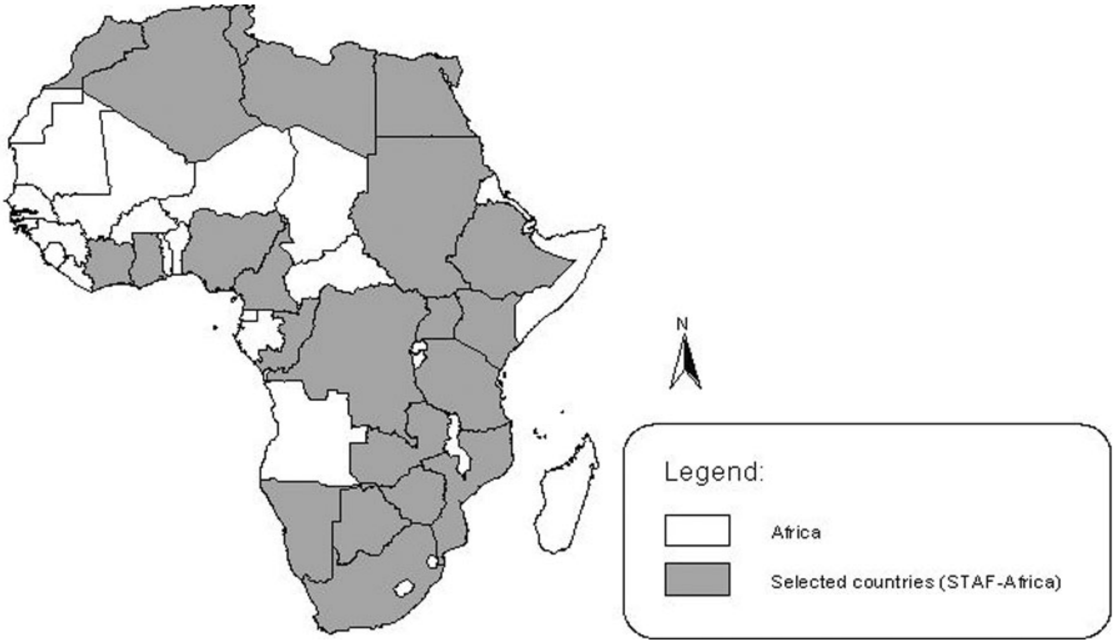


Figure 1—African countries selected for inclusion of this study (STAF-Africa)

Table II

African countries selected for inclusion in this study (STAF-Africa)

Country*	Population—1994[11] [million persons]	GDP—1993[11] [billion US$]	GDP per capita [US$/capita]	Area [1000 km^2]
Algeria	27.9	89.0	3,200	2,321
Botswana	1.4	6.0	4,400	580
Cameroon	13.1	19.1	1,500	466
Congo	2.4	7.0	2,900	345
Democratic Republic of Congo	42.7	21.0	500	2,337
Egypt	60.8	139.0	2,300	983
Ethiopia	54.9	22.7	400	1,132
Ghana	17.2	25.0	1,500	240
Ivory Coast	14.3	21.0	1,500	322
Kenya	28.2	33.2	1,500	584
Libya	5.1	32.0	6,300	1,621
Morocco	28.6	70.3	2,500	404
Mozambique	17.3	9.8	600	789
Namibia	1.6	3.9	2,400	826
Nigeria	98.1	95.1	1,000	912
South Africa	43.9	171.0	3,900	1,223
Sudan	29.4	21.5	700	2,490
Tanzania	28.0	16.7	600	945
Tunisia	8.7	34.3	3,900	155
Uganda	19.1	24.1	1,300	243
Zambia	9.2	7.3	800	755
Zimbabwe	11.0	15.9	1,400	391
Total STAF-Africa	562.9	884.9	2,000**	20,064

*The selected countries are listed in alphabetical order
**Average GDP per capita for STAF-African countries

[a]Previously noted as amount of refined metal *'consumed'* by semi-fabricators, the ICSG now notes, *'Recognizing that metals are not consumed, but rather used, and therefore available for future reuse and recycling, the ICSG now refers to refined copper production and refined copper usage in its reports.'* This paper adopts the term *'usage'* to denote the apparent usage from the formula: refined copper production +refined import -refined exports +refined beginning stocks -ending stocks

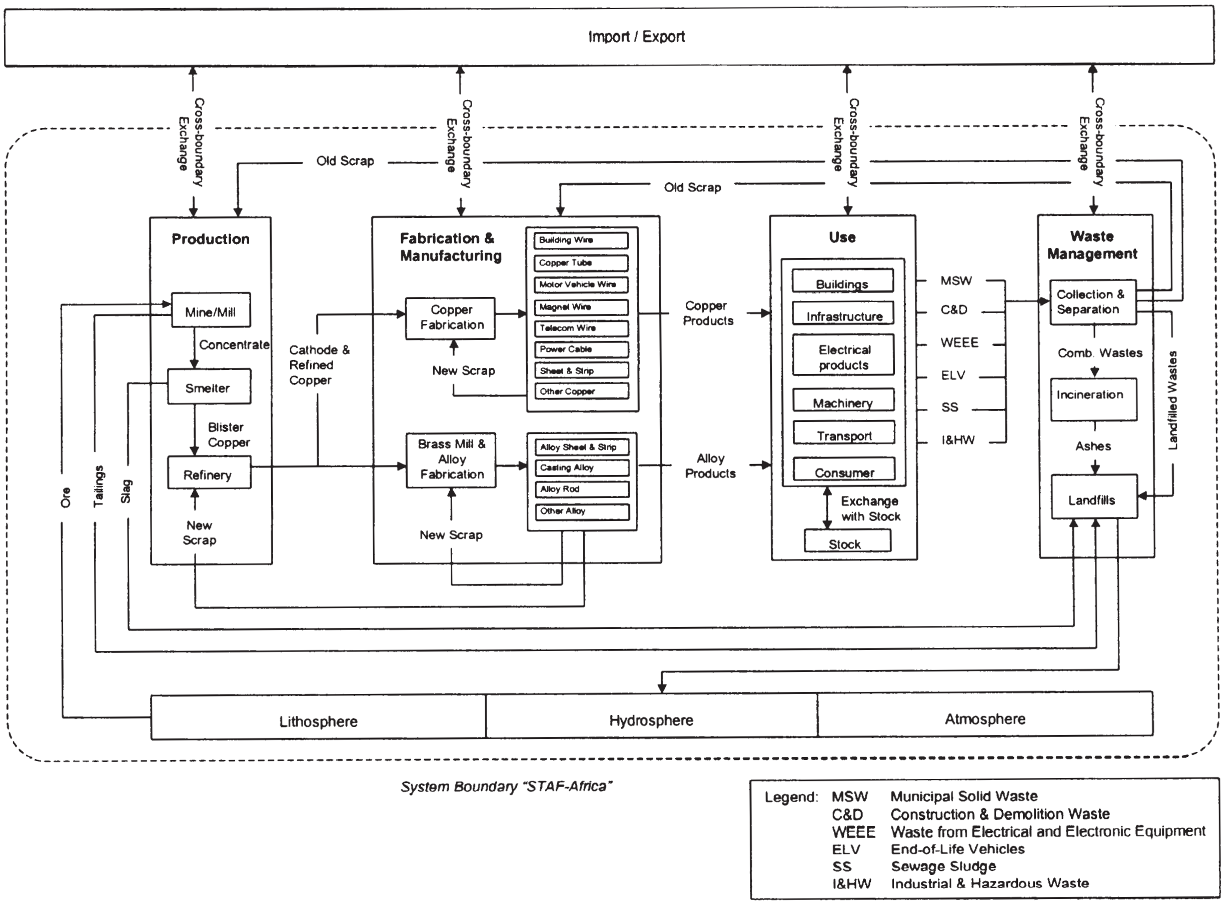


Figure 2—The copper cycle model used in STAF-Africa

1994 appeared to be a representative year for the production and consumption of copper in the mid-1990s. No irregularities were found in the production and usage[a] data between 1992 and 1997, nor did 1994 seem to be year showing significant variations from previous and subsequent years.

Selection of materials and processes

Figure 2 shows all flows captured in this copper cycle as described in Spatari *et al.*[4], neglecting losses of copper to the biosphere. The copper flow consists of four main processes: production, fabrication and manufacturing, use, and waste management. Where appropriate, these four processes are sub-divided into several sub-processes.

The production process includes the sub-processes mining, milling, smelting, and refining. Ore is mined and, after separation from overburden, milled to produce a concentrate that, on average, contains about 25 per cent copper. The waste stream associated with the milling process is known as tailings. The concentrate is then melted in order to purify it to blister copper (98 per cent copper); slag is produced during this smelting process. The blister copper is finally refined to cathode copper that has a purity of over 99 per cent copper.

The fabrication process converts the cathode copper into semi-products such as bars, sheets, strips, and tubes. Finished products are then manufactured from these semi-products. The use process includes the employment and storage of finished products. These finished products are either discrete, as in motor vehicles or household equipment, or become part of the infrastructure, such as power cable and telecommunication wire. When finished products reach their end-of-life phase, they enter the formal and informal waste management system in which they are collected for separation, incineration and/or to be landfilled.

Both old and new scrap is assessed in this study. Old scrap consists of scrap that enters the waste management system and is regarded as a post-consumer waste stream. New scrap includes all scrap that is produced during the manufacturing of finished products. This scrap does not enter the waste management system but is immediately recycled by the production facility. Compared to old scrap, new scrap has a much shorter life-time. The so-called old scrap is utilized for secondary copper production.

A detailed description of the processes and sub-processes of the copper cycle is provided in Graedel *et al.*[3].

Data collection

An inventory analysis of copper flowing in and out of the selected African countries provided the foundation for the compilation of the African copper cycle. Following the framework developed for the contemporary European copper cycle, a database was created to track specific flows within the life cycle of copper in Africa. This database is constructed according to the MFA methodology and the terms and definitions as outlined in Table I.

Statistical reports, databases, and periodicals, made available by government agencies, industry associations and industry contacts, provided the data for the model. Informed estimates were made if data were not available. The collected data were allocated to the four main processes of the copper flow model, and, where possible, to the sub-processes.

Calculations of the net imports and exports of copper into and out of the system boundary (STAF-Africa) were employed, since total imports/exports of individual countries may include imports and exports from other STAF-Africa countries. The trade within the system boundary was cancelled by adding all imports and exports and calculating the difference between these flows.

Data for the production stage

Two main sources provided the data on the production, imports, exports, and stock changes of copper from ore to cathode copper, namely the International Copper Study Group (ICSG)[13] and the World Bureau of Metal Statistics (WBMS)[14]. The quantities of copper flows from concentrate to cathode were documented on a country-by-country basis.

Table III outlines the main copper flow categories from ore to cathode within the production process, as well as the approach taken and assumptions made for these flows.

Data for the fabrication and manufacturing stage

The copper flows within the fabrication and manufacturing process comprise the fabrication of copper and copper-based alloy semi-products (e.g., wire, sheets, strips, bars), often called semis, and the manufacturing of intermediate commodities and finished copper (alloy) products.

Data on the fabrication and imports/exports of copper and copper-based alloy semis were published in statistical tables by ICSG[13] and WBMS[14]. Both the manufactured quantities of copper and copper-based alloy semis were estimated by calculating the difference between the input flows and the net import/export flows.

The approaches, assumptions, and data sources for the fabrication and manufacturing process are documented in Table IV.

Data for the use stage

The output of the manufacturing process can be categorized either into finished copper products (e.g., building wire) or finished products in which copper products are assembled (e.g., motor vehicles).

The trade in finished products was investigated for a comprehensive set of products including industrial machinery, metalworking machinery, computers, televisions, radios, telecommunication, insulated wire, and consumer and electronic products. This selection is based on the availability of import/export data[18] and estimated copper contents[19]. The net trade volume, estimated copper content, and net copper flow of the assessed commodities are given in Table V.

Copper (alloy) products can have a residence time in the economy up to 60 years, and in a few cases even longer. The quantity of copper products entering the use process is, historically, greater than the amount of old copper (scrap) generated in the same period, meaning that there is a retention of in-use copper in the form of increasing stock levels.

Table VI documents the assumptions and approaches for the use process and its sub-processes; the data sources are also documented in this table.

Data for the waste management stage

In the one-year budget scenario, it is not possible to determine the retirement rate of copper products unless one has knowledge of the total mass of copper stocks already

Table III

1994 Copper production—assumptions and data sources

Sub-process	Flow	Assumptions/approaches	Data sources
Mill	Ore	Estimated by difference from output flows	
	Concentrate	Country-level concentrate production was taken from literature and summed for all STAF-African countries The net import/export of concentrate into Africa was calculated as the difference of total imports and exports to all selected countries	ICSG[13] WBMS[14]
	Solvent Extraction—Electrowinning (SX-EW)	Country-level SX-EW production was taken from literature (only applicable to Zambia) The net import/export of SX-EW into Africa was calculated as the difference of total imports and exports to all selected countries	ICSG[13]
	Tailings	Calculated from empirical model of mining and milling operations	Model documented by Gordon[15]
	Reworked tailings	70% of input SX-EW process concerns reworking from landfilled tailings	Coakley[16]
Smelter	Blister copper	Country-level blister copper production rates were taken from literature and summed for all STAF-Africa countries The net import/export of blister copper into Africa was calculated as the difference of total imports and exports to all selected countries	ICSG[13] WBMS[14]
	Slag	Calculated from empirical model of smelter waste	Model documented by Gordon[15]
Refinery	Cathode copper—primary and secondary production	Country-level cathode copper—primary and secondary production rates were taken from literature and summed for all STAF-Africa countries The net import/export of cathode copper into Africa was calculated as the difference of total imports and exports to all selected countries	ICSG[13] WBMS[14]

Table IV

1994 Copper fabrication and manufacturing—assumptions and data sources

Process	Flow	Assumptions/approaches	Data sources
Copper fabrication	Copper semis	Country copper semi-fabrication rates were taken from literature and summed for all STAF-Africa countries	ICSG[13] WBMS[14]
Copper-based alloy fabrication	Copper-based alloy semis	Fabrication rate was estimated by difference from input flows and net import/export flows of fabrication process subtracted by copper semi production The net import/export of copper-based alloy semis (copper alloy ingots and masters) into Africa was calculated as the difference of total documented imports and exports to all selected countries	ICSG[13] WBMS[14]
Copper and copper-based alloy fabrication	Copper and copper-based alloy semis	Country re-melt rates were taken from literature and summed for all STAF-Africa countries	ICSG[13] WBMS[14]
Manufacturing of copper products	Finished copper products	Manufacturing rate was estimated by difference from input and net import/export flows The net import/export of copper semis into Africa was calculated as the difference of total documented imports and exports to all selected countries	ICSG[13] WBMS[14]
Manufacturing of copper-based alloy products	Finished copper-based alloy products	Manufacturing rate was estimated by difference from input and net import/export flows	
Manufacturing of copper and copper-based alloy products	New scrap—copper and copper-based alloy	Country new scrap production rates were taken from literature and summed for all STAF-Africa countries 80% of new scrap is directly remelted, the remainder is returned to secondary refineries	ICSG[13] WBMS[14] Bertram *et al.*[17]

Table V

1994 Copper trade of finished products in STAF-Africa

Product	Estimated copper content[19] [%]	Trade volume (+ = net import /- = net export) [Gg/year]	Copper flow (+ = net import /- = net export) [Gg/year]
Industrial machinery	2.0	+ 414.5	+ 8.3
Metalworking machinery	14.5	+ 144.3	+ 20.9
Electronic products	2.0–4.6	+ 152.7	+ 5.0
Insulated wire	60.0	+ 74.0	+ 44.4
Vehicles	1.0–1.45	+ 712.6	+ 9.1
Aircrafts	2.0	+ 3.1	+ 0.1
Boat and ships	0.5	+ 47.1	+ 0.2
Total STAF-Africa			+ 88.0

Table VI

1994 Copper use—assumptions and data sources

Process	Flow	Assumptions/approaches	Data sources
Use	Copper entering use	The net import/export of copper and copper-based alloy finished products into Africa was calculated from an empirical model based on import/export data of commodities in weights and their estimated copper content	UN[18] Fuse[19]
Use	Copper entering stock	Calculated as the difference between new copper entering use and the flow of copper in waste streams	

present in Africa, together with their residence-times and period of entry into use. Therefore, in the contemporary copper cycle, the total mass of copper retired from the use process is estimated from data on waste streams that leave the use stage and enter the waste management system.

The following post-consumer waste categories are assessed in this study: municipal solid waste (MSW), construction and demolition waste (C&D), waste from electrical and electronic equipment (WEEE), end-of-life-vehicles (ELV), sewage sludge (SS), and industrial and hazardous waste (I&HW). These waste categories comply with classical waste management approaches[17]. These post-consumer wastes exclude wastes from primary copper production in mills (tailings), smelters (slag), and refineries (refinery waste). However, the production wastes are also incorporated in the copper flow model. Gordon[15] assesses the generation rates, composition and recovery potential of these production wastes.

All copper waste is managed in one of the following ways:

- ➤ some is recovered and returned to smelters, refineries, and brass mills
- ➤ some is sent to landfill sites, but a portion escapes as loss to the environment
- ➤ some is sent to an incinerator, with a portion of this stream going to landfill (ash) and another portion being lost to the environment[b]

The modelling of the waste management system is based on various assumptions. Apart from copper scrap, imports and exports of waste (i.e., products containing copper destined for disposal rather than recycling) to and from STAF-Africa are not considered. Reported statistical values for transcontinental scrap trading are assumed to consist exclusively of old scrap since new scrap is mainly re-melted and returned directly within a production facility of semi-products.

Waste generation rates and recycling and disposal quantities are determined by a literature survey, with informed estimates being made if data were not available. Losses into the environment from treatment and disposal facilities were not assessed during this study.

Table VII documents the assumptions, approaches, and data sources for the waste management process. A more detailed description of the assessed waste streams is provided in the following subsections.

Municipal solid waste (MSW)

MSW accounts for all non-hazardous waste generated in urbanized areas, and generally includes domestic household waste, rubble, garden refuse, and commercial and general industrial waste. MSW may also contain small quantities of hazardous materials, such as batteries, paints, and insecticides discarded from domestic, commercial and industrial premises. The collection and processing of MSW is usually the responsibility of a local governmental authority.

Various studies[20,23,44,45] have indicated that African MSW generation rates are dependent on two main variables, namely population and dwelling intensity, and per capita income level. The demographics of the area generating the waste have a great influence on the content of the MSW. Factors such as cultural characteristics, the number and type of dwellings, population and population density, percentage employed and income levels[45] are also relevant factors.

As a result of inconsistencies in applied definitions and quantification, MSW generation data in Africa are generally unreliable. Estimates of waste generation rates (kg/capita/year) were found for various African countries (e.g., Ghana, Ivory Coast, Nigeria, South Africa, Tanzania and Zimbabwe). If no MSW generation data were available for a selected African country at all, informed estimates were made using GDP per capita as a proxy indicator, as outlined in Table VII.

The copper content in MSW for STAF-Africa was estimated based on the various African and international literature sources listed in Table VII.

[b]In state of art incinerators in, for example, the US, non-ferrous metals are recovered from incinerator ash, we assume in this study that such recovery does not take place in conjunction with incineration in Africa

Construction and demolition waste (C&D)

The European Commission[46] defines C&D as waste arising from the construction and total or partial demolition of buildings and/or civil infrastructure; soil, rocks, and vegetation arising from land levelling, civil works and/or general foundations, and materials arising from road maintenance activities.

Data on total C&D quantities generated were only found for two countries, South Africa and Tanzania. Based on these sources, a C&D waste generation rate (kg C&D/million US$ GDP) was derived. As no data could be found on the overall copper content of C&D generated in Africa, the estimation of the copper content was taken as the composition of C&D generated in Europe[26].

Wastes from electrical and electronic products (WEEE)

There are no reliable datasets available for wastes from electrical and electronic equipment in STAF-Africa.

According to Siemers and Vest[33], the overall composition of WEEE includes 67 per cent consumer goods and 33 per cent industrial goods. Consumer goods can be products used in information technology, office and telecommunication equipment, household appliances, and entertainment electronics, among others. Examples of industrial goods are control gears, measuring equipment, medical equipment, and money transaction equipment.

According to WEKA[35], consumer and industrial goods have an average copper content of 4.6 per cent and 14.5 per cent respectively. Sum[34] also assessed the content of WEEE and concluded that WEEE are composed of plastic (ca. 22 per cent), ferrous metals (ca. 47 per cent), non-ferrous metals (ca. 9 per cent) and other materials (22 per cent). The non-ferrous fraction includes ca. 6 per cent copper. On the basis of these studies, the average copper content of WEEE for all STAF-African countries was estimated to be 6 per cent.

The proportion of WEEE that is disposed of in urban centres in developing countries will not reach the same level as in industrial countries since higher rates of secondary use (with export to rural regions) can be expected. The study conducted by Siemers and Vest[33] also provided data on the WEEE generation rate for various regions in Africa, ranging from 1 to 3 kg/capita/year.

For industrial goods it is assumed that all countries have collection systems in place. As there is a lack of environmental regulation and policy concerning WEEE disposal in developing countries, post-consumer WEEE are assumed to be disposed along with MSW. However, WEEE are assessed separately in this study due to its high copper content and high potential for recycling.

End-of-life-vehicles (ELV)

Limited information on the production and import/exports of motor vehicles and ELV prevented the authors from determining the generation rate of ELV. At best, approximations can be made on the quantity of ELV in Africa.

Based on United Nations[37] and American Automobile Manufacturers Association[38], the number of in-use motor vehicles is estimated at 15,700,000 units in STAF-Africa. A retirement ratio of 1.5 per cent per year is assumed. This is the number reported over a 10-year period for Peru[39] and is used here as a generic developing country vehicle retirement rate.

Table VII
1994 Copper waste management – assumptions and data sources

Process	Flow	Assumptions/approaches	Data sources
Waste management	Copper in MSW	Country-level waste generation data for MSW were collected from literature. If data were not available, informed estimates were made: GDP per capita < 2,000 US$, then MSW generation is 100 kg/capita/yr GDP per capita > 2,000 US$, then MSW generation is 200 kg/capita/yr Copper content in MSW was estimated based on various literature sources	*Generation rates:* Ghana: Porter *et al.*[20] Ivory Coast: IDRC[21], Nigeria: Haskoning & Konsadem Ass.[22] South Africa: DWAF[23] Tanzania: Ame[24] Zimbabwe: Tevera[25] *Copper content:* Schachermayer *et al.*[26] Morf *et al.*[27] Belevi and Mönch[28] Morf *et al.*[29]
	Copper in C&D	Informed estimates were made on waste generation rates for C&D based on available literature Copper content in C&D was estimated based on various literature sources	*Generation rates:* South Africa: Macozoma and Benting[30] Tanzania: DCC[31] *Copper content:* Brunner and Stampfli[32]
	Copper in WEEE	Informed estimates were made on waste generation rates for WEEE based on available literature GDP per capita < 500 US$, then WEEE generation is 1 kg/capita/yr GDP per capita is between 500 and 2000 US$, then WEEE generation is 2 kg/capita/yr GDP per capita > 2,000 US$, then WEEE generation is 3 kg/capita/yr Copper content in WEEE is an informed estimate based on various literature sources	*Generation rates:* Siemers and Vest[33] *Copper content:* Sum[34] WEKA[35] Rechberger[36]
	Copper in ELV	Number of registered motor vehicles was taken from literature Number of ELV in a given year was assumed to be 1.5% of number of in-use motor vehicles, based on data representing a developing country in South America Copper content of ELV was estimated based on literature	*Number of in-use vehicles*: UN[37]; AAMA[38] *Number of ELV:* AAMA[39] *Copper content:* Keoleian *et al.*[40]
	Copper in SS	Informed estimates were made on waste generation rates for SS based on available literature (if connected to sewage treatment) It is assumed that 20% of population in Africa is connected to a sewage treatment facility Copper content in SS waste was estimated based on literature	*Generation rates:* South Africa: DWAF[23] *Copper content:* Rechberger[36] Wei *et al.*[41]
	Copper in I&HW	Informed estimates were made on waste generation rates for I&HW based on available literature Copper content in I&HW was estimated	*Generation rates:* South Africa: DWAF[23] Tanzania: DCC[31]; van den Brink and Szirmai[42] *Copper content:* Rechberger[36]
Collection and separation	Old scrap	Data on the import and export of old scrap were taken from literature and summed for all STAF-Africa countries Old scrap is recycled in fabrication as re-melt and to secondary production, we assumed the ratio from the feed side (e.g., secondary production uses 80% old scrap and 20% new scrap)	ICSG[13] Bertram *et al.*[17]
	Copper into incineration	It is assumed that 5% of collected waste is being incinerated	IETC[43]
Landfills	Copper to landfills	It is assumed that 90% of incinerated waste is being landfilled It is assumed that wastes not being incinerated or exported go to landfills	IETC[43]

Keoleian *et al.*[40] estimated the copper content of ELV at 1.4 per cent, which corresponds to vehicles built in the 1980s. Larger vehicles, such as trucks and buses, are assumed to have a copper content of about 0.5 per cent. The estimated quantity of copper in ELV was calculated as the weighted average of copper in cars, buses, and trucks.

Sewage sludge (SS)

Reliable data on the copper concentration and waste generation rates for SS from wastewater treatment plants are not available, so estimates were to be made based on available literature[17]. Copper in SS are mainly losses from copper piping in wastewater systems.

In South Africa, approximately 40 per cent of the population is connected to a sewage treatment facility[23]. As no data were obtained for the other STAF-African countries, 20 per cent of the population in those countries was assumed to be connected to wastewater treatment plants.

Industrial and hazardous waste (I&HW)

Hazardous waste is waste that has, even in low concentrations, the potential to have a significant adverse effect on public health and/or the environment on account of inherent toxic, ignitable, corrosive, carcinogenic, or other chemical or physical characteristics[23]. A generic I&HW generation rate (kg/capita/year) was extracted for STAF-African countries from literature sources from South Africa and Tanzania. Data on copper concentrations in I&HW were assumed to be 500 mg/kg (0.5 per cent), based largely on data from I&HW from Europe[17].

Data on generated quantities and composition of non-hazardous industrial waste is often not documented separately, since it is usually a component of other waste groups (e.g., MSW, C&D, and HW). We assume that non-hazardous industrial waste generated is included in the quantities of the other waste groups, and that hazardous waste applies to both domestic and industrial waste.

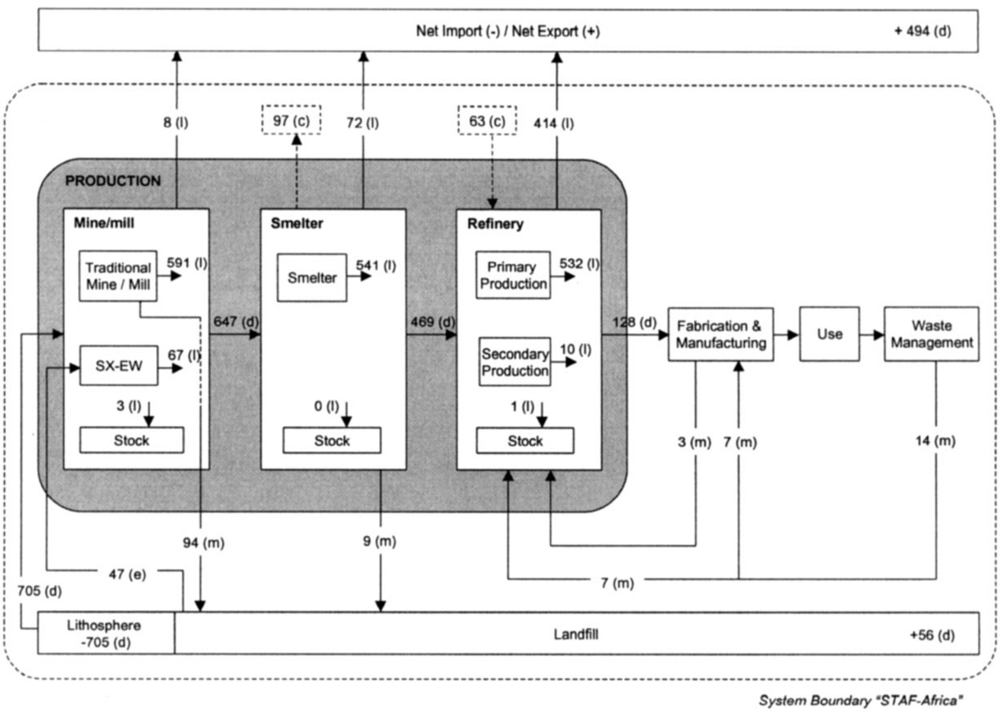
Generation of scrap

On a global average, secondary copper used in smelters and refineries is composed of 70 per cent old and 30 per cent new scrap. Secondary copper used in manufacturing (re-melt) must have a higher purity, and consists of 80 per cent new and 20 per cent old scrap[13]. This results in the following equation for the estimation of old and new scrap, based on available data on re-melt and secondary copper production:

$$\begin{aligned}\text{Old scrap} &= (0.2 * \text{re-melt fabrication}) + \\ &(0.7 * \text{ secondary copper production})\end{aligned} \quad [1]$$

$$\begin{aligned}\text{New scrap} &= (0.8 * \text{re-melt fabrication}) + \\ &(0.3 * \text{ secondary copper production})\end{aligned} \quad [2]$$

Due to its high purity and economic value, almost 100 per cent of the copper fabrication and manufacturing waste is recycled. Exceptions include galvanic sludge and chemical and electrolysis residues, for which recycling is currently not economically feasible. These fabrication and manufacturing wastes are normally discarded as part of hazardous waste.



The letters in parentheses following the flow numbers indicate how the numbers were obtained: (l) = based on literature; (d) = calculated by difference; (m) = calculated by empirical model; (e) = informed estimate; (c) = closure balance.
All quantities measured in Gg Cu / year (thousand metric tons/year).
The dashed boxes indicate the magnitude of addition or removal of mass required to achieve closure in the smelter and refining budgets, but which we are unable to allocate because of discrepancies in the literature.

Figure 3—1994 Copper production diagram for STAF-Africa

Results and discussion

Results for the production stage

The detailed process flow diagram for the production stage of STAF-Africa in 1994 is given in Figure 3.

In the first of the sub-processes, mining/milling, an estimated 94 Gg Cu (16 per cent) is landfilled as mining tailings. A small fraction of the produced concentrate is exported out of STAF-Africa (ca. 1 per cent). The export fractions are higher for smelter and refining production, at 13 per cent and 77 per cent respectively. The solvent extraction-electrowinning (SX-EW) process (used in Zambia[13]) accounts for about 10 per cent of the total copper production in STAF-Africa.

The size of secondary smelter production (10 Gg Cu/yr) is small compared to the primary smelter production (532 Gg Cu/yr). A slag formula developed by Gordon[15] estimates a total copper flow of 9 Gg in landfilled slag in 1994.

The stock changes in the three sub-processes of production are very small, only a few Gg Cu/yr.

The sub-processes mining/milling, smelting, and refining in the production process, as given in Figure 3, do not balance i.e., the budget does not achieve closure; the magnitude of these discrepancies are indicated in dashed boxes. It is assumed that these discrepancies arise from incompleteness or inaccuracy of data in the assessed literature (e.g., undocumented stock changes in the sub-processes of the production stage).

Results for the fabrication and manufacturing stage

The detailed process flow diagram for the fabrication and manufacturing stage is given in Figure 4.

Within fabrication and manufacturing, 27 Gg and 7 Gg of new and old scrap respectively are recycled and used as part of the input for the fabrication of approximately 105 Gg and 57 Gg of copper and copper-based alloy semi-products.

The manufacturing of copper products (124 Gg Cu/yr) is based on domestic production of copper semis (73 per cent) as well as imports (27 per cent). The manufacturing of copper-based alloy products accounts for approximately 42 Gg Cu/yr.

Results for the use stage

The detailed flow diagram for the use stage of STAF-Africa is given in Figure 5. The copper flow contained within finished products entering the use stage is estimated at 254 Gg/yr or approximately 0.45 kg/capita/yr. This input to the use stage consists 65 per cent of copper in products manufactured in Africa, 35 per cent of copper in imported products. By taking the difference between the input and output of the use process, a net-addition to the in-use copper stocks is estimated at 137 Gg Cu/yr, the equivalent of 0.25 kg/capita/yr.

The storage of copper in products in service is by far the largest growing stock in the copper cycle. This growing stock is retained in buildings and construction (29 per cent), infrastructure (18 per cent), electrical and electronic products (14 per cent), industrial machinery and equipment (12 per cent), transport (13 per cent) and consumer and general products (15 per cent). The above percentages have not been explicitly determined for each country, rather, they indicate typical end-use demand for copper in developing countries[47].

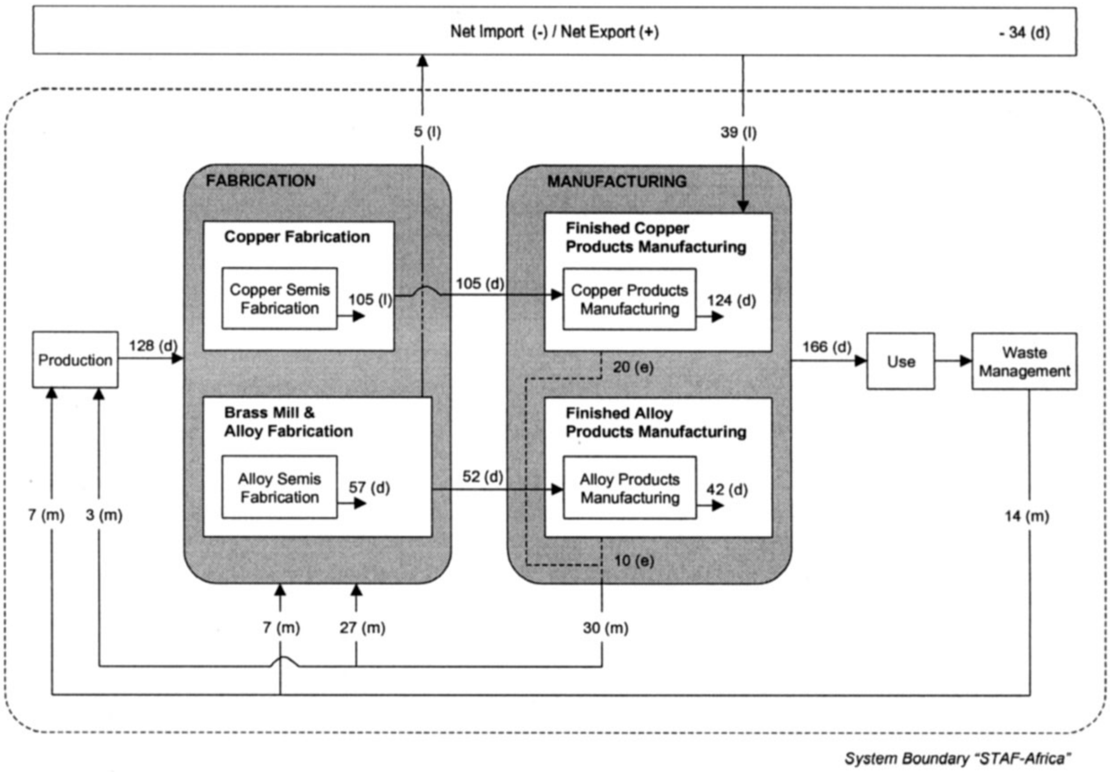


Figure 4—1994 Copper fabrication and manufacturing diagram for STAF-Africa

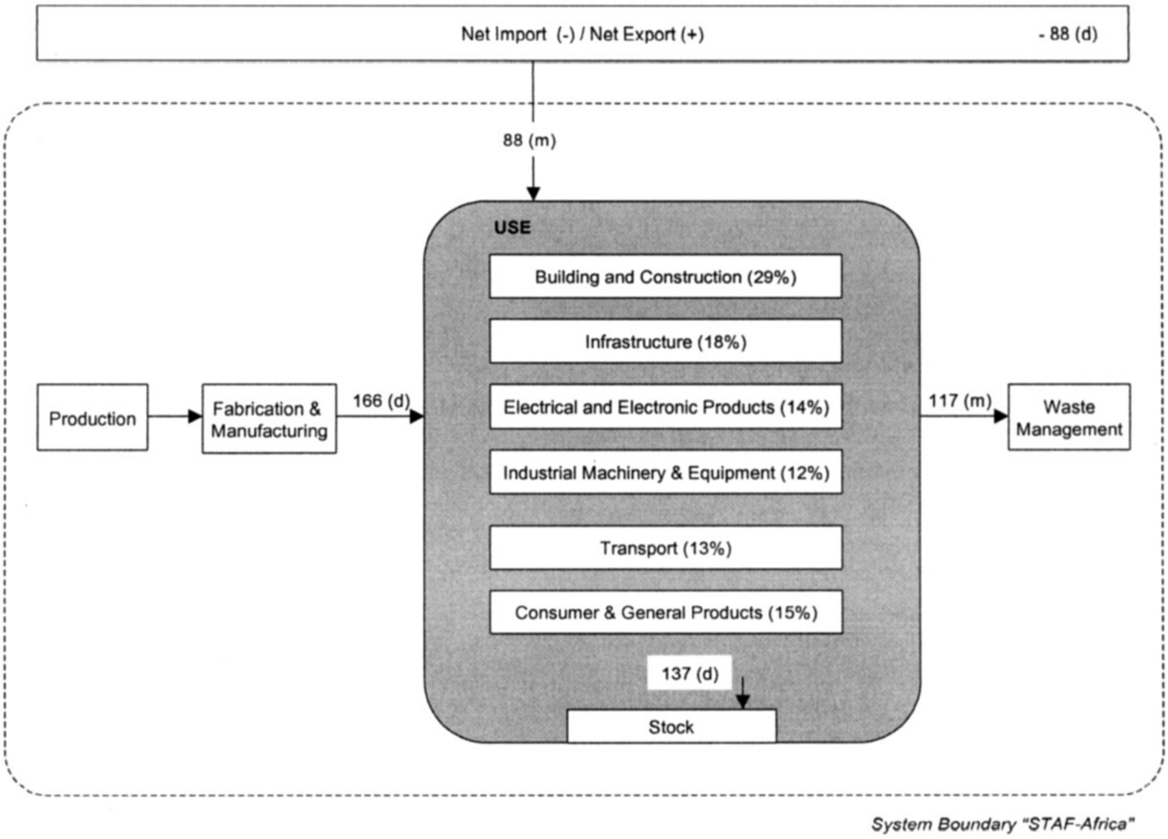


Figure 5—1994 Copper use diagram for STAF-Africa

There is uncertainty about the fraction of the copper flow in traded finished products that is captured by our set of assessed products (see Table V). Based on end-use demand for copper in developing countries[47], as outlined above, we estimate that the selected set of products account for up to 80 per cent of the copper flow in finished products. However, additional research is required to refine the applied approach.

Results for the waste management stage

The detailed process flow diagram for the waste management stage is given in Figure 6.

The waste generation rates and total quantities of generated waste and its copper contents for STAF-African countries are listed in Tables VIII and IX respectively. These tables are based on the assumptions, approaches, and data sources outlined in the previous section.

The accumulated copper flows in the waste categories MSW, C&D, ELV, WEEE, SS and I&HW amount to approximately 117 Gg/yr. The most important waste streams, in terms of total copper flow, are WEEE (73 Gg Cu/yr) and MSW (33 Gg Cu/yr). The primary focus for optimizing the recycling efficiency of copper should therefore be given to these waste streams. The total copper flows in C&D (4 Gg Cu/yr), ELV (4 Gg Cu/yr), SS (1 Gg Cu/yr) and I&HW (3 Gg Cu/yr) are less significant, at least at the present state of African economic development.

The waste stream with by far the highest copper concentration is WEEE (6 per cent). ELV also have a relatively high copper concentration, namely 1.4 per cent. The remaining waste streams have estimated copper concentrations in the range of 0.03–0.07 per cent. Although MSW is estimated to have a low copper content (0.036 per cent), the accumulated copper flow in this waste stream is still significant in absolute terms, due to its large quantity of total generated waste.

MSW accounts for the largest waste stream (92,400 Gg/yr), while the waste flows of C&D and I&HW are estimated to be 6,200 Gg/yr and 5,600 Gg/yr respectively. The total generated wastes of WEEE, ELV and SS are significantly lower, of a magnitude of 300 to 2,500 Gg/yr.

In the year under review, about 26 Gg/yr of old scrap was exported outside the boundaries of STAF-Africa. The partitioning of old scrap (14 Gg/yr) between production (refineries) and fabrication has been estimated as 50:50.

Approximately 71 Gg/yr of copper in wastes is directly landfilled after collection, while another estimated 6 Gg/yr of copper ends up on landfills after passing through the incineration sub-process. The total copper in landfilled post-consumer waste is thus 77 Gg/yr, which is less than the copper in waste generated in the production process (103 Gg/yr).

Two key parameters (waste generation and copper concentration) were selected to validate the sensitivity of the final results to estimates of copper entering the waste management system. This approach was discussed by Bertram *et al.*[17]. In the base scenario, 117 Gg/yr of copper (hereafter referred to as the base flow) enters the waste management system. For each of the six waste streams, the waste generation rate and copper concentration were varied independently while keeping other variables constant. The

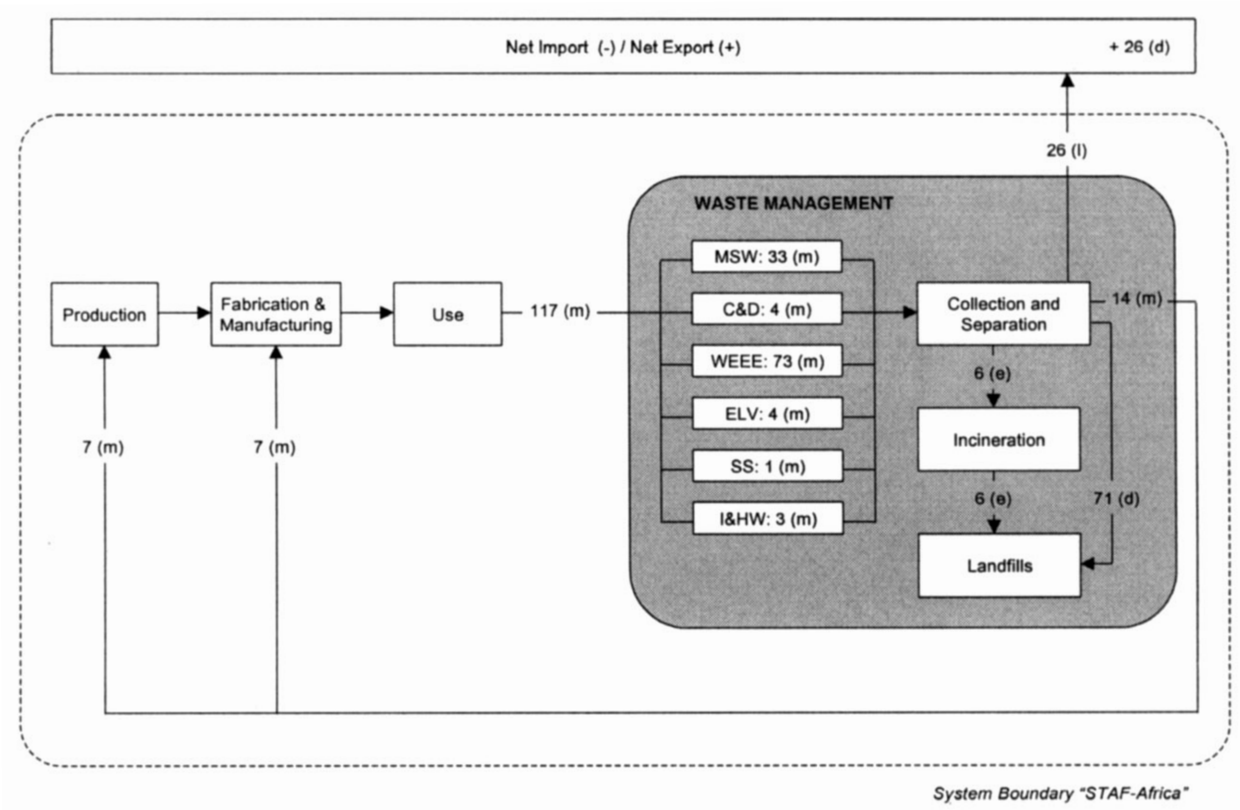


Figure 6—1994 Copper waste management diagram for STAF-Africa

Table VIII

Waste generation rates for STAF-Africa

Country	MSW [kg/capita/yr]	C&D [kg/capita/yr]	WEEE [kg/capita/yr]	ELV [kg/capita/yr]	SS* [kg/capita/yr]	I&HW [kg/capita/yr]
Algeria	200	22	3	1.6	19	10
Botswana	200	31	3	1.0	19	10
Cameroon	100	10	2	0.1	19	10
Congo	200	20	3	0.3	19	10
Dem. Rep. of Congo	100	3	1	0.3	19	10
Egypt	200	16	3	0.5	19	10
Ethiopia	100	3	1	0.0	19	10
Ghana	183	10	2	0.0	19	10
Ivory Coast	382	10	2	0.2	19	10
Kenya	100	8	2	0.3	19	10
Libya	200	44	3	4.2	19	10
Morocco	200	17	3	1.0	19	10
Mozambique	100	4	2	0.1	19	10
Namibia	200	17	3	0.5	19	10
Nigeria	219	7	2	0.0	19	10
South Africa	170	27	3	2.6	19	10
Sudan	100	5	2	0.1	19	10
Tanzania	142	4	2	0.1	19	10
Tunisia	200	28	3	1.3	19	10
Uganda	100	9	2	0.1	19	10
Zambia	100	6	2	0.1	19	10
Zimbabwe	201	10	2	0.8	19	10
Total averages STAF-Africa	168	14	2	0.7	19	10

*Dry weight sewage sludge, if connected to sewage treatment facility

Table IX

Waste generation and copper concentrations for STAF-Africa in mid-1990s

Waste category	Waste generation [Gg/yr]	Mass fraction [%]	Copper concentration [%]	Copper concentration [Gg/yr]	Copper fraction [%]
MSW	92,400	85.6	0.036	33.3	28.4
C&D	6,200	5.7	0.067	4.1	3.5
WEEE	1,200	1.1	6.0	72.5	61.9
ELV	300	0.3	1.2	3.6	3.1
SS	2,300	2.1	0.035	0.9	0.7
I&HW	5,600	5.2	0.05	2.8	2.4
Total STAF-Africa	108,000	100.0		117.2	100.0

estimated uncertainty ranges are shown in Table X. The effect of changing the waste generation rates and copper concentrations over the given uncertainty is shown in Figure 7.

The sensitivity analysis reveals that changes in the waste generation rates of WEEE and MSW affect the base flow the most, ± 22 Gg/yr and ± 13 Gg/yr respectively. Changes in the WEEE generation rate alone can cause the base flow to vary between 95 and 139 Gg/yr. Waste generation rates for C&D also affect the base flow, although less significantly than MSW and WEEE, ± 4 Gg/yr. Regarding copper concentrations of the waste streams, the base flow is affected most greatly by WEEE (+24/-36 Gg/yr), and to a lesser extent by MSW (+4/-6 Gg/yr). Changes in the generation rate or copper concentration of ELV, SS and I&HW do not affect the base flow significantly.

The sensitivity analysis shows that, except for WEEE, the estimated uncertainties in the waste generation rates and copper concentrations have only a limited effect on the results that we derive.

The comprehensive copper cycle for STAF-Africa

By combining the information in Figures 3–6, we derive the contemporary copper cycle for STAF-Africa as shown in Figure 8. To our knowledge, this is the first characterization of any anthropogenic element cycle for the African continent.

A number of features of interest in the cycle can readily be identified. These include the following:

- In 1994, some 705 Gg Cu was extracted from the African lithosphere. 70 per cent of this material was exported following processing. About 18 per cent was sent on to fabricators on the African continent, and about 12 per cent was discarded in tailings and slag.
- The largest export flow in the African copper cycle is the export of cathode copper from the refinery process (414 Gg Cu/yr). The largest import flow in the copper cycle is the import of finished copper and copper-based alloy products into the use process (88 Gg/yr). The production process of the copper cycle is characterized by relatively high levels of exports, while the fabrication and manufacturing, and use process showing high import levels.
- According to the developed copper cycle, copper in semi-products from African fabricators is about 65 per cent in elemental form and about 35 per cent in alloy form (mostly brass). This distinction is potentially important at the recycling stage, since elemental copper can readily be re-used in either elemental or alloy form, while alloy copper is economically recycled only in alloy form.
- We estimate the difference between the input and output flows to the use phase at 137 Gg Cu/yr; this is material that is being added to the in-use stock. It is predominantly in electrical wiring and plumbing pipe (long-term uses) and in electrical and electronic products (short-term uses).
- The apparent separation rate for copper waste on the African continent is about 35 per cent. Two-thirds of that amount is exported and recycled elsewhere, while one-third is recycled on the African continent. However, it is expected that the actual recycling rate is higher, as informal (and undocumented) recycling takes place on a large scale in Africa.
- About 77 Gg Cu is landfilled as post-consumer wastes each year in Africa, and about 103 Gg Cu deposited on the ground near milling, smelting, and refining operations. It is estimated that 47 Gg Cu/yr is extracted from old mine dumps in Zambia for reworking of tailings[16]. Small but undetermined amounts are dissipated in various ways. Overall, the movement of about 705 Gg Cu/yr from natural reserves is thus partially balanced by a return flow of about 180 Gg Cu/yr.

Analysis of data sources and detail

As shown in the tables outlining the assumptions and data sources for the four main processes, this copper cycle consists of a mixture of flows derived from literature, estimations using empirical models (e.g., tailings and slag) and documented copper concentrations in various flows (e.g., waste streams). The level of detail and accuracy in the literature on copper flows in Africa varies greatly from country to country. No (or very limited) information was available for certain countries (e.g., Democratic Republic of Congo, Libya, and Algeria), which posed a challenge in deriving reliable estimates for them.

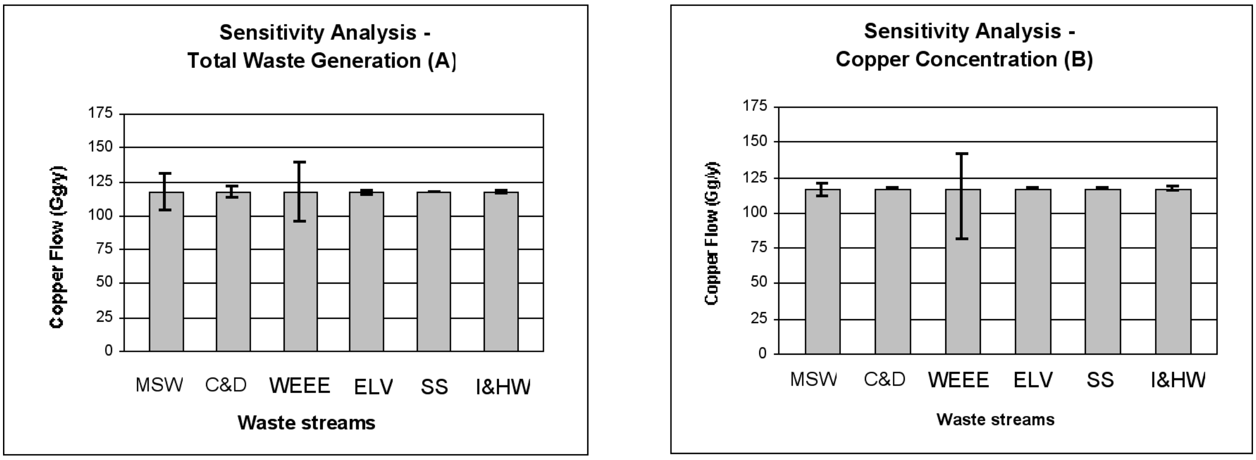
Databases available through industrial trade associations and governmental bureau provided relatively accurate and reliable data for certain parts of the copper model, particularly the processes dealing with production and fabrication of copper semi-products. However, the level of detail and availability of data on product manufacturing, use, and waste

Table X

Waste generation, copper concentrations and uncertainties

Waste category	Waste generation		Copper concentration	
	Base value Gg/year	Uncertainty* %	Base value %	Uncertainty* %
MSW	92,400	± 40	0.036	0.03–0.04
C&D	6,200	± 100	0.067	0.06–0.07
WEEE	1,200	± 30	6.0	3.0–8.0
ELV	300	± 40	1.2	1.0–1.4
SS	2,800	± 30	0.035	0.02–0.04
I&HW	5,600	± 30	0.05	0.02–0.08

*Uncertainty ranges are assumptions made for the purpose of the sensitivity analysis



Columns represent the flow of copper entering the waste management system (base flow, 117 Gg/yr), bars the sensitivity in the base flow to changes in (a) waste generation and (b) copper concentration of each waste stream

Figure 7—Effect of uncertainty ranges to base flow for waste management process

management was poor. In many cases, assumptions had to be made based on the limited in-country data that were available, or on data from other African countries.

The scope of this study was to estimate and assess copper flows in Africa over a one-year period. From this perspective, the overall representativeness of data sets used in the STAF-Africa model was judged to be of a low to moderate reliability.

Conclusions

This MFA-study provides a quantitative framework for the further refinement of a contemporary copper cycle for the African continent. It reveals that it is feasible to compile a relatively reliable one-year copper cycle for Africa. However, the cycle's limitations and restrictions due to limited data availability and reliability for certain parts of the model need to be borne in mind. Improvements in data availability, consistency and detail are required to construct more accurate flow cycles on a continental level for copper and other materials.

In order to determine the magnitude of copper stocks in various reservoirs, an investigation over a multi-year period should be carried out. The accuracy of the copper cycle could then be improved as variations in production stocks and other discrepancies could easily be identified by using a multi-year time-frame. This MFA study, as discussed herein, provides the basis for moving forward using 1994. Carrying out a multi-year study for the African continent is one of the long-term goals of the STAF-project.

The reservoir of in-use copper is growing faster than the copper stocks in landfilled production wastes such as tailings and slag. However, the difference is not as significant as it is for Europe[4]. These in-use reservoirs should be managed in such a way that they may serve as a possible supply of secondary resources in the future. This is particularly true of copper in discarded electrical and electronic products, which is more than 60 per cent of copper in the African discard flows, and much easier to collect and re-use than the less concentrated copper in other discard flows. To enable a future recycling goal to be achieved, the spatial distribution and composition of in-use copper stocks should be further investigated. An example of such a study is the case-study on the magnitude and distribution of in-use copper stocks in the City of Cape Town conducted by van Beers and Graedel[48].

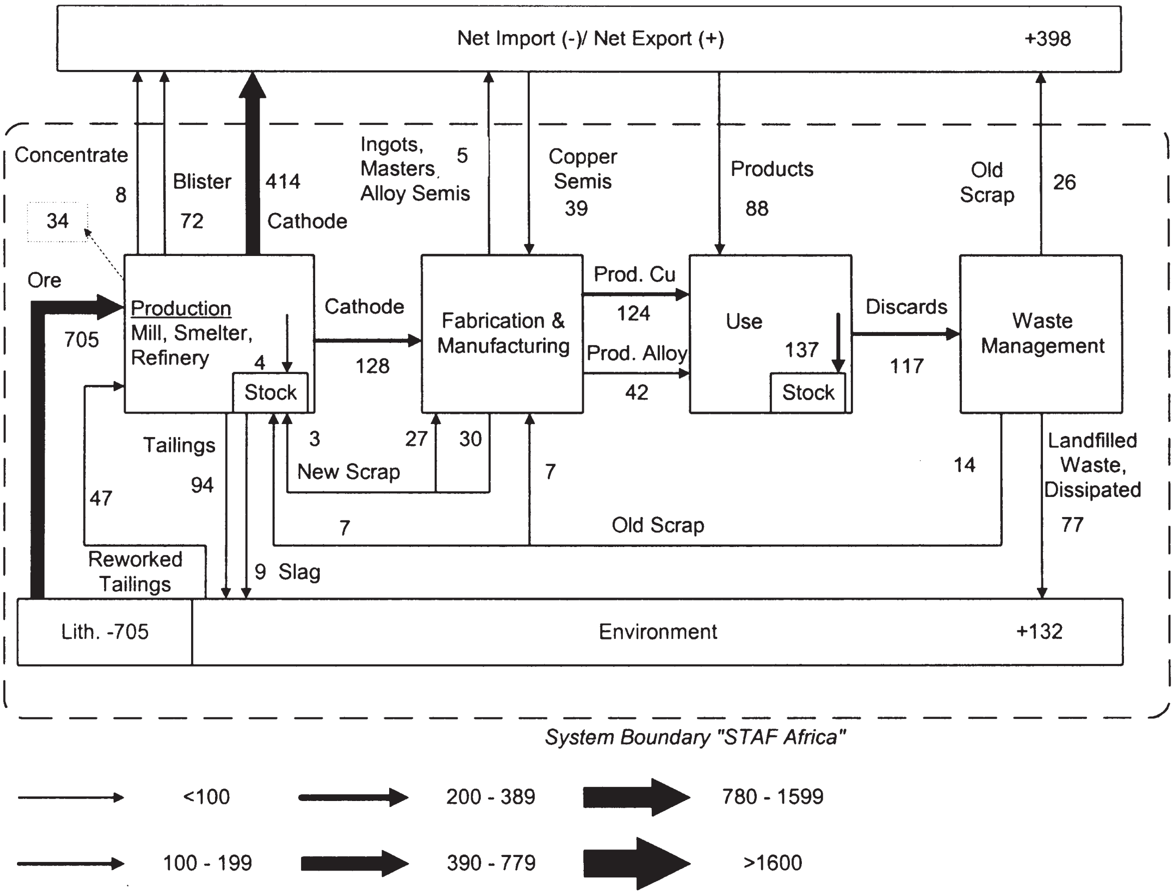


Figure 8—1994 Total copper flow diagram for STAF-Africa

Copper is employed extensively both as a pure metal or as an alloy (mostly brass), and these forms are important factors in recycling potential. Copper is a good case study material to fully explicate the possibilities for efficient and effective recycling. According to the copper cycle we have characterized, about one-third of all copper in post-consumer wastes is recycled. Most copper in post-consumer wastes (about two-thirds) appears to eventually end up on landfill sites. We realise, however, that informal scavenging takes place on a large scale in Africa; the amounts of these recycled wastes are generally not registered or documented. The low recorded percentage may thus point to discrepancies and gaps in the assessed literature. A further source of uncertainty in recycling statistics is the lag time present in the secondary scrap markets. It is our opinion that there is a need for further in-depth research in assessing the efficiency of recycling of copper in Africa, and the recovery of copper and other metals from waste depositories.

A comparison of developing world versus first world practices (e.g., additions to stock, waste generation rates, recycling efficiency) provides insights on the relationships between state of development and use of materials. This comparison is made and discussed in Graedel *et al.*[49].

Finally, future research should focus on assessing dissipative losses and their environmental impacts across the total copper cycle, an aspect that was not addressed in this study.

Acknowledgements

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