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Key drivers of the e-waste recycling system: Assessing and modelling e-waste processing in the informal sector in Delhi

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Abstract

The management and recycling of waste electrical and electronic equipment WEEE was assessed in the city of Delhi, India. In order to do this, the personal computer was defined as the

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tracer for which a model was designed. The model depicts the entire life cycle of the tracer, from production through sale and consumption—including reuse and refurbishment—to the material recovery in the mainly informal recycling industry. The field work included interviews with the relevant stakeholders, transect walks and literature study, which was followed by a software-supported material flow analysis (MFA) of the whole life cycle chain of the tracer item. In addition to the MFA, several economic aspects of the recycling system were investigated. The study revealed that the life span of a personal computer has considerable influence upon the system, most notably in the following two aspects: (i) a prolonged life span creates value by means of refurbishing and upgrading activities, and (ii) it slows down the flow rate of the whole system. This is one of the simplest ways of preventing an uncontrolled increase in environmentally hazardous emissions by the recycling sector. The material recovery of the system is mainly driven by the precious metal content of personal computers. A first estimate showed that precious metal recovery contributes to over 80% of the personal computer materials' market value, despite the small quantity of them found in computers.

Keywords: Material flow analysis; Informal sector; E-waste recycling; WEEE; Developing countries; Countries in economic transition; Personal computer; Upgrading and refurbishing

1. Introduction

1.1. Situation and problem description

Electronic waste, e-waste or waste electronic and electrical equipment (WEEE) can be considered a danger to human and the environment. The directive from the European Union on the restriction of the use of certain hazardous substances in electrical and electronic equipment intends to contribute to the protection of human health and the environmentally sound recovery and disposal of waste electrical and electronic equipment by means of these restrictions. "Member States shall ensure that, from 1 July 2006, new electrical and electronic equipment put on the market does not contain lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE)." (EC, 2002a).

E-waste is a generic term embracing various types of electronic equipment. According to the definitions in the directive of the Parliament and European Union Council on waste electrical and electronic equipment, WEEE can be subdivided into the ten different categories listed in Table 1. The categories "IT and telecommunications equipment" and "consumer equipment" constitute e-waste (EC, 2002b).

In the former 15 European Union member countries (EU15) the amount of WEEE produced varied between 3.3–3.6 kg per capita for the period 1990–1999 and has been projected as 3.9–4.3 kg per capita for the period 2000–2010 (EEA, 2003). According to this study (which assessed only five appliances: refrigerators, personal computers, televisions, photocopiers and small household appliances), this amount covers only 25% of the whole WEEE stream of the EU15. Hence, these numbers correspond to other estimates of total WEEE amounts, which range between 14 (Keynote, 2003) and 20 kg per capita (estimated by AEA, cited in Enviros, 2002). The amount of WEEE generated

Table 1
WEEE categories according to the EU directive on WEEE

1	Large household appliances
2	Small household appliances
3	IT and telecommunications equipment
4	Consumer equipment
5	Lighting equipment
6	Electrical and electronic tools (with the exception of large-scale stationary industrial tools)
7	Toys, leisure and sports equipment
8	Medical devices (with the exception of all implanted and infected products)
9	Monitoring and control instruments
10	Automatic dispensers

constitutes one of the fastest growing waste fractions, accounting for 8% of all municipal waste (The Economist, 2005).

Although the per capita waste production in populous countries like China and India is still relatively small (estimated < 1 kg per capita and year), these countries are already huge producers of WEEE. These countries tend to also have the fastest growing markets for electrical and electronic equipment (EEE), ones that are far from saturation. From 1993 to 2000, the number of PC users in China increased 1052% whilst the average growth throughout the world was much lower at 181%. During the same period, India showed an increase of 604%. From 1996 to 2002, the number of mobile phone users in China rose to 200 million (LRD, 2005).

Due to these developments, countries like India face a fast increasing load of WEEE originating both inland and through illegal imports. For emerging economies these material flows offer a business opportunity. The backlog demand of EEE in developing countries as well as the lack of national regulation and/or lax enforcement of existing laws promotes the growth of a semi-formal or informal economy. An entire new economic sector revolves around trading, repairing and regaining materials from redundant electronic devices. It provides a living for the urban and rural poor, but causes severe risks for humans and the local environment. For some of the densely populated regions poorly controlled WEEE recycling with extremely risky techniques is a grim reality. Most of the participants in this sector are not aware of the risks, do not know of better practices or simply have no access to investment capital to finance profitable improvements.

1.2. Environmental impact assessment and material flow studies for information technologies

Environmental impacts of information technologies have been assessed on various scales. A first group of studies discussed and evaluated how Information and Communication Technologies (ICT) change national economies and societies. These studies covered indirect as well as direct effects of the services provided by ICT industries on the natural environment (Allenby, 2004) and discussed the rebound effect of the ongoing change (Binswanger, 2001). Gleiber et al. (2005) investigated the direct and indirect impacts of Information Technology (IT) including the consumption of resources and energy during the production and use of ICT products.

A second group of studies evaluated the effect of changing entire systems for providing certain services. Hischier and Reichart (2003) compared the environmental impacts related to reading a printed newspaper to the impacts related to reading an online version and related to watching news on television. Matthew and Hendrickson (2002) analyzed different systems of distributing consumer goods.

The third group of studies investigated the life cycle of individual electronic products or components of EEE (e.g. Anders et al., 2004; Alonso et al., 2003; Vehlow et al., 2003). Hilty et al. assessed the future impacts of pervasive computing on health and the environment (Hilty et al., 2003). A major finding was that, due to continually increasing innovation cycles and material throughputs, electronic products are increasingly being thrown away which in principle could still be considered functionally sound.

The last category of studies however, focuses on the end of the life cycles of electronic products and the management of electronic waste on national or international scales. ICT equipment is representative of other EEE. This research supported the development of strategies to manage and recycle WEEE. A comprehensive report of the material flow of 17 EU countries and the EU15 (countries having been EU members longer) has been executed by the European Environmental Agency (EEA, 2003). An assessment methodology was developed in order to estimate the quantities of WEEE generated during the period from 1990–1999. By applying different algorithms for the life span of appliances' future WEEE streams were extrapolated for the period 2000–2010. From this data the emissions of dangerous substances was estimated. AEA Technology Environment compiled a comprehensive and detailed report on the medium composition of WEEE and hazardous waste (Ogilvie, 2004). The report on a WEEE demonstration project carried out in 1999 and 2000 in the US state of Minnesota (Minnesota Office of Environmental and Assistance, 2001) stated that voluntary partnerships for the collection of EEE and product responsibility shared between the private and public sectors create opportunities to prevent the disposal of WEEE in municipal waste.

The Technology and Society Laboratory at the Federal Institute for Materials Testing and Research (www.empa.ch/tsl) is currently conducting a study of the situation of WEEE recycling in three selected regions in developing countries. The overall project aim is to reduce hazards without reducing the attractiveness of the WEEE recycling business. This implementation-oriented project has been scientifically complemented by two master theses both dealing with the pilot region in India: Sinha (2004) compared the recycling of e-waste in Switzerland as one of the very few countries with long-term experience in managing e-waste with India, which handles huge amounts of imported e-waste, but is continually experiencing problems. Steiner (2004) focused on a spatial risk assessment of the burning of copper cables, which is an important process in WEEE recycling.

Toxics Link, a non-governmental organization (NGO) active on the supervision of harmful and hazardous substances in India, has published several reports on the matter of WEEE recycling in Delhi and Chennai including an estimate of material flow, a toxicological overview as well as an analysis of the economics of WEEE processing (ToxicsLink, 2003, 2004).

Many assessments focus on the environmental and economic evaluation of industrial processes or the activities of sectors of an industry. This paper in contrast focuses on the assessment of the informal sector of the recycling industry in Delhi. The goal of this study is to identify key drivers within the WEEE managing system. Which factors influence (i) the establishment of an informal industry and (ii) maintain such a highly inefficient system? The challenge that would really improve this situation is to prevent pollution without taking away the income from the local population.

2. Methods

The method applied to support the material and substance flow management in the waste and especially the e-waste sector of third world countries is the Material Flow Analysis (MFA). Material Flow Analysis is a generic term for analyses of matter flows (chemical elements, compounds, materials or commodities) which are based on material balancing representing the law of material conservation. In general, three different types of MFA have been presented in recent literature: (i) Substance Flow Analysis (SFA), which is primarily used to relate critical emissions of substances to processes, products and material inputs in the system (Baccini and Brunner, 1991; Baccini, 1996 and Bader, 1996; Van der Voet, 1996; Graedel et al., 2002; Spatari et al., 2003; Vexler et al., 2004); (ii) Process-based Material Flow Analysis, which is primarily used to analyze specific questions of resource and waste management (Baccini, 1996 and Bader and Baccini, 1996; Bringezu, 2000a) and (iii) Industry-based MFA, which is a tool to assess the environmental impact of economic development by analyzing the total material throughput of a system (Adriaanse et al., 1997; Bringezu, 2000b; Matthews et al., 2000; Daniels and Moore, 2002; Daniels, 2002).

In this study, a process-based Material Flow Analysis is applied. This choice of method is motivated by its ability to link material flows (resources as well as waste) to consumer needs, economic structures or technological development (Müller, 1998; Kohler et al., 1999; Redle, 1999; Faist, 2000; Hendriks et al., 2000; Faist et al., 2001; Hug and Baccini, 2002). Process-based MFA studies deliver indicator values for a system’s characteristics (e.g. recycling rates), performance (e.g. resource efficiency, rates of resource depletion) and impacts (e.g. range of available resource deposits or landfill capacities). As the method focuses on system comprehension rather than on environmental impact assessment, it is apt to reveal options for future development at an early stage of decision making.

This method taps to its full potential by applying a mathematical formulation and modelling as suggested by Baccini and Bader (1996). In the last 10 years this mathematical MFA has been applied in numerous studies in different fields: Zeltner et al. (1999), Real (1998), Binder et al. (2001), Sörme (2003), Hedbrant (2003), Van der Voet et al. (2000), Hug et al. (2004), Bader et al. (2003), Bader et al. (2005), Müller et al. (2004), Johnstone (2001), Kohler et al. (1999), Schmid et al. (2004 a,b), Kwonpongsagoon et al. (2005) and others and ongoing works, respectively.

Furthermore, process-based MFA can be used as starting point for a joint evaluation of physical and economic characteristics of industrial systems (Kytzia et al., 2004; Kytzia and Nathani, 2004). The corresponding method, called Economically Extended MFA (EE-MFA), builds upon the similarities between process-based MFA and (economic) Input Output Analysis (IOA). If applied to analyze industrial systems, both methods describe flows of commodities between the various producing and consuming sectors within an economy over a stated period of time (Leontief, 1966; Miller and Blair, 1985; Duchin, 1998). If each flow in a process based MFA is multiplied with its market price, the result can be interpreted as a kind of IOA, neglecting some conventions normally used in input output economics but following its basic principles. For example: the surplus gained by the sales of refurbished electrical items minus the payment for second hand or broken items and intermediates, is the value added created by the refurbishment industry. From point of view of input output economics, however, the process based MFA can be interpreted as a physical input output model and incorporated in a Leontief price model (Duchin, 1992). For example: the physical input output coefficients can be used to relate the product prices (e.g. for refurbished computers) to the prices of value added (e.g. wages per hour).

In this study a first outline was drawn suggesting how such a method could be applied to an informal recycling sector such as the one in Delhi, the capital of India. The national capital territory is spread over an area of 1485 km^2, which also forms the physical system border of the model applied in this study. The city of Delhi borders in the west on the state of Haryana, in the east on Uttar Pradesh.

Solid waste management and recycling are organized by an informal industrial sector. Approximately 85,000 people are estimated to work in this sector, a lot of whom are immigrants from other Indian states such as West Bengal, Bihar or Uttar Pradesh, and neighbouring countries such as Bangladesh (Datta, 1997 in Agarwal et al., 2005 and Agarwal et al., 2005).

For this study the tracer item chosen was the personal computer (PC). A tracer item in this context stands for an electrical or electronic item which is surveyed along its whole life span, from the cradle to the grave. The definition of one tracer item PC represents all sorts of PCs. As the study focuses on the investigation of the years 1996–2003, a PC from that generation includes a processing unit of a standard PC terminal, a cathode ray tube (CRT) monitor, keyboard and mouse, and a printer and weighs on average 27.2 kg (Table 2). MCC (1996) calculated the average weight of a PC as 60 lb, which correlates with the above mentioned number. Reliable statistics of sales data, measurable recycling practices and the high dynamics in the information technology sector were reasons for the decision to use the PC as a tracer.

The assessment strategy followed a certain order: first players and stakeholders of the WEEE recycling stream were identified including importers, producers/manufacturers, consumers, traders, (individual households and the business sector), repair shops, dissemblers, scrap dealers and dismantlers. After establishing a rough system model, we decided on the assessment methodology. With transect walks and semi-structured interviews the different recycling processes were identified and described in detail, including photo documentation. Secondly, semi-structured interviews were carried out subsequently with the relevant stakeholders mentioned above. As some of the recyclers

Table 2
Fractions and medium weight of a personal computer (Atlantic Consulting and IPU, 1998; IRGSSA, 2004)

Tracer item PC	Control unit (CPU)	Monitor	Keyboard and mouse	Printer	Total
Total in grams	8380	12,106	1180	5490	27,156

Table 3
Time series for the PC market saturation in India [PCs/1000], the resulting annual growth and the shipment of new PCs

Year	PCs/1000	Population India	India			Delhi		
			PC base	Sales	Growth	Base	Sales	Growth
1996	0.7	934,300,000	650,000	600,000		160,000	150,000	
1997	1.4	949,900,000	1,330,000	800,000	680,000	330,000	200,000	170,000
1998	2.1	965,600,000	2,030,000	1,000,000	700,000	510,000	250,000	180,000
1999	3.1	981,300,000	3,040,000	1,400,000	1,010,000	760,000	350,000	250,000
2000	4.5	997,000,000	4,490,000	1,740,000	1,450,000	1,120,000	440,000	360,000
2001	6.3	1,012,400,000	6,380,000	1,800,000	1,890,000	1,600,000	450,000	470,000
2002	8	1,027,600,000	8,220,000	2,430,000	1,840,000	2,060,000	610,000	460,000
2003	9	1,043,500,000	9,390,000	3,300,000	1,170,000	2,350,000	830,000	290,000
2004	11	1,060,000,000	11,660,000		2,270,000	2,920,000		570,000

For all these figures a constant share of 25% for Delhi is assumed, rounded off at a 10,000 (MAIT, 2003, 2004; Census of India, 2001).

operate illegally, the assessment team had to interview them often in a totally casual manner and compile the information thereafter. Thirdly the assessment included the calculation of published and unpublished data from producers and manufacturers' associations.

To estimate quantities of PCs in Delhi a simplified calculation was used, as explained in the following two steps.

1. The MAIT (Manufacturers' Association of Information Technology India 2004) published data which give an overview of PC market penetration over the period 1996–2004 for all of India and for Delhi (Table 3).
2. We assumed obsolescence time by applying a very simple model and calculated the resulting quantities for scrap PCs: PCs shipped to the market (sales in Table 3) entirely and suddenly drop out, for instance, after 5 or 7 years. Hence, the number of obsolete PCs in 2003 equals the sales in 1998 (5 years earlier) and 1996, respectively, (7 years

Table 4
Total number of scrap PCs entering Delhi's dismantling/recycling market

Scrap PCs in Delhi (2003)	Obsolete after years	
	5	7
Local PCs	250,000	150,000
Imported PCs	133,000	133,000
Grand total	383,000	283,000
Total number of PCs dismantled/day	1277	943
Scrap mark up (ratio imported/local)	53%	89%

Imported PCs may arrive from abroad or from other Indian cities. Field surveys showed that 2 truckloads of scrap PCs arrive in Delhi on 300 days in a year. Considering a truck having a capacity of 6t, the total weight of scrap PCs imported into Delhi's dismantling market is 3,600 t/a. If an average PC weight of 27 kg is assumed, this results in some 133,000 units imported per year. The scrap mark up indicates the ratio of imported scrap PCs to local scrap PCs. For an assumed obsolescence time of 7 years, for instance, the quantity of locally produced PC scrap is almost doubled by imports (+89%) (Source: MAIT, 2004; Empa Survey, 2004).

earlier). The obsolescence time is subsequently fixed to match the number of actually found scrap PCs (comparison of Tables 3 and 4). This obsolescence time is valid if it stays in a window of the actual life spans indicated by the age of current scrap PCs (somewhere between 5 and 9 years).

3. Results

A field survey was conducted in order to confirm these data as well as to derive quantified regional data of the city of Delhi. At the same time an iterative process with participants from Indian non-governmental organizations, and Swiss and Indian research institutes produced a model. The survey results are presented first, followed by the model calculations and the economic aspects of the material flow analysis.

3.1. Field survey

Traditionally Delhi has recycled large quantities of imported waste streams. This is also true for e-waste. Truckloads of scrap PCs arrive from all over India. Although the origin of this e-waste was not tracked, we distinguish between local e-waste (generated in Delhi) and imported e-waste (generated in India and abroad), (Table 4).

In order to confirm these quantities, the CRT (cathode ray tube/monitor) was identified as a tracer item mainly because in the e-waste recycling chain in Delhi all scrap CRTs are processed in a small number of informal enterprises. There it is possible to count the units processed daily. It was thus possible to estimate the annual total obsolete PCs (assuming one monitor per PC) and to confirm an obsolescence time of approximately 7 years (Table 5).

Mainly two stakeholders were identified to be involved in CRT handling:

- monitor dismantlers (very small informal enterprises, often in private households)
- CRT re-gunners (re-gunning=replacing the electron gun). These are small informal enterprises with several semi skilled workers and with some rather sophisticated equipment such as vacuum pumps to evacuate the re-gunned CRTs. The total number of re-gunning enterprises identified and operating in Delhi is 7. Their average daily output is 45–50 re-gunned CRTs totalling 320–350 re-gunned CRTs/day in Delhi.

Table 5
Summary of the assessment of CRT recycling units in Delhi

Description	Units/day
CRTs operational/day	47
CRTs being re-gunned (320–350 units/day)	350
CRTs rejected for re-gunning/day	544
Total number of monitors/day	941

The number of re-gunned units was assumed to be at the upper limit of the range. The resulting total number of monitors is approx. 941 per day, which corresponds well with an obsolescence time of 7 years, which would produce 943 scrap PCs per day (refer to Table 3).

Taking the timelines of Steps 1 and 2 we constructed the confirmed obsolescence time of CRT recycling/day and the scrap mark up factor from imported and locally produced PC scrap, yielding a timeline for obsolete PCs (Fig. 1).

3.2. Model description

During a workshop in 2004, various stakeholders established a material flow model. Representatives from ToxicsLink (2005) and SAAHAS (2005), two Indian based NGOs, which have conducted surveys in the field of WEEE recycling, and the authors participated in this discourse. The resulting model (Figs. 2, 3 and 4) shows a chain of processes through which the tracer item PC was followed. The material flow was calculated for the year 2003.

The system can be split into two sections: pre- and post-recycling processes. Fig. 2 describes the material flow in kilograms per day of the pre-recycling processes. Figs. 3 and 4 show the post-recycling processes. The process “Recycling” links the two sections of the system and at the same time symbolises a “point of no return”. After entering the “Recycling” process, no items, components or material ever return directly to the pre-recycling processes. The material recovered during the post-recycling processes may enter factories of manufactures or producers later, but in this study the material leaves the system simply for further use.

The boxes indicate processes, whereas the arrows show material flows for the scenarios 5 and 7 years’ life span of a personal computer. The live spans have been calculated in order to estimate the potential output. The life span of a personal computer is one of the crucial values needed to calculate future loads of waste. Darby and Obara (2005) outlined the consumer behaviour of WEEE disposal in the UK and IRGSSA (2004) described a

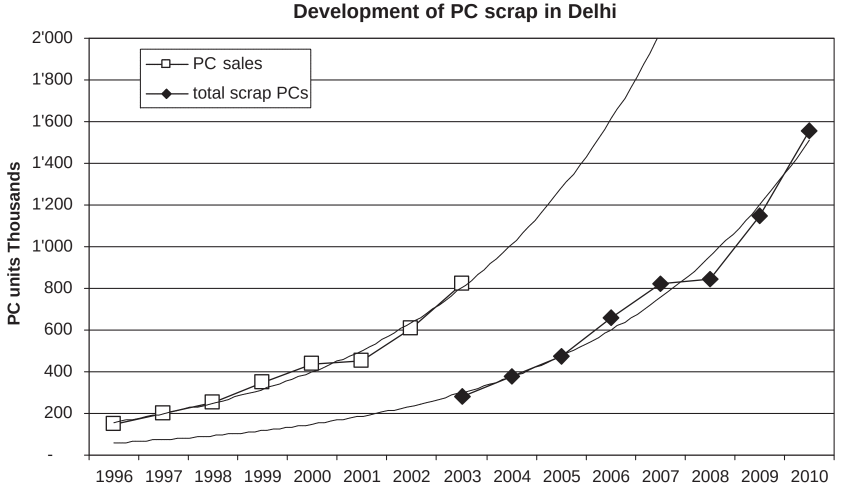

Fig. 1. Trend of growth rate of PC sales in the Delhi market and the resulting scrap PC projection using the procedures described above: the time series of PC sales is shifted 7 years into the future and scaled up with a factor 1.89 (mark up of 89% according to Table 3).

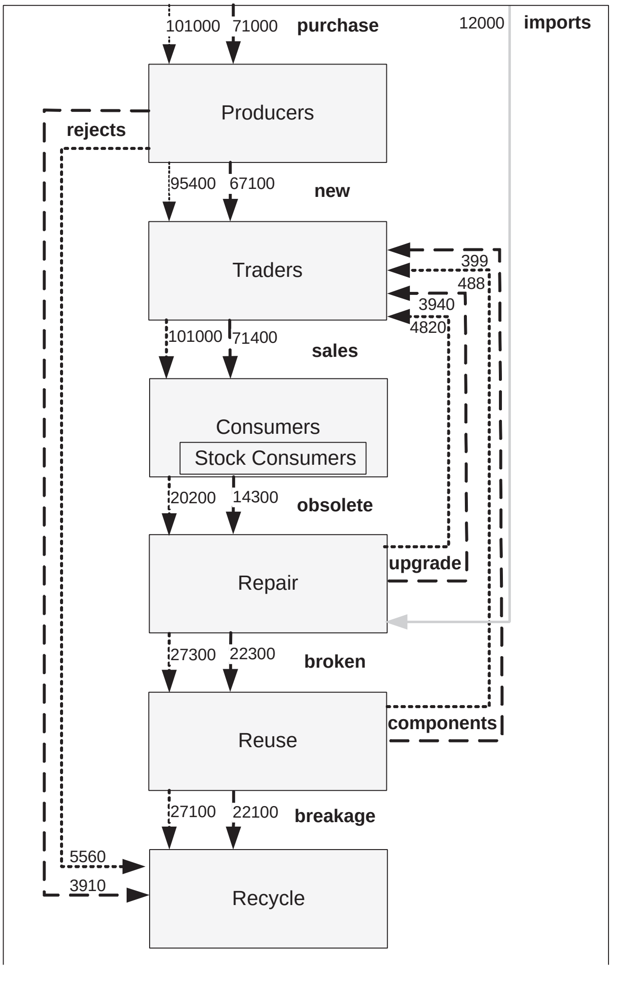

Fig. 2. Material flow of the pre-recycling processes of the tracer item personal computer within the system border Delhi in kilogram/day. Balance calculated for the year 2003. The stock of the process consumer is according to Table 3: 2,350,000 PCs (or 86,330,000 kg) plus “sales” minus “obsolete”, (rounded off at three and four digits).

sophisticated chain of reuse and refurbishing of personal computers in Delhi. The life spans of 5 and 7 years as scenarios were chosen according to the estimations of these studies.

3.3. Material flow analysis

After the life span of a personal computer has expired, the tracer item enters the “Repair” process. The process chain is characterised by a forward supply chain including the cascade of the tracer good PC through the process chain. The daily input into the “Producer” process accounts for 3712 PCs for the 5 year scenario, and 2609 PCs for the 7

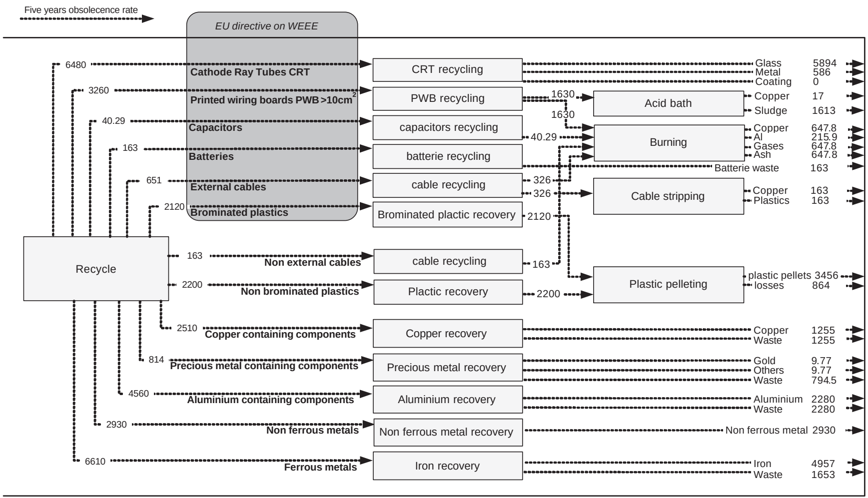

Fig. 3. Material flow of the post recycling processes of the tracer item personal computer within the system border Delhi in kilograms/day. Balance calculated for the year 2003.

year scenario. About 441 PCs are imported daily into the system. This number is a rough estimate of the daily load brought into Delhi from the country or abroad. This import stream feeds into the “Repair” process, which sorts the functioning from the broken items. Five percent of the items produced are rejected and go directly into the “Recycling” process.

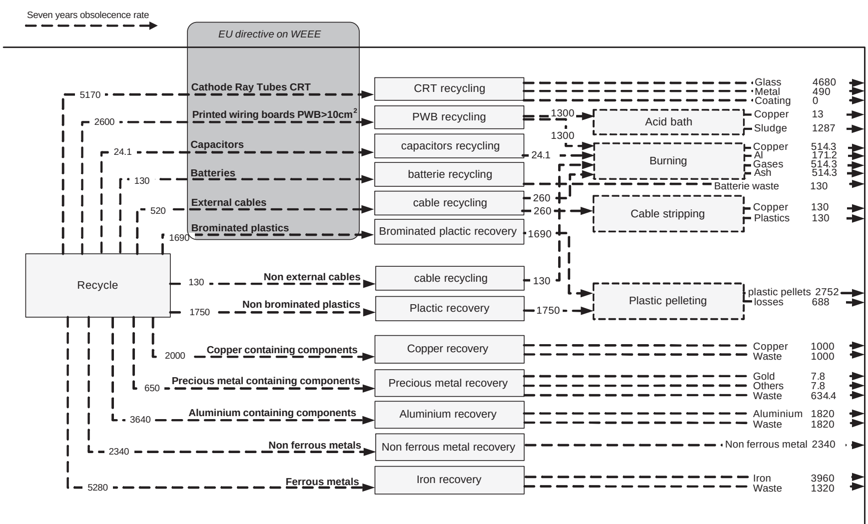

Fig. 4. Material flow of the post recycling processes of the tracer item personal computer within the system border Delhi in kilograms/day. Balance calculated for the year 2003.

The second characteristic is a reverse supply chain, which is of particular interest in counties such as India. The field assessment of this study revealed the existence of a vital refurbishing and upgrading industry, dealing exclusively with used personal computers. The back-log demand of different social strata in developing countries for PCs has fostered an informal industry, which specialises on the refurbishment and upgrade of used items. The numbers of the flow from the "Repair" to "Traders" processes shown in Fig. 2 include the upgrading of PCs with faster processors, increase in hard disc memory or other replacements of whole components. One example is the re-gunning of CRT tubes. This refurbishment includes several manufacturing processes as described above. The output is CRTs which are manufactured to produce unbranded PC monitors and re-enter the market through traders. With a medium weight of 12 kg per monitor the numbers shown in Fig. 2 account for 325 (7 years) and 398 (5 years) re-gunned CRTs per day. The field data of the discovered daily re-gunning rates are slightly lower (300–350) than these calculated data (Table 5). The reuse of components (flow from "Reuse" to "Traders") depicts the recycling of components—such as IC processing chips, memory cards, capacitors or other individual components—which enter the market by being sold after having their functionality checked.

The post recycling processes showed in Figs. 3 and 4 list the fractions of WEEE which have to be separated from the waste steam according to the EU directive on WEEE. The fractions have been calculated according the literature sources. Whereas the Minnesota report on recycling practices for used electronics (Minnesota Office of Environmental and Assistance, 2001) provided information on the total fractions of plastics in PCs, ToxicsLink (2004) provided information from the Handy and Harman Electronic Materials Group on the total material composition of PCs. Richter et al. (1997) measured the content of components in and the medium material composition of printed wiring boards (PWB). The IRGSSA (2004) report calculated the medium weight of a PC monitor and the share of that comprised by cathode ray tube glass. The Indian specific recycling processes discovered during the field survey are indicated.

The manner in which the Indian recycling system deals with these fractions is illustrated in the following graph. By comparing the EU requirements to the existing recycling processes in Delhi, it may be noted that the Indian recycling system already complies with a regulative instrument such as that of the directive. The reason for and goal of this comparison is to draw attention to the general lack of clear guidelines for the management of WEEE and the presumption that some practices of informal industries in developing countries already conform to legal requirements. For example, the recycling of plastics in India separates all sorts of different plastics, produces plastic pellets and feeds them into the plastic industry. These markets are particularly dependent on the current price of plastic pellets or raw materials for the plastic producing industry. Nevertheless a sound system of recycling plastics was observed during the field survey of this study.

The largest material flow for the tracer item PC occurs within the CRT recycling and produces CRT glass (5984/4680 kg/day), (amounts for the 5/7 year scenario are given in brackets, note from the editors). Current glass recycling in India does not consider the hazardous substances contained in CRTs' coating. The glass from CRTs is fed into a secondary glass market. Glass containing heavy metals and other contaminations enable the melting of glass at a lower temperature and is therefore welcomed by second-rate glass manufacturers.

Plastics constitute the third largest flow (3456/2752 kg/day). This amount in addition to the amount of burned plastic in the system adds up to the total amount of plastic in a PC. Halogenated plastics are of particular environmental and human toxicological concern; examples of them include: PCBs (polychlorinated dibenzo-*p*-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs)), substances with similar properties such as polybrominated biphenyls (PBB), polybrominated diphenyl ethers (PBDEs) and tetra-bromobisphenol a (TBBP-A). PCBs are very persistent in the environment since they are very resistant to biodegradation. In addition, they are fat soluble, and tend to accumulate in organisms, with those highest in the food chain being most affected. Heating and burning of materials containing PBBs, PBDEs and other brominated flame retardants can produce polybrominated dibenzo-*p*-dioxins and dibenzofurans, which have similar toxicological effects similar to those of chlorinated dioxins (WHO, 1998). Halogenated plastics are flame retardant and abundantly used in electronic consumer products. The process of plastic recycling has to be assessed in a more detailed manner in order to estimate environmental impacts; nevertheless the fate of the plastics after they leave the system has to be included if the overall burden is to be properly evaluated.

The metal fractions of the recycling process are iron (4957/3960 kg/day), aluminium (2280/1820 kg/day), copper (1255/1000 kg/day) and precious metals (19.54/15.6 kg/day). These fractions are probably recycled in smelters, as they either form a large flow or contain valuable materials. The nonferrous metals are a mixed flow of a whole range of metals. In the order of prominence this flow contains lead, zinc, tin, nickel and others. This flow needs further examination, as the study revealed no information of the future fate and behaviour of these metals.

3.4. Economic aspects of the MFA

The economic analysis of the recycling system revealed the following information: The monetary flows of the pre-recycling processes are much greater than those from the post-

Table 6
Economic evaluation of the refurbishing or upgrading processes

Scenario	INR/refurbished or upgraded items (min. and max.)	$/item	$/day
Monitors			
5 years	6000	137	54,595
5 years	9000	206	81,893
7 years	6000	137	44,582
7 years	9000	206	66,872
PCs			
5 years	10,000	229	40,466
5 years	15,000	343	60,700
7 years	10,000	229	33,150
7 years	15,000	343	49,726

Table 7
Economic evaluation of the material recovery of the recycling processes

Scenario	Recovered material	$/kg	$/day	%	%
	Gold				
5 years	9.77	13,721.93	13,4063	81.97	
7 years	7.8	13,721.93	10,7031		85.07
	Silver				
5 years	9.77	228.27	2230	1.36	
7 years	7.8	228.27	1781		1.42
	Aluminum				
5 years	2280	1.95	4444	2.72	
7 years	1820	1.95	3547		2.82
	Copper				
5 years	1255	3.39	7070	4.32	
7 years	1000	3.39	5624		4.47
	Scrap				
5 years	4957	0.10	496	0.30	
7 years	3960	0.10	396		0.31
	Plastic				
5 years	3456	1	3456	2.11	
7 years	2752	1	2752		2.19
	Glass				
5 years	5894	1	5894	3.60	
7 years	4680	1	4680		3.72
Sum of 5 year scenario			163,547	100	
Sum of 7 year scenario			12,5811		100

recycling. This is hardly surprising, as a functional PC has a value far greater than the value of its material, no matter whether new or second hand. The “upgrade” flow from “Repair” to “Traders” results in a considerable monetary flow. These monetary flows have to be handled with caution, as they only refer to the surplus obtained from sales of refurbished or upgraded PCs or CRT monitors. Costs for additional components, wages, packing and transport costs have not been included in this calculation. In order to calculate the value added to the recycling system through upgrading and refurbishing, the exact input of all intermediate costs have to be considered. For this, a more detailed economic data inquiry is necessary.

The extent to which revenue can be gained by upgrading PCs depends upon several factors. The age of a computer, its brand, processor and general condition are just of the many factors which influence the second hand market in India. The value of a used computer also depends on the cost of new computers, which currently range from 15,000 to 20,000 Indian Rupees (INR) for a PC of 2.4 GB. The rough cost of second hand computers (up to 2–3 years old) ranges from approximately 2000–3000 INR for a monitor, 6000–9000 for a control unit (CPU) and 2000–3000 for a printer (authors’ own investigations). The overall revenue generated by the process “Repair” (by means of refurbishing and upgrading monitors and PCs) ranges from 40000 to 80000 US dollars (USD) per day for the 5 year scenario, and from 30000 to 70000 USD for the 7 year scenario (Table 6).[1] The scenarios have been calculated for monitors and PCs, as the field

[1] Calculated on the 8th of April 2005 with international exchange rates.

study only provides an estimate for the daily rate of refurbished CRTs. One can suppose that for each CRT refurbished one monitor will re-enter the market. The calculation of the refurbished or upgraded PCs was carried out accordingly. Employment created through refurbishing and upgrading has yet to be analyzed in full.

The largest material flows of the post recycling system do not correlate with the monetary flows. The greatest monetary value of the material recycling is created by the precious metal content of personal computers. If one assumes that half the precious metal flow constitutes gold and the other half silver, these material recoveries would generate 134,063 / 107,031 USD for gold and 2230/1781 USD for silver per day.[2] The value of gold would account for more than 80% of all the material recovered during the recycling processes (Table 7). Profits from sales of nonferrous metals have not been included in this calculation.

4. Discussion and conclusions

The refurbishment and upgrading of PCs and monitors constitute one of the key drivers of the pre-recycling processes. However the calculation of the monetary flow is only based on the market value of the upgraded or refurbished items. This scheme comprises one of the most effective mechanisms to: (i) create additional value and (ii) to prevent an accelerated flow rate through the whole system. The incentive is the increasing need for low cost personal computers among the ever-increasing group in the Indian population that uses computers. This market demand creates jobs and business in a second hand industry and at the same time decreases the overwhelming load of PC waste.

The precious metal flow is one of the key economic drivers of the system. The high material value of gold and concentrations of this metal of up to 4 g per PC create strong incentives to recover this material fraction.

The study has shown that the main material flows for the recycling processes split into glass, plastic and metal fractions. The glass fraction creates little economic incentive, as the material is extremely cheap and cannot be used for high quality products without better separation techniques. In terms of volume, however, the glass fraction outweighs all other flows.

Similarly, the plastic recycling creates raw materials for other industries, but does not gain in quality or price. Although the selling price of recycled plastic pellets depends on the cost of primary plastic production—and hence on fossil fuel prices, the study reveals the existence of effective plastic recycling for several different plastic fractions.

The metal flows split into ferrous metals (the second largest group of the whole system), aluminium, copper and mixed and precious metal flows. The first three flows most likely go to specialised smelters, as the material can be regained quite easily during such processes. The considerable amount of these flows will certainly be of interest to the smelting industries, although the overall generation of value through copper, iron and aluminium recovery contributes less than 10% to the value added.

[2] Calculated on the 30th of March 2005 with international trading prices.

The fact that lead is potentially environmentally hazardous means that a future examination of the mixed metal flow must be undertaken, especially as lead constitutes a large fraction of this flow. Another metal of potential interest in this flow may be nickel.

Although the data base was not optimal, the methods applied in this study (such as the combination of a systematic analysis of material flows and economic values, as well as the field assessment) showed the potential to generate robust results. To develop a concise economic model of the whole MFA, detailed economic data on the informal industry will be required.

The model created allows the researcher to plan future assessments in a more focused way. Another research step will be the development of a dynamic model. Such a dynamic model would make the integration of data possible to describe (i) the continuously changing material composition of EEEs and (ii) the different life spans of EEEs, including changes in consumer behaviour.

The results of this research will be fed into the "Indo–Swiss–German national WEEE project" in India. In addition to this study, a research partnership project has been established among the University of Cape Town, the Bangalore based NGO "Resource Optimisation Initiative", the Swiss Laboratory for Materials Testing and Research, St. Gall, and the Federal Institute of Technology, Zurich. This study will contribute substantially to the further development of the model, as well as a monitoring tool for WEEE management and recycling.

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