# Material flow and economic analysis as a suitable tool for system analysis under the constraints of poor data availability and quality in emerging economies

Clean Techn Environ Policy (2007) 9:325–345
DOI 10.1007/s10098-007-0114-7

ORIGINAL PAPER

# Material flow and economic analysis as a suitable tool for system analysis under the constraints of poor data availability and quality in emerging economies

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Received: 20 October 2006 / Accepted: 27 August 2007 / Published online: 21 September 2007


**Abstract** Waste from electrical and electronic equipment or e-waste is increasingly processed in transitional or developing countries. The waste originates from both national consumption and waste imports. In these countries the e-waste processing and recycling is managed almost entirely by informal recycling businesses. Due to the application of inappropriate techniques, this sector bares high risks of environmental and occupational hazards and also looses valuable materials. Formal recycling industries have to compete with the informal businesses and simultaneously comply with environmental and occupational regulations. The presented model applies a dynamic stock-driven material flow model and an economic evaluation of gold and copper flows to the Indian personal computer (PC) recycling sector. The metal concentration per PC and value of these metals mainly determine the profits for recyclers. The study introduced threshold values for formal and informal gold and copper recycling according to their recycling cost per PC. At present level of metal concentration per PC and metal prices the formal sector will not become active. Two scenarios, one with double metal prices and a second with reduced threshold values for formal recycling, have been calculated. Also under theses scenarios the formal recycling sector will not overtake a majority of the recycling. The model proves that a stock-driven dynamic material flow model can be combined with an economic evaluation of material flows. The analysis included a calculation of error propagation and a sensitivity analysis.

**Keywords** E-waste recycling · Personal computer · Stock-driven · Dynamic model · Consumer stock · Mathematical material flow analysis (MMFA) · India

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**Abbreviations**

| | |
|---|---|
| BAT | Best Available Technology |
| EEE | Electrical and electronic equipment |
| ITOPS | Indian IT hardware market study |
| ICT | Information and Communication Technology |
| IMRB | International Market Research Bureau |
| ITU | International Telecommunication Union |
| MAIT | Manufacturers Association for Information Technology |
| MFA | Material flow assessment |
| MMFA | Mathematical material flow assessment |
| PC | Personal computer |
| SWICO | Swiss Association for Information, Communication and Organisational Technology |
| WEEE | Waste of electrical and electronic equipment |

## Introduction

In the last decade the number of personal computers (PCs) sold increased continuously to more than 210 million in the year 2005. Such appliances will eventually become obsolete and enter the waste stream. PCs contain first, valuable materials for recovery and recycling and second, hazardous substances which run the risk of being toxic to humans and the environment if not handled properly. The focus of this paper is on these two important problems. In Europe, a number of different recycling systems for waste of electrical and electronic equipment (WEEE) have been put in place, motivated by the EU directive on WEEE (EU 2002). This directive obliges EU member states to install a recycling system for electrical and electronic equipment (EEE) with the objectives of (a) reducing the quantity of WEEE that goes to landfills, (b) increasing the recovery, reuse and recycling of WEEE, and (c) mandating extended producer responsibility for the whole life-span of EEE. The directive has been in force since August 2004 and continues to dictate implementation beyond the original deadline of August 2005. Similar WEEE recycling systems can be observed, such as in Japan and several USA states. Moreover the EU directive on reduction of hazardous substances bans the use of lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE) and stipulates the substitution of hazardous containing components for safe or safer materials where technically/economically feasible. Thus, this directive is of greater international relevance than that of the WEEE Directive, as producers will not be able to import products to Europe before having proved that they have not used any of the mentioned substances.

Many emerging economies; however, have not yet started to install WEEE recycling systems. One hindrance for the setting up of such systems is that the dominant informal economies in WEEE recycling do not comply with regulations for preventing damages to human health or the environment. (Puckett et al. 2002; ToxicsLink 2003, 2004; Puckett et al. 2005). Although low labour costs in the informal economy result in optimised recycling activities in terms of economic profit, such recycling activities cause a multitude of environmental and human toxicological effects. Many independent publications have recently devoted much attention to the subject of uncontrolled WEEE recycling, which was brought to light by the research undertaken by non governmental organisations (Puckett et al. 2002; Steiner 2004; Brigden et al. 2005; Hicks et al. 2005; Keller 2006; Wong et al. 2006, 2007). Pressure from international regulations, such as the Basel Convention (1989) and environmental activists (e.g. The Basel Action Network, Silicon Valley Toxics Coalition, and Toxics Link) does encourage developing countries to improve their WEEE recycling systems but, as yet, little progress has been made.

A number of studies on production, use and recycling of WEEE using Material Flow Assessment (MFA) have estimated the future amount and composition of WEEE (EEA 2003). In addition, Life Cycle Assessment and Life Cycle Costing are used to evaluate regulations of WEEE recycling (Huisman 2003; Williams and Sasaki 2003). Several studies applied models that estimate future WEEE generation. From the information gained from collected sales data over a period of several years and assumptions about the medium life spans for different categories of EEE, they estimate the volume of WEEE in the future (Matthews et al. 1997; Matthews and Matthews 2003; Jain and Sareen 2006). An overview is given in Lohse et al. (1998). However, an input driven model does not describe correctly the cause effect relations underlying the demand for durables such as electronic devices. Input driven approaches are appropriate to describe expendable goods like food or cosmetics, which are characterised by a short period of life span (days, weeks), while they deliver the intended service. The reason is that consumers use a certain amount of an expendable good per time, i.e. they determine the input of the good into use. In contrast, durable goods which provide a service during a longer life span (years) have to be modelled by a stock driven approach. For durable goods, consumers are interested to have continuous access to a certain amount of those, i.e. they determine the stock. The input representing stock increase and replacement is determined according to the life span of the good.

In this paper we will introduce a dynamic MF model for PCs in India that is driven by the development of the stock of PCs in households and industries. This model aims at better understanding the driving forces behind the generation of WEEE in India and the decisions made concerning specific pathways of WEEE recycling. To achieve a system understanding and collect data systematically, the following questions to be answered are:

- What are the main characteristics of WEEE systems in emerging economies and how can an appropriate model best represent them?
- What forces drive WEEE systems in emerging economies?
- What do we learn from model calculation about the design of a data collection scheme for future studies?

Such a model approach assumes future stock developments as well as the development of certain key parameters such as commodity prices, material composition and the weight of PCs. Such assumptions may seem somewhat arbitrary; yet they have been set making conservative assumptions about the stock development as well as the material prices. The assumed stocks describe a bottom line for the minimum stock of PCs reached in 2050. For the first assumption, the material prices remain at their present levels—a conservative prediction if we take into account the recent rise of metal prices.

The time horizon 2050 was chosen in order to go beyond the trend development of recent years which frequently tend only to look at the very near future. The suggested model implies both a stock driven approach for medium and long lived consumer goods as well as a recycling model determined by technological and financial parameters.

Unfortunately, little data on the current WEEE recycling systems in India is available. The actual in-use stocks of EEE have hardly been assessed and the illegal imports of WEEE cannot be quantified, as those active in this business always find ways to mislabel or hide container loads. The whole recycling sector in emerging economies is dominated by the informal business sector, which typically does not use standardised accounting tools. Only the sales figures and import statistics collected provide any sort of systematic data. This study will bridge the gap between the lack of reliable information and the need to systematically assess the present and the future situations.

The paper is structured as follows. In "Methods", the material flow modelling is introduced as method of investigation. The section "System analysis for metal recovery from obsolete PCs in India" provides a description of WEEE recycling in India with special emphasis on PCs. The section "Model description" shows how the studied system is represented in a material flow model for India. In "Application of model", this model is used to calculate different scenarios for the future development of the Indian WEEE system, whilst the final section is devoted to discussion and conclusions.

## Methods

The method applied to support the material and substance flow management of WEEE is the MFA. MFA is a method to analyse material 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: (a) Substance flow assessment (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 and Bader 1996; van der Voet 1996; Spatari et al. 2003; Vexler et al. 2004), (b) Process-based MFA, which is primarily used to analyse specific questions on resource and waste management (Baccini and Bader 1996; Bringezu 2000a) and (c) Industry-based MFA, which is a tool used to assess the environmental impact of economic development by analyzing the total material throughput of a system (Adriaanse et al. 1997; Matthews et al. 2000; Bringezu 2000b; Daniels 2002; Daniels and Moore 2002).

In this study, a process-based MFA is applied. This method was chosen for its ability to give a systematic overview of the system by describing and simulating the material flows of the whole system, including the flows at the sources and not only the emissions to the environment. Therefore this method is suitable for "early recognition": by considering the flows at the sources it is possible to "act" and not only to "react" if emissions exceed the thresholds. The process-based MFA links material flows (resources as well as waste) to consumer needs, economic structures or technological development and has been used traditionally to describe the current state (Baccini and Bader 1996a; Baccini and Brunner 1991; 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). This method taps into its full potential by applying a mathematical formulation and modelling as suggested by (Baccini and Bader 1996b). In the last 10 years mathematical MFA's called MMFA have been applied in numerous studies in different fields: (Real 1998; Kohler et al. 1999; Zeltner et al. 1999; van der Voet et al. 2000; Johnstone 2001; Bader et al. 2003; Hedbrant 2003; Sörme 2003; Hug et al. 2004; Müller et al. 2004; Schmid et al. 2006; Kwonpongsagoon et al. 2007; Bader et al. 2006; Hilty et al. 2006) and others and ongoing works, respectively.

## System analysis for metal recovery from obsolete PCs in India

The analysis of the WEEE recycling system in India aims to describe and understand the material flows linked to the use of PCs, including their main driving forces. The first step is an analysis of the system. It is used to define the system (see "System analysis"), select indicators to depict its specific behaviour (see "Selection of indicators") and define evaluation criteria to assess the system's performance (see "Evaluation criteria").

### System analysis

The system was defined based on the PC process chain of consumption, trade and recycling activities. However, this system definition can vary under different business environments. To assess the specific characteristics for the

Indian WEEE systems, we reviewed literature and documents and carried out a field study in Delhi—including non-participatory observations and interviews. These field studies were done in close cooperation with local partners.

The system consists of the following processes (see Fig. 1), defined according to the functions they provide.

*Consumption*

As it is well known, PCs are in industries, business, and private households. In India we observed a rather large market for second hand PCs or PC components. PCs are thus used for a long period of time—by different users—and a large variety of different PC types are in use (Streicher-Porte et al. 2005). This cascade use is brought about by large differences in income between the different social strata in Indian society. The Indian business sector and rich Indian households can afford to buy the newest PC types that are replaced after a certain lifetime. These will still be very attractive for lower income groups, after which, yet poorer people will take them on, despite their being out-of-date. These patterns of consumption in a society can be described as a "cascade use" (see Binder et al. 2001; Matthews and Matthews 2003; Peralta and Fontanos 2006).

*Trade*

This process includes collection, transport, reuse and segregation of waste PCs. PCs are replaced for different reasons such as operational failure or insufficient performance. Replaced PCs are collected by private enterprises or public services. Collectors transport and distribute these items to either reuse, dismantling or waste treatment. In dismantling, various components in a PC are separated, such as printed circuit boards, cables, plastic and metal casings, etc. These components are traded on, either for reuse or for recycling.

In India, the waste collectors from households are called "raddiwallahs". They pay the owner of the waste and sell the collected waste to specialised second hand traders or recyclers, making their living from the minimum profits gained. This profession lies between formal and informal business. Another major source of replaced ICT equipment is the auctions, in which equipment from business, industries or state organisations are sold. Private enterprises bid for offered ICT equipment and have to make revenues from reuse of whole units or components, or from material recovery.

*Recycling*

Recycling consists of pre-processing of PC components, material recovery, energy generation and final deposition. There is a large variety of technical processes that can be used for recycling. Developed countries tend to apply capital intensive processes such as metal smelting with appropriate waste treatment. In India, however, almost all recycling of PC components is carried out by small enterprises using processes with low capital costs and not complying with state regulations regarding taxation, environmental protection or safety standards. Certain preliminary studies have shown that uncontrolled WEEE recycling is a risky business for recyclers themselves, both in the immediate vicinity of the recycling locations and in areas further away, especially when emissions are carried by air or water (Steiner 2004; Toxics Link 2004; Brigden et al. 2005; Saahas 2005; Toxics Link 2005). To represent this phenomenon in the MFA system definition, we differentiate between informal and formal recycling. These terms are further specified in "Evaluation criteria".

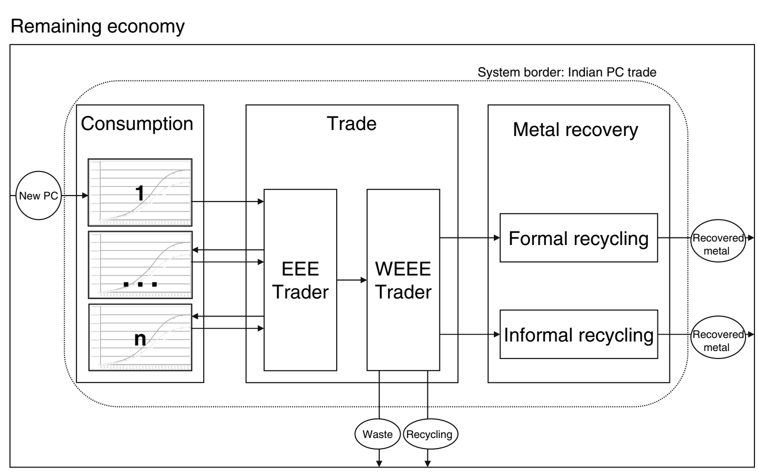



**Fig. 1** Personal Computer (*PC*) recycling in India, system definition

Figure 1 shows the system definition in detail. The cascade use is captured in the subsystem "Consumption" with *n* processes each including a stock of PCs in use in a specific age group. The PC supply comes either from domestic production and imports or from the second hand market. Imports of PCs are, therefore, represented in the individual stock developments as long as reliable data is available. When PCs are no longer used–later called PC scrap—they are collected by EEE traders (second hand market) who decide over reuse of still functional units and sort out obsolete PCs to WEEE Traders. WEEE Traders dismantle PCs and sell the components to specialised recyclers, who carry out the final material recovery. However, the international trade of PC scrap—whether imported illegally or legally—is not considered in the model. Thus, the waste volumes of obsolete PCs considered in the recycling model are generated by the consumption model. This is due to the fact that waste generation from national EEE consumption in countries with a fast growing economy outnumbers the volume of imported WEEE. Refurbishment activities involving the reuse of whole PC parts or individual components are not represented in the system definition. Such activities do, however, take place, but go beyond the scope of this model. The analysis of the recycling processes focuses on metal recovery of copper and gold. All PC components including sufficient amounts of copper and gold are sold to processes in the subsystem "Recycling" by the WEEE Trader. The remaining components are either recycled (e.g. glass, plastics) or deposited in landfills. The subsystem "Recycling" is further differentiated between recycling processes in the formal and in the informal economy as mentioned above (see "Evaluation criteria").

## Selection of indicators

In MFA, indicators are selected for the following reason: to analyse pathways of certain substances through an economy. For example, it can be sufficient to select one specific substance whose behaviour in chemical reactions is representative for a whole group of other substances. Baccini and Brunner (1991) generalised this idea by suggesting that indicator substances or goods can be selected not only for chemical reactions but also for resource management in general: carbon, for example, can be used as an indicator for biomass consumption; phosphorus serves as an indicator for food.

In our analysis, we follow this idea and select copper and gold as indicator substances for WEEE recycling. This choice is motivated by the high material value of copper and gold in PCs. A first rough estimate is given in Table 1. Currently, recovery of copper and gold are the two main sources of income for recyclers (Streicher-Porte et al. 2005). WEEE recycling activities are therefore very sensitive to the magnitude of gold and copper flows originating from PCs.

**Table 1** Material composition, metal prices and maximum expected revenues

| | Percentage (%) | Gram/PC | US$/kg | Maximal expected revenues (US cent) |
|---|---|---|---|---|
| Ceramics and fiber | 6.8 | 838 | – | |
| Plastics | 13.0 | 1,600 | – | |
| Iron | 66.2 | 8,160 | 0.1 | 41 |
| Aluminium | 6.6 | 813 | 1.9 | 152 |
| Copper | 6.5 | 801 | 3.6 | 287 |
| Lead | 0.2 | 25 | 1.0 | 2 |
| Zinc | 0.1 | 12 | 1.5 | 2 |
| Tin | 0.3 | 37 | 6.2 | 23 |
| Nickel | 0.1 | 12 | 14.9 | 18 |
| Other metals | 0.2 | 25 | – | |
| Gold | 24[a] | 0.30[a] | 14.3[b] | 423[b] |
| Silver | 107[a] | 1.32[a] | 0.2[b] | 31[b] |
| Palladium | 9[a] | 0.11[a] | 6.5[b] | 72[b] |
| | 100.0[a] | 12,320[a] | | |

Nonferrous metal prices: http://www.lme.co.uk accessed on 26 October 26 2005

Ferrous metal prices: http://www.meps.co.uk accessed on 11 January 2006

[a] Values are given in ppm

[b] Values are given in US$/g

## Evaluation criteria

Evaluation criteria are introduced to evaluate whether a certain development is preferable to the status quo or not. In this study, the evaluation focuses on issues of environmental protection and resource conservation. Comparable analyses often use evaluation criteria which try to capture the system's impacts on the environment (e.g. Huisman 2003). This was, however, not possible in our study as data collection in informal WEEE recycling businesses is very difficult. Informal recycling processes have not, as yet, been quantified or described in any kind of detail. Emissions have equally not been measured, nor the degree of and consequences of human exposure to the different processes involved. The great number of enterprises active in trading and recycling, as well as the variety of practices used, makes such a task impossible. In addition to this, it is difficult and even dangerous to collect data in the informal economic sector which dominates WEEE in India today.

We, therefore, use system-orientated criteria as suggested by Bringezu. Such criteria indicate the deviation of present systems from a desired system or from one which should be prevented (Bringezu 2000b). In the case of WEEE recycling, two main requirements have to be met: a material recovery rate as high as possible and an appropriate waste treatment ensuring damage prevention for human health and the environment. The first evaluation criterion, therefore, is material recovery. We consider the choice of a WEEE strategy to be preferable, if material losses are to be kept as low as possible. In our system definition, material losses are represented by the flow of material from the WEEE Trader to landfills.

The second evaluation criterion is not as evident because the environmental sound treatment of the waste stream is much harder to assess. There is strong evidence that informal recycling as it is currently practiced is neither environmentally compatible nor harmless for health.

Indeed there are numerous studies showing that there are uncontrolled emissions and risks for health caused informal recycling techniques such as open burning of the burning of cables and printed circuit boards (Steiner 2004; Brigden et al. 2005; Wong et al. 2007), roasting of printed circuit boards over burners for component separation or for solder recovery (Brigden et al. 2005; Wong et al. 2007), toner sweeping, plastic chipping and melting, burning wires to recover copper, heating and acid leaching of printed circuit boards (Leung et al. 2006), gold recovery from printed circuit boards with cyanide salt leaching or nitric acid and mercury amalgamation (Keller 2006), and manual dismantling of cathode ray tubes and open burning of plastics (Puckett et al. 2005; Jain and Sareen 2006). Therefore the current informal recycling should be replaced by recycling techniques preventing damages to human health and the environment. Clearly formal recycling has to be done according to global Best Available Technology (BAT) standards. For metal recovery these are, for example, complex metal refining plants combine the capabilities of a smelter, refinery, recycling plant or other specialised metal-recovery process into one integrated facility. Such integrated metal smelters are capable of recycling nonferrous metals and precious metals, not only from ore-concentrates or metallic scrap but also from mixed metal concentrates, metal–plastic mixtures and compound material such as printed circuit boards (Hagelüken and Kerckhoven 2005).

The equations "informal = hazardous" and "formal = BAT", however, are rather crude assumptions that will have to be verified and adapted in future. Only recently, the Karnataka State Pollution Control Board approved E-Parisaraa as the first officially recognised WEEE treatment plant. The company has been audited and certified for ISO 14001 standards and independently certified by several multinational companies. An ongoing research project will deliver first results on the performance of this process (Keller 2006). Yet, no data is available up to now. So far the argumentation was only concerning environmental and health standards. Another important aspect is that the informal recycling is the basis for life of a lot of people. The transition from informal to formal recycling should not destroy their basis for life. How this can be done is a difficult question. One way could be to employ such people in formal recycling companies.

## Model description

MF models are based on balance equations for each process in the system and model equations describing the system behaviour. In our model, we assume that the system of WEEE recycling for PCs in India is basically driven by two processes. First, consumption provides the input into the trade and recycling processes (see "Consumption"). Second, the WEEE Trader determines the pathways of PC waste through the process chain of recycling activities (see "WEEE Trader"). Both EEE trade and metal recovery process a given input and deliver their products to the subsequent processes according to the current standards. We therefore focus the model description for consumption and WEEE Trader and refrain from giving all equations for the processes shown in Fig. 1.

The model is generally defined for three different levels of analysis: material flows of PCs and substance flows for copper and gold. The substance flows are derived from the mass flows as follows: (1) each mass flow has to be subdivided into "age-subflows" according to their age. (2) These "age-subflows" have to be multiplied with the corresponding concentration of gold and copper in order to give the corresponding "substance-age-subflows". (3) These flows have to be summed up resulting in the substance flows. However, the substance flow systems are not only "derived systems" following the system behaviour determined by PC flows. They also influence the system behaviour by their own means by determining the activity levels of metal recovery processes (see "WEEE Trader"). In the following subsections, we provide a general description of the model not differentiating between the different levels of analysis.

### Consumption

The consumption $I$ is described by the three variables Input $I_i(t)$, Output $O_i(t)$ and stock $M^{(i)}(t)$.

The demand for PCs (inputs) and the amount of obsolete PCs to second hand and recycling markets (outputs) are determined by the development of the PC stock in use over time, the medium life-span of PCs in use and the entrance age into the successive PC stock.

The mathematical formulation of this stock driven approach is as follows:

Stock for PCs:

$$M^{(i)}(t) = P^{(i)}(t) \tag{1}$$

Balance equation:

$$\dot{M}^{(i)}(t) = I_i(t) - O_i(t) \tag{2}$$

Replacement of PCs:

$$O_i(t) = \int_0^t k_i(t,t')\, I_i(t')\, dt' \tag{3}$$

$P^{(i)}(t)$ is the stock (number of PCs) in class $I$ at time $t$.

$k_i(t,t')$ is the transfer function or life-span distribution of the PCs in class $I$, installed at time $t'$ and replaced at time $t$.

We assume the life span of each stock to be distributed following a Gaussian function, namely: (see Fig. 2)

$$k_i(t,t') = \frac{1}{N_0^i(t')} e^{-\frac{(t-t'-\tau(t'))^2}{2(\sigma(t'))^2}} \tag{4}$$

$\tau(t')$ is the medium life-span of PCs of class $I$, put into operation at time $t'$

$\sigma(t')$ is the standard deviation (SD) of the life-span of PCs of class $I$, put into operation at time $t'$. $N_0^i(t')$ is the normalisation factor.

This life-span distribution has been discussed in detail in Baccini and Bader (1996) and applied in many case studies (Zeltner et al. 1999; Hug et al. 2004; Müller et al. 2004; Bader et al. 2006).

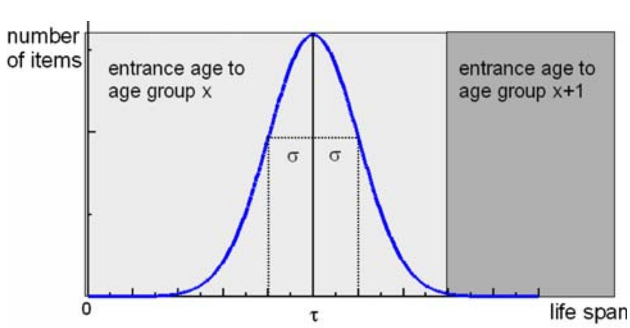



**Fig. 2** Gaussian function of life-span distribution for age group "x" and entrance age to the subsequent age group "x + 1"

These three parameter sets are given for each PC stock, 1,…, $n$.

The PC stock development $P^{(i)}(t')$ as well as the life-span distribution $k_i(t,t')$ have to represent adequately time series of the past for stock development and input flows. Clearly these time series for the past do not determine uniquely the parameter functions $P^{(i)}(t)$ and $k_i(t,t')$. In addition, assumptions on the future behaviour have to be used. Of course many different strategies are possible: linear growth (no saturation of consumer needs), logistic growth (saturation of consumer needs at a given level) and others. The choice of an appropriate parameter function for PCs in India is described in "WEEE Trader". The model in general is able to include different assumptions on stock development.

## WEEE Trader

### *Recycling of copper and gold*

The recycling of PC components containing copper and gold is primarily driven by the amount of money a recycler gains by selling the recovered amount of metal to metal processing industries. This amount is included in the model as "value concentration" per PC defined as product of metal content per PC and metal price. We assume that the metal recyclers will start processing metal containing PC components, once the "value concentration" exceeds a certain threshold value. Obviously, the total number of PCs available for recycling is another import factor. Yet, in light of the fast growing amount of obsolete PCs in India, we refrained from explicitly including such a parameter in our model. In consequence, recycling activity will increase with the growing "value concentrations", until all available PC components have been processed. This behaviour has been simulated using a logistic growth curve as follows (see Fig. 3):

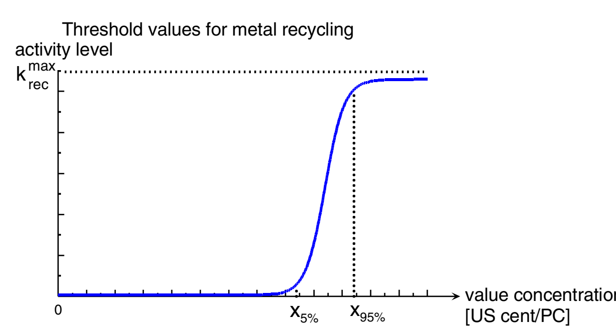



**Fig. 3** Threshold level for metal recycling activities

$$k_{\mathrm{rec}}(x,t) = \frac{k_{\mathrm{rec}}^{\max}}{1 + e^{-\alpha(t)\left(x - \frac{x_{5\%}(t) + x_{95\%}(t)}{2}\right)}} \quad (5)$$

where

$k_{\mathrm{rec}}^{\max}$ is the maximum recycling rate

$x_{5\%}(t)$ is the value concentration for 5% of maximum recycling at time $t'$

$x_{95\%}(t)$ is the value concentration for 95% of maximum recycling at time $t'$

Mathematically $x_{5\%}$ and $x_{95\%}$ are defined as follows:

$$k_{\mathrm{rec}}(x_{5\%}(t), t) = \frac{5\%}{100\%} k_{\mathrm{rec}}^{\max}. \quad (6)$$

$$k_{\mathrm{rec}}(x_{95\%}(t), t) = \frac{95\%}{100\%} k_{\mathrm{rec}}^{\max}. \quad (7)$$

Thus the threshold values always consist of a pair of numbers describing the activity of the relevant recycling sector, starting with lower value (5%) and going up to the saturation value (95%). Between these ranges, the recycling sector becomes active.

Value concentrations are given in US cent/PC.

From Eq. (5) and the definition of $x_{5\%}$ and $x_{95\%}$ follows for the reciprocal growth factor $\alpha(t)$:

$$\alpha(t) = \frac{2}{x_{95\%}(t) - x_{5\%}(t)} \log\left(\frac{95\%}{5\%}\right). \quad (8)$$

We assume that formal and informal recycling rates can be described by such a logistic threshold function. The threshold values for informal recycling are lower than for formal recycling, as informal businesses can start their activity with almost no investment. Informal recyclers will be the first players on the market, but, with growing value concentrations, formal recyclers will eventually follow. When both informal and formal recyclers are active, we assume that formal recyclers have superior assess to supply of obsolete PC components. Consequently, the model gives priority to formal recycling.

In addition, a maximal recycling rate is introduced to represent material recovery of gold and copper. Material recovery from obsolete PC components depends on (a) effectiveness of collection of recyclable material and (b) the technically determined recovery rates in material recovery processes. The parameter $k_{\mathrm{rec}}^{\max}$ in Eq. (5) expresses the technically determined recovery rate. A further parameter is introduced to capture the effectiveness of the collection system for both formal and informal recycling. It shows the share of all obsolete PCs available for recycling. This parameter is not represented in Eq. (5).

*Recycling of all other materials*

We further assume that the material recovery rate for the sum of other materials depends on the activity levels of both formal and informal copper and gold recycling. If no gold or copper is recycled, at least plastic casing, ferrous-metal components and aluminium parts are dismantled and transferred to recycling processes. This amount of material is represented by the flow-recycled material. If gold and copper are recovered, an additional amount of material is added to the flow recycled material. This is due to the fact that other materials from PC components containing copper and gold are recycled while copper and gold are recovered, e.g. plastic from cable insulation or ferrous metal from copper coils. Yet, formal recyclers use techniques which are much more effective in recovering other materials than informal recyclers, especially in recovering other precious metals. Additionally, formal recyclers, use non-metal material as fuel and flux material (Hagelüken 2005), which is also considered as material recovery in our model.

Therefore, the total amount of recycling can be seen to have a bottom line, which is the minimum recycling rate and is the same for both recycling practices. The maximum recycling rates depend on the ratio between formal and informal recycling of copper and gold. The transitions from the minimum recovery, with no copper and gold recycling, to the maximum material recovery, with maximum copper and gold recycling, are assumed to be linear.

Mathematically, then, the total recycling rate is a linear function in the four recycling rates for copper and gold of formal and informal recyclers, defined by Eq. (5). Since no data was available we made this assumption as a first approximation.

## Calibration

This procedure aims at finding parameter functions that fit the available data. Obviously this is in general not uniquely possible and not independent of subjectivity of the investigator. However, our choice of parameter functions aims at simplifying the model in an appropriate way to guarantee a minimal set of necessary parameters. In this sense the following parameter functions were found to be most suitable.

Within this study, no research on data has been performed. Instead, data from already existing studies have been used, and only few additional data was collected selectively if necessary.

*Consumption*

*Database* In India, only little is known about the current in-use stock of PCs and its development in the past. Yet, the pervasiveness of IC technology is of general interest, for India as well as on global scale. The International Telecommunication Union (ITU) regularly collects statistical data on this issue (International Telecommunication Union 2006a). A core set of indicators informs about the amount of ICT infrastructure and its access per capita. In the case of India, they serve as unique source of information for the World development indicator: PCs per 1,000 capita, which is used in the study on hand under the term "PC penetration rate" (Gray 2006). The number of PCs includes "PCs, laptops, notebooks, etc., but excludes terminals connected to mainframe and mini-computers that are primarily intended for shared use, and devices such as smart-phones that have only some, but not all, of the functions of a PC (e.g. they may lack a full-sized keyboard, a large screen, an Internet connection, drives, etc.)" (International Telecommunication Union 2006b). To obtain the necessary data, ITU sends out questionnaires to national authorities, generally ministries, regulating authorities or organisations which are mandated to collect ICT data. In India, the information is collected by means of household surveys, which are conducted Ministry of Communication and Information Technology and a subsidiary organisation: the Telecom Regulatory Authority of India (Kumar 2006).

On this basis, the in-use stock of PCs in India is estimated by multiplying the penetration rate of a given year with this year's population. In this study the total population data from the World Bank was used. The data is culled from various sources including census reports, the United Nations Statistics Division's Population and Vital Statistics Report, country statistical offices, and the Demographic and Health Surveys which is coordinated by a private organisation (ORC Macro International Inc.) (World Bank 2006a).

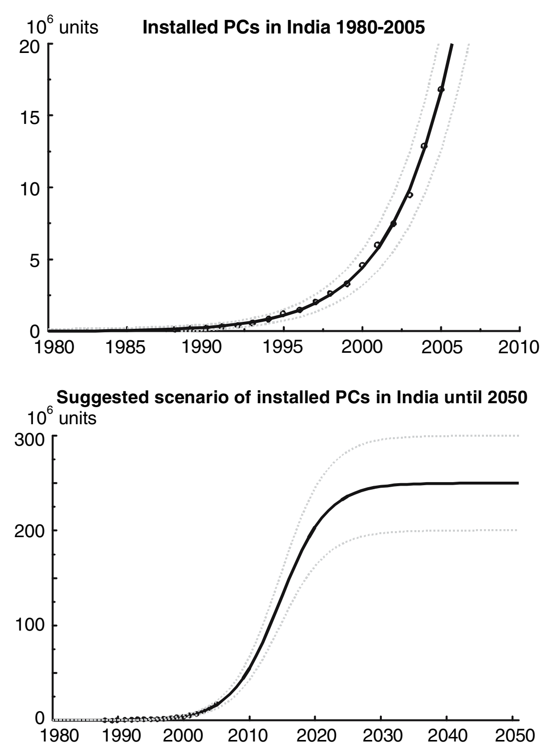
To project the development of the in-use stock of PCs in the future, we use population prospects for India published by the United Nations Population Division. Out of the scenario set given in this publication we choose the projection variant "medium", assuming a medium fertility, normal mortality and normal international migration (World Bank 2006b). Yet, no information is available for the projection of PC penetration rates.

An additional data set for PC consumption in India is available from the International Market research Bureau (IMRB), a market research consultancy offering research services in the filed of telecommunication, office automation, information technology. Since 1999, this organisation carries out the Indian IT Hardware Market Study (ITOPS), a biannual study covering in 2004/2005 more than 20,500 establishments and 35,000 households across 22 cities. ITOPS investigates on the demand side by sending out questionnaires to a selection of businesses and households. The study takes in account the changing patterns of ICT use in business and access to ICT equipment for different social strata. The findings from ITOPS are accepted as the official market performance of Indian IT hardware market by Manufacturers Association for Information Technology (MAIT). The published sales data include ICT equipment from national production, assembly of equipment in India as well as imports form multinationals companies.

Yet, no data is available on the average life span for PCs in India.

*Calibration* Based on this set of data (ITU and IMRB), it is not possible to capture the cascade use of PCs in India as suggested in the system analysis (see "System analysis"). We, therefore, simplify the system by comprising the process "consumption" into one single in-use stock.

We further assume that the development of this stock follows a logistic growth curve (see Fig. 4). Such growth curves are typical for industrial goods. The given data,




**Figs. 4 and 5** Installed PCs in India according to World Development Indicator from 1980 to 2005. Suggested scenario of installed PCs in India until 2050. The level reached in between 2040 and 2050 corresponds with a 150 PCs/1,000 capita saturation rate assuming a medium growth rate of the population

1980–2004, suggest an exponential growth. But obviously, the need for IT services in India will be satisfied at some point in the future. Looking at the number of PCs which have been installed in India since 2005, it can be said that this process is still in an early "growth phase" (i.e. a "turning point" is as yet far from being reached). A non-linear fit of a logistic curve cannot find the saturation volume. Moreover, it is not possible to foresee the accurate level of saturation. Consequently, the assumed stock development does not claim to be a forecast. Rather, the conservative assumption of until 2050 intends to go beyond a trend analysis and draw a bottom line of the least reached Indian PC penetration. Yet, Indian PC penetration rates will hardly reach the level of industrialised countries in the coming decades. We, thus, chose a conservative estimate for the saturation level of 150 PCs per 1,000 inhabitants in 2050, compared to 15.4 in 2005 (see Fig. 5). In comparison, more than 800 PCs are currently available per 1,000 inhabitants in Switzerland. The conservative assumption describes a growth of Indian PCs saturation by a factor of ten until 2050. Any higher PC saturation will affect the stocks but will not disturb the fundamentals of the suggested model. Based on this time series and the assumed saturation level, a curve fit for the following logistic growth curve has been performed:

$$P(t) = p_{\text{init}} + \frac{p_{\text{sat}} - p_{\text{init}}}{1 + e^{-\alpha(t - t_{\text{turn}})}}. \qquad (9)$$

$p_{\text{init}}$ is the initial value in the past, $p_{\text{sat}}$ the saturation value, $\alpha$ is proportional to the maximum growth rate and $t_{\text{turn}}$ is the turning point of the growth curve, respectively. The result of the fit is presented in Fig. 4 and shows that the logistic growth curve fits well the available data. The value 0.275 for $\alpha$ is quite high but not unusual for large growing economies (Bader et al. 2006).

To obtain values for the average life span of PCs in India (mean and SD) the data set for PC sales (IMRB data set) has been fit to the input of PCs into consumption (see Fig. 1). The calculation has shown that $\tau = 8$ and $\sigma = 2$ fit best the available data. This result is presented in Fig. 6. The uncertainties of the growth curve and the life span have again been set at a conservative level, in the sense that the uncertainty range covers all available data for installed PCs and sales data.

*WEEE Trader*

*Threshold values* *Database* We have basically no data on the threshold values for formal and informal recycling of copper and gold containing PC components in India (see "Recycling of copper and gold"). Such information could only be gained by disclosing the profit and loss accounts of WEEE recyclers. Even in industrialised countries, such as Switzerland, such information is not available (Streicher-Porte 2006). In India, data availability is even more restricted: access to informal recyclers is limited and, informal recyclers will most likely not even keep any kind of systematic profit and loss account. Formal recycling, however, has not yet been established in India. Only one pilot plant in Bangalore has been set up (see "Evaluation criteria") and it is yet impossible to judge whether it is representative for formal PC recycling all over India in future.

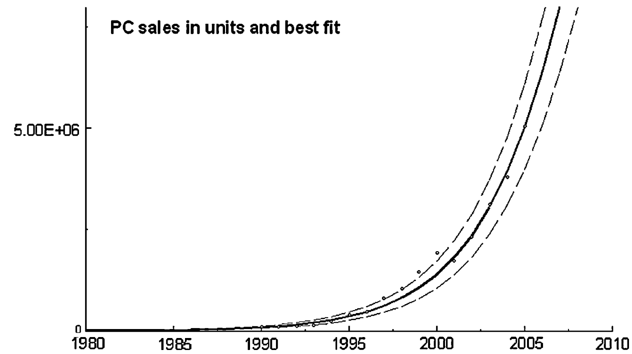



**Fig. 6** Sales data according to IMRB 2005 and best fit of sales with confidence interval

Yet, the prices paid by recyclers for WEEE provide some information about the threshold values. Field surveys and interviews show that the prices paid by informal recyclers per PC vary from 5 to 10 Indian rupees/kg of scrap material. Recyclers do not pay additional costs for collection and transport, organising such services themselves. Hence, the market value of an obsolete PC which enters the informal recycling market as a complete unit varies between one and three US$/PC.[1] For the formal recycling plant in Bangalore, however, the actual costs for the waste material range between 20 and 40 Indian rupees/kg, including costs for collection, packaging and transport. Only scrap from the ICT sector is considered in this calculation (Rochat, personal communication, 2006). Consequently, the threshold level for gold and copper recycling in the formal sector ranges from 560 to 1,120 US cent/PC calculated for a 12.8 kg medium weight from 1997. This value is relatively high compared to the existing recycling costs of the European WEEE systems. According to a study of Hewlett–Packard, European WEEE systems offer recycling prices between 50 and 800 US cent/PC (Martens 2006). This means that some European systems offer recycling at even lower levels than those assumed for the informal sector, and that the upper level of the Indian

[1] Calculated with exchange rates: USD/INR of 45.92 and the USD/CHF of 1.23 on 5 July 2006.

**Table 2** Different literature sources on gold and copper content in PCs

| Source | Huisman (2003) | Hagelüken (2006) | SWICO (2006) | Schischke and Kohlmeyer (2005) | MCC (1996) | SD |
|---|---|---|---|---|---|---|
| Sample size | 20 | Average from 521 entries in 2002 | 500 | 2 | ? | |
| Gold in printed circuit boards | – | 250 ppm | 288 ppm | 360 ppm | – | 56 |
| Copper in PCs | 5.69% | – | 6.12% | 6.21% | 6.93% | 0.51 |

threshold values is above the highest costs of the most expensive European system. The HP study compares very different WEEE recycling systems and also different costs declared by each of the individual systems. In light of this, the comparison should not be stretched too far.

Another source of information is the value concentration per PC that can be interpreted as expected revenues from metal recovery (see "Recycling of copper and gold"). To calculate value concentrations we need data on gold and copper content per PC (mass per unit) and gold and copper prices.

Data for the metal content of PCs has been collected in several studies motivated by issues of WEEE recycling (see Table 2). Therefore, most data for the gold content is given as metal concentration for printed circuit boards rather than per unit PC. Additional data is thus required for the weight of a PC per unit and the relative weight of printed circuit boards in mass percent. Data for PC weight was taken from a study which was conducted on PCs recycled in 2006. It gives a medium weight of recycled PC of 12.3 kg (sample size $n = 500$) (SWICO 2006). The weight of PCs that are currently sold and will enter the recycling markets in the coming years was estimated by additional market investigations carried out by the authors of this paper. It revealed a medium weight of 11.1 kg (sample size $n = 54$). Data on the relative weight of printed circuit boards were taken from SWICO (2006). This study revealed a share of 8.1 mass percent/kg of PC.

Data on gold and copper prices is taken from the London Metal Exchange (London Metal Exchange 2006).

*Calibration* In 2006, almost all recycling activities for PCs were carried out by the informal sector. Informal recyclers seem to operate profitably—even when dealing with very low levels of valuable materials. According to expert interviews, they took care of all obsolete PC available on the WEEE market in the last 15 years which corresponds with an activity level of 100%. Yet, it is impossible to obtain data on the business environment which encouraged informal recyclers to start their business in the past (lower threshold value) or the development of recycling activities before informal recycling reached the maximum activity level.

In consequence, we have to make an "informed guess" on threshold values for informal recycling. We do so by setting the 50% activity of informal recyclers for each metal at the lowest-theoretical value concentration over the last 15 years. This value is determined by the lowest annual gold and copper prices in the last 10 years and the lowest concentration of each metal per PC in this period. For gold, this is 320 US cent/PC (year 1980 with 11.14 US$/g of gold and 0.287 gram of gold/PC). In the case of copper, this is 115 US cent/PC (year 2005 with 0.22 US cent/g of copper and 670 g of copper/PC, see Figs. 6, 7). It was observed that recycling businesses make their decision to buy obsolete PCs on a "rule of thumb", according to commodity prices and their knowledge of the PCs material value. This lead us to the additional assumption that formal and informal recycling businesses start their activity within a price range per PC, which is described by the values $x_{5\%}$ and $x_{95\%}$ in the recycling curve Eq. (5). According to the fluctuations of the gold and copper price in Figs. 6 and 7 a range of 100 US cent/metal and PC seemed plausible. Hence, the margins for the informal sector for gold ranges between 270 (5%) and 370 (95%) US cent/PC and for copper between 65 (5%) and 165 (95%) US cent/PC. These assumptions suggest that informal recycling today operates with expected revenues above the upper threshold values for copper, and within the margin of the threshold values for gold. The sum of both upper threshold values for copper and gold (535 US cent)

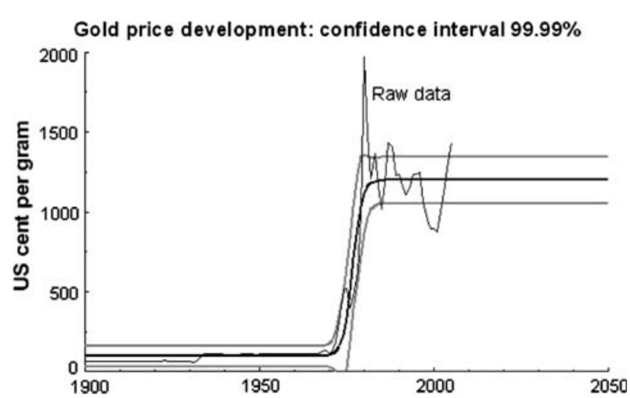



**Fig. 7** Historical gold and copper prices and best fit of future development

is in the range of the current market value of an obsolete PC, which is roughly between 2 and 3 US$. Thus, revenues of informal recyclers only from gold and copper cover more than the costs of an obsolete PC. Other materials such as aluminium, ferrous metals or plastics can add to the profits. In consequence, theses parameter function tends to underestimate informal recycling activities.

For formal recycling, we assume that the lower threshold values must be above the currently expected revenues as almost no formal recycling activities can be observed in India today. Only data from the pilot plant for WEEE recycling in Bangalore give some indication on threshold values (see values given above). Based on these data, the threshold level for gold and copper recycling in the formal sector is assumed to range from 560 (5%) to 1,120 (95%) US cent/PC calculated for a 12.8 kg medium weight from 1997. We justify the higher range of the threshold values because of higher investments costs in the formal sector. This conservative assumption means that formal businesses have a longer start-up phase than their informal counterparts, having to cover their investment costs. The threshold value function was introduced in "Recycling of copper and gold" and Fig. 3; the values are listed below in Table 3.

The model determines the development of recycling activities using the parameter functions for threshold values and the value concentrations of PCs in the WEEE

**Table 3** Parameter values used in the base line

| Parameter | Unit | 1980 | 2050 | Data source or explanation |
|---|---|---|---|---|
| Medium life span | Years (sigma in years) | 8 (2) | | Calibration results, expert interviews, Culver (2006), Matthews et al. (1997) and Matthews and Matthews (2003) |
| Medium weight per unit | Kilogram | 19.6 | 8.0 | Decrease from 1980 until 2050 according to Fig. 9, SWICO batch examination and own estimates |
| Metal content per unit | | | | |
| Gold | Gram | 0.288 | | SWICO (2006) batch examination, Hagelüken (2006), Schischke and Kohlmeyer (2005) |
| Copper | % | 6.1 | | |
| Metal prices | | | | |
| Gold | | | | As shown in Figs. 7 and 8 for gold and copper price developments |
| Copper | | | | |
| Sector | | 5% | 95% | |
| Threshold value | | | | |
| Gold | US cent per unit | | | As explained in chapter 4.2.1 Recycling of copper and gold and 4.3.2 WEEE Trader |
| Informal | | 270 | 370 | |
| Formal | | 560 | 1120 | |
| Copper | | | | |
| Informal | | 65 | 165 | |
| Formal | | 560 | 1120 | |
| Maximum recycling rate | | | | |
| Gold | Transfer coefficient | | | Huisman (2003) and own assumptions |
| Informal | | 0.5 | | |
| Formal | | 0.98 | | |
| Copper | | | | |
| Informal | | 0.5 | | |
| Formal | | 0.95 | | |
| Minimum recycling without gold and copper recovery | Transfer coefficient | 0.7 | | SWICO (2006) batch examination, Schischke and Kohlmeyer (2005) and own assumptions |
| Additional recycling | | | | |
| Gold | Transfer coefficient | | | SWICO (2006) batch examination, Schischke and Kohlmeyer (2005) and own assumptions |
| Informal | | $25 \times 10^{-6}$ | | |
| Formal | | 0.090 | | |
| Copper | | | | |
| Informal | | 0.061 | | |
| Formal | | 0.121 | | |

market (see “Recycling of copper and gold”). To obtain value concentrations of PCs we need data on the development of gold and copper prices as well as gold and copper contents in the waste stream. Gold and copper prices were calibrated by estimating a parameter function for price development based on data series from the London Metal exchange from 1900 to 2005 (London Metal Exchange 2006). The time series of the prices for gold and copper from 1900 to 2005 seem to follow logistic growth behaviour (see Figs. 7, 8). It is not surprising, that the fit procedure results in logistic growth curves which best reflect the behaviour of the data in function of time. These curves reach the saturation value for gold in 1980 and copper in 2000. In contrast to the fit of the growth curve for the stock in “Consumption”, the saturation value was also a result of the fit. Although the time series data show a high fluctuation in prices over recent years, it seems reasonable to smooth out such short-term phenomena to get the long-term trend. As with PC stocks, conservative assumptions were also made for commodity prices. The recycling model intends to distinguish between the distributions between formal and informal recycling. The fitted functions for gold and copper prices are relatively low in comparison to current prices. This conservative assumption shows that the recovery of these metals will remain attractive for the informal sector. Any increase in prices will make the recycling more attractive for the formal sector. This case will be investigated in the scenario analysis later on. Yet, price fluctuations might have a significant influence on the development of recycling activities and this influence will be discussed at the end of this paper. The model takes these large fluctuations into account by assuming confidence intervals of 99.99 and 99.9% for gold and copper prices, in contrast to the common used value of 95%.

The development of copper and gold contents in PCs is determined as follows.

For gold, we assume that the gold content per unit remains stable over time. Although, the gold content of circuit wire boards tends to decrease per unit, this development is counteracted by the use of bigger motherboards, additional sound components, graphic and memory cards and other newer media drives (Schischke and Kohlmeyer 2005; Hagelüken 2006; SWICO 2006). We thus determine the parameter function for gold content per unit by multiplying the gold content in circuited wire boards (288 ppm, see Table 2) the share of circuit wire boards in PCs (8.1 mass percent) and the medium weight of a PC (12.3 kg/unit). All data is taken from one single study (SWICO 2006) to ensure data consistency. We assume a SD of 20% for all three parameters.

For copper, we assume a decreasing copper content per unit which is brought about by a decreasing weight of PCs. The copper concentration per kilogram of PC is kept constant (6.05% with a SD of 20% according to Table 2). The parameter function of PC weight per unit is based on two data points, 12.3 kg/unit for a PC sold in 2001 and 11.1 kg for a PC sold in 2006. Both data sets represent a mix of different types of PCs ranging from large and heavy units to small and light PCs. We assume that this mix is representative for both years and will not change significantly in future. For the early years form 1980 to 1990 we assume an upper limit of PC weight: 18 kg in 1990 and 20 kg in 1980 In addition, we assume that the decrease of weight per unit will slow down over time and reach a saturation value at 8 kg/unit. This assumption is not based on data and can be interpreted as a conservative estimate assuming that the prevailing trend of miniaturisation of electronic devices will not continue for PCs.

Based on this information, we again fitted a logistic decrease function for the development of PC weight (see Fig. 9). Note that the logistic decrease function differs from the logistic growth function only by the + sign in the exponential term.

*Recovery rates* *Database* Information on recovery rates can be distinguished into two types: (a) technically

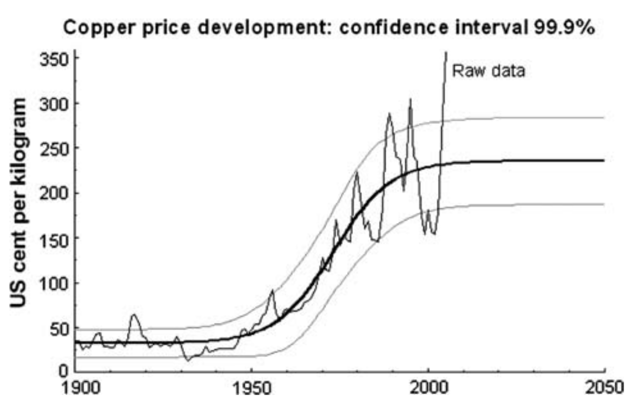



**Fig. 8** Historical gold and copper prices and best fit of future development

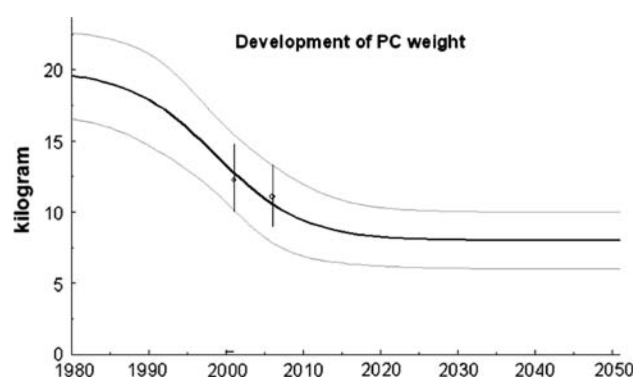



**Fig. 9** Development of medium PC weights and standard deviations

determined recovery rates in material recovery processes and (b) data on the effectiveness of the collection of recyclable materials. Type (a) can be even finer distinguished into recovery rates of the formal recycling and the informal recycling.

*Gold and copper recovery* Information in (a) can be obtained from Huisman (2003). He collected literature data for the average recovery rates of metals at copper smelters and gives material recovery rates of 95% for copper and 98% for gold. In addition (Hagelüken and Kerckhoven 2006) provide data on recovery rates of other materials in formal gold recycling. Up to now, no published data is available for informal recycling of gold and copper in the informal sector. Yet, a recent diploma thesis on gold recovery in India shows that metal recovery rates in informal recycling are significantly lower than in formal recycling (Keller 2006).

*Recycling and recovery of all other materials* In India, no data is available for (b), the effectiveness of the collection of recyclable materials. The collection of WEEE is organised by small-scale enterprises which are part of the free market. No official statistics are kept.

Yet, no additional data was collected in this study for recycling of other materials such as plastics and ferrous metals. The calibration of recycling rates for these materials is solely based on data on material composition of PCs from (Schischke and Kohlmeyer 2005; SWICO 2006).

*Calibration* Recovery rates in collection are assumed to be 90%. This is a very optimistic estimate assuming that a market based collection system works very effectively. We further assume that recovery rates in collection for informal recycling equal recovery rates in collection for formal recycling.

We further take the data given by Huisman (2003) as best estimated for recovery rates in formal copper and gold recycling. For informal recycling we assume metal recovery rates of 50% for both copper and gold.

For other materials, we assume that about 70% of PC weight is recycled comprising mostly plastic casing, ferrous metal casing and aluminium parts which are easy to dismantle and recycle. This assumption is based on the material composition of PCs taking all components into account which do not contain copper or gold. The implications of this assumption will be discussed at the end of the paper.

From the gold containing components (motherboard, PWBs from drives and gold containing pins), formal recycling processes can, at the least, recover gold, silver, palladium and copper. In addition to this, formal processing uses the non-metal material as fuel and flux material in the smelting process. As a result, the recovery rate for other material increases by 9%, which is roughly the total amount of weight of all gold containing components (SWICO 2006). The same logic is followed for copper containing parts. If copper recycling is conducted by the formal sector, an increase of 10% of the total recycling is assumed, as copper smelters can use plastics as fuel (6.1% copper and 6% other materials). Informal recycling, however, does not recover any other materials. To sum up, informal recycling can achieve a recovery rate of 76.1% (70% other materials and 6.1% copper and gold), whereas formal recycling can reach that of 91.1% (70% other materials separately recovered, 9% of gold containing components and 12.1 of copper containing components).

## Application of model

The model, described mathematically by Eqs. (1)–(6) has been implemented in the computer program SIMBOX. SIMBOX uses the Newton Raphson algorithm to solve the system of integro-differential equations numerically. All calculations have been performed on a Pentium IX PC.

### Base line and selected scenarios

Table 3 shows all parameters used in the base line scenario. They have been introduced and discussed in "Model description". The table links the parameter to the relevant figures and tables and also gives an overview of the consulted literature sources.

To represent the main driving forces of PC recycling in India, two scenarios have been selected: (1) a price scenario for both metals and (2) a threshold scenario for formal recycling. The main motivation to select these scenarios is the urge to investigate under which conditions formal recycling becomes profitable. Fact is that the value of the waste stream from obsolete PCs is influenced to a great extends from raw material prices, mainly those of metals. It is also known that an organised recycling sector has great potentials to lower costs for recycling by means of increasing its efficiency.

#### *Price scenario*

For the price scenario we assumed a linear increase of copper and gold prices from 2005 to 2050. We have assumed that the prices in 2050 will be twice as high as the saturation value of the base line. This means that in 2050 the gold price will reach 2,400 US cent/g, the copper price will reach 470 US cent/kg. The prices until 2005 are the same as in the base line in order to prevent distortion of the historical data.

*Threshold scenario*

In the threshold value scenario the threshold levels for formal recycling were decreased by 50%. Only the threshold levels for formal recycling were altered as only this sector has the potential to increase the efficiency or to profit from subsidies for environmental sound recycling. Both measures are decreasing the level at which formal recycling becomes profitable. Therefore, the threshold values for formal recycling were set at 280 (5%) and 560 (95%) US cent/PC.

## Results

The results of the model calculations are presented in the same graphic, allowing a direct comparison of the three scenarios. With respect to the evaluation criteria, environmental sound treatment and material recovery, we have focused on the following variables.

1. total material recycling,
2. formal gold recycling,
3. informal gold recycling,
4. gold losses,
5. formal copper recycling,
6. informal copper recycling,
7. copper losses.

These variables are shown for the entire time period considered in Figs. 10, 11, 12, 13, 14, 15 and 16.

Figures 11, 12, 13, 14, 15 and 16 show the annual creation of waste, recovered substances per sector and losses per sector. The corresponding accumulated values are listed in Table 4 later in the text. Figures 11, 12, 13, 14, 15 and 16 clearly show the distribution of gold and copper in obsolete PCs to the three paths losses, informal and formal recycling. For both scenarios, the "price" as well as the "threshold" scenario, formal recycling is still small, namely about 15% for gold and 0.2% for copper in 2050. From the point of view of environmentally sound treatment this is far too low. This clearly demonstrates that "doubling" the metal prices or "halving" the threshold values for formal gold and copper recycling is not enough to reach an environmentally sound treatment of PC residues.

The uncertainty ranges of the variables for the baseline scenario are quite high for the future—after about the year 2015. This is a well-known phenomenon if imprecise data from a short time period (here 1995–2005) is used for simulations of the distant future (here ∼2050). In this study, the first rough estimates of the parameter uncertainties were accurate enough for the calibration period 1990–2005, see Figs. 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15 and 16. However, for the simulation of the more distant

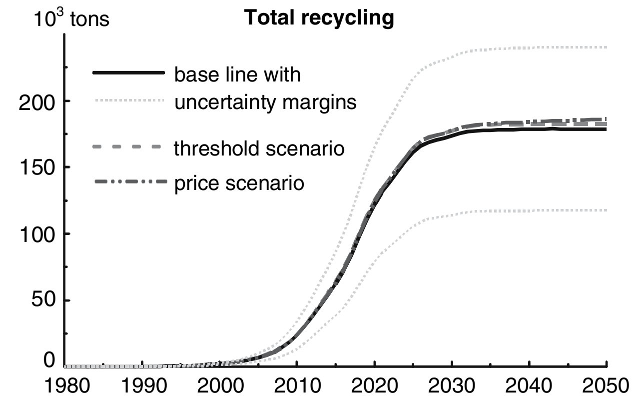



**Fig. 10** Total recycling volumes for the baseline (with uncertainties) and the two scenarios

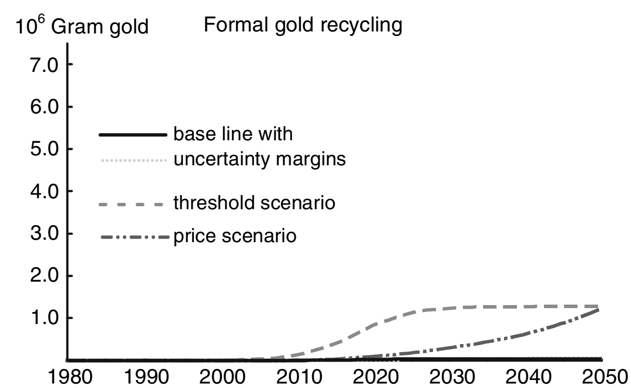



**Fig. 11** Gold recycling in the formal sector for the baseline (with uncertainties) and the two scenarios

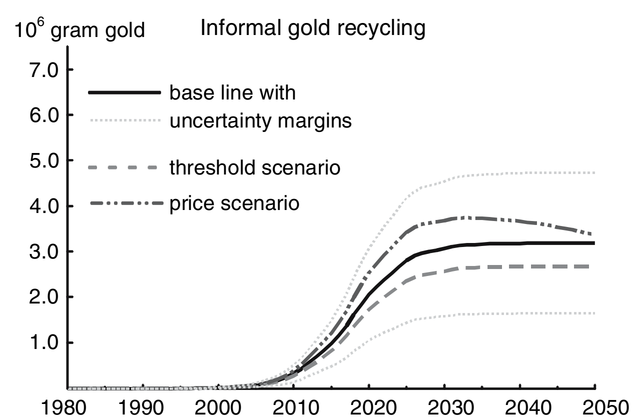



**Fig. 12** Gold recycling in the informal sector for the baseline (with uncertainties) and the two scenarios

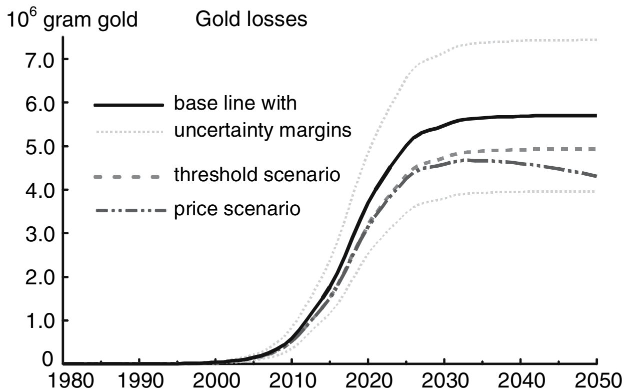



**Fig. 13** Gold losses for the baseline (with uncertainties) and the two scenarios

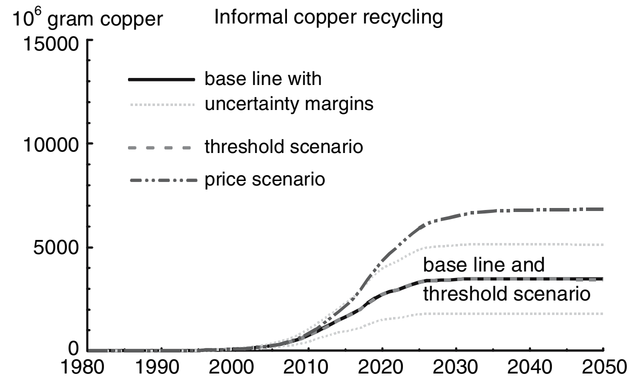



**Fig. 15** Copper recycling in the informal sector for the baseline (with uncertainties) and the two scenarios

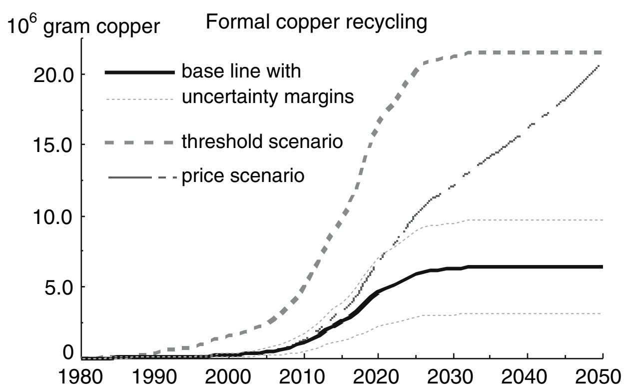



**Fig. 14** Copper recycling in the formal sector for the baseline (with uncertainties) and the two scenarios

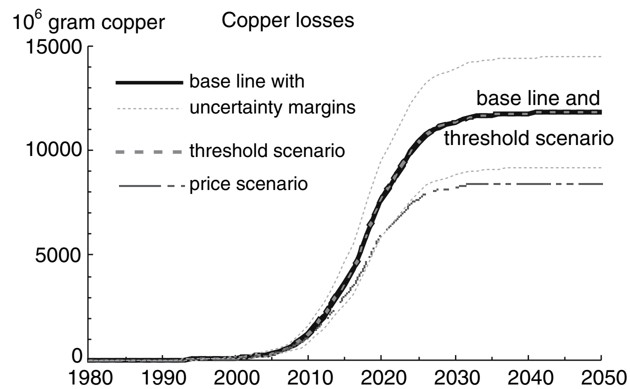



**Fig. 16** Copper losses for the baseline (with uncertainties) and the two scenarios

**Table 4** Accumulated recycling volumes, share of formal and informal recycling, losses as well as monetary value of gold and copper volumes over the whole time period (1980–2050)

| Cumulated material | Scenarios | | | | | |
|---|---|---|---|---|---|---|
| | Base line | | Price scenario | | Threshold scenario | |
| Recycling volume | 5,884[a] | – | 6,034[a] | – | 6,015[a] | – |
| Losses | 2,330[a] | – | 2,180[a] | – | 2,200[a] | – |
| Gold recycling of formal sector | 1.4[c] | 1.6[b] | 16.0[c] | 33.8[b] | 42.7[c] | 51.2[b] |
| Gold recycling of informal sector | 103.7[c] | 124.3[b] | 121.5[c] | 235.2[b] | 87.1[c] | 104.4[b] |
| Gold losses | 183.0[c] | 219.4[b] | 150.7[c] | 291.8[b] | 158.3[c] | 189.7[b] |
| Copper recycling of formal sector | 0.2[a] | 0.1[b] | 0.5[a] | 0.2[b] | 0.8[a] | 0.2[b] |
| Copper recycling of informal sector | 122.0[a] | 28.7[b] | 220.4[a] | 83.8[b] | 121.9[a] | 28.6[b] |
| Copper losses | 380.5[a] | 89.5[b] | 281.8[a] | 106.4[b] | 380.1[a] | 89.4[b] |

[a] Values are given in 1,000 tons

[b] Values are given in Billion US$

[c] Values are given in Tons

future ~2020–2050 it turned out that these estimated uncertainties were too inaccurate. The following procedure has been applied to reduce the uncertainty: (1) the confidence intervals of the available time series such as gold and copper prices were reduced to the usual 95% instead of 99.9% and more; (2) the uncertainties of the parameters where no time series were available such as threshold values were also reduced. This was justified on the grounds that those parameters are scenario-like parameters, since no data was available. In conclusion, the shown uncertainty range of the baseline scenario has to be considered as an uncertainty of a scenario rather than a prognosis. The effect of these parameters will be further elaborated in the discussion.

The future volumes of annually obsolete PCs will increase to over 250,000 tons in 2050. The material going to landfill will increase to almost 70,000 tons per year. These values are the same for each scenario as the input from the stock remains unchanged (not shown in the figures).

The total recycled material will increase as shown in Fig. 10. The three scenarios differ only slightly. In the base line the recycled material from PCs will reach 179,000 tons per year, 183,000 tons per year for the threshold scenario, and 186,000 tons for the price scenario.

Volumes of gold recycling of the different sector vary. Under the base line almost no formal recycling is present (42.7 kg/year). A total of 1,250 kg of gold per year becomes recovered by the formal sector under the price scenario, and 1,330 kg of gold per year under the threshold scenario (Fig. 11). Nevertheless, the biggest share of recovered gold is generated by the informal sector. A total of 3,230 kg under the base line, 3,410 kg under the price scenario and 2,710 kg of gold per year under the threshold scenario become recovered (Fig. 12).

But almost double the amount of gold is lost in each scenario. These losses are a combination of not collected material as well as material losses from recycling. A total of 5,700 kg of gold per year will be lost under the base line. The losses are also very high under the threshold scenario (4,930 kg/year) and under the price scenario (4,310 kg/year) (Fig. 13).

For copper the situation is even more extreme. The majority of copper is lost either from not being collected or from losses during the recovery process. The formal sector by far does not reach the size of the informal one.

Formal recycling of copper will only reach 6.4 tons/year (base line), 21.0 tons/year (price scenario) or 21.5 tons/year (threshold scenario) as shown in Fig. 14. Informal copper recycling will recover 6,867 tons of copper per year under the price scenario, whereas almost no difference could be detected between the base line (3,470 tons) and the threshold scenario (3,466 tons), shown in Fig. 15.

The volume of copper lost exceeds the sum of both recycling volumes. Again, no substantial difference can be seen between the losses of copper per year under the base line (11,830 tons) and the threshold scenario (11,820 tons). The losses under the price scenario are lower due to the higher informal recycling at 8,414 tons of copper per year.

The accumulated material values, listed in Table 4, allow for an estimation of the overall material intensity of the PC market as well as for potential losses from applied techniques. The monetary values of the accumulated amounts of gold and copper are also shown. They have been calculated with the metals prices of the corresponding year.

The accumulated material losses which have to be deposed of in landfills until 2050, add up to over 2,000,000 tons. The total volume of obsolete PCs is the sum of recycling volume and losses. It is the same for each scenario.

For all scenarios the losses of gold and copper, and consequently the financial losses, exceed the amount of recovered material or earned profits. This is even the case if the volumes of informal and formal recycling are summed up.

By comparing the threshold scenario with the base line, only a slight improvement of gold recovery can be detected, for both, formal and informal recycling. If the same set of scenarios is compared for copper recycling, also only lightly higher volumes become recovered. Reason for this is a situation under which formal and informal recycling are competing for recycling material. An increase of volume in the formal sector decreases the volume processed in the informal sector.

The comparison between the base line and the price scenario shows that more volumes become recovered in both sectors. But even in this scenario the sum of informal and formal recycling never reaches the volume of the losses. Reason for this is that under both scenarios formal and informal recycling are not fully active and, therefore, do not recycle their maximum level.

## Discussion

The main goal of the presented study was to describe the characteristics of PC recycling in India in a model. The gained system understanding was then analysed in a structured way, in order to understand the underlying cause–effect chains and to identify the main driving forces of the system.

The results are discussed in the light of the research question:

- What are the main characteristics of WEEE systems in emerging economies and how can they be best represented by an appropriate model?

In emerging economies we observe a large second hand market for PCs. The model captures this phenomenon by defining a cascade use of PCs, driven by the development of different stocks of PCs representing the behaviour of different consumer types. Understanding this cascade is crucial to obtain information on average PC life spans for the entire systems, the levels of saturation and the underlying drivers. Therefore, a stock-driven dynamic MFA model is a most suitable tool. Due to restricted data availability, however, we were not able to calibrate a cascade model in consumption. This means that the cascade use of PCs is described implicitly in a one box model for consumption, which does not allow any separate analysis of the individual stocks or flows. To calibrate a cascade model, first, the single stocks and; second, the single inputs to the different stocks are required. The reuse of PCs could, therefore, not be quantified. Yet, the model reveals the waste volume of obsolete PCs taking into account the time shift between purchase and dumping of PCs and thus allows assessing alternative recycling schemes.

The recycling model depicts the competition between two recycling sectors, formal and informal. They compete for material according to their ability to make profits from the recovered material. This describes accurately the present situation under which many informal recyclers deal with the majority of waste, while some first formal recyclers start to build up facilities and try to get hands on material.

Finally, material prices and material concentration in obsolete PCs define whether a specific treatment is profitable or not. These dynamics have been represented in the model as gold and copper flows from recycling were analysed.

Yet, some very important characteristics of WEEE recycling in India are not represented in the model.

The prevailing pattern of trading and recycling facilities is much more complicated that the one shown in Fig. 1. An obsolete PC undergoes many dismantling and sorting steps. Components that are still required on the market are sold as used replacement parts; components that are not required are traded as waste material. Consequently, the phase "trade" in our model is simplified, insofar as we have reduced the net of trading relationships to only two traders. Intensive trade affects the revenues of final material recyclers, due to the fact that the intermediate trading steps increase the costs of the secondary resource.

Consumer stocks and the in-use stock of material might change considerably. But the relative changes in the demand, use and output of the system as outlined will happen—with or without a technology revolution. Thus, an appropriate waste treatment system will be required.

- What forces drive WEEE systems in emerging economies?

Without the model, the calculation of the uncertainty ranges of the variables and the sensitivity analysis of the parameters, one can only guess at which forces drive the system. The model has shown that mainly following parameters influence the distribution of PC treatment in formal and informal recycling:

1. content of valuable materials,
2. market value of these,
3. economic threshold level for a recycling activity,
4. size of the PC stock,
5. medium life span, and
6. maximal recycling rates.

This is not surprising as the metal content, the metal prices and the threshold level determine which recycling sector becomes active. However, with a dynamic model not only qualitative dependencies on parameters can be discussed, but also the quantitative sensitivities in function of time—in particular for the "transition phase" such as that involving the introduction of formal recycling.

For the first two parameters a close look on the development of medium metal content and naturally of the metal prices is of great importance. Bodies which are in charge of setting up, monitoring and supervising recycling systems should, therefore, be aware of the material composition of the products of concern.

For metal prices, we have decided not to use the annual fluctuations in our calculation but a best fit. This best fit of the metal prices is supposed to balance out some of the losses and profits recyclers make. It may leave out some of the opportunities for recyclers which arise from high metal prices, but it represents the actual situation recyclers, mainly formal one, have do deal with. Formal recyclers must build up financial reserves that secures their survival over periods with low prices or gives them the chance to do brokerage and hold back material at periods with low prices. Informal recyclers react much faster and do not have so many liabilities, which is one of the biggest competitive advantages of this sector.

The third two parameters, the threshold values, are of great interest to recyclers, ICT industry and policy makers. Therefore, to confirm the actual necessary costs for formal recycling as well as the profits gained in the informal sector would be very useful. Formal recycling is under the set conditions, not able to squeeze the informal recyclers out of the market. Also the results of the two scenarios show how far the formal sector is away from being competitive with informal recyclers. Under the base line as well as the both scenarios, the formal sector was not able to overtake a substantial level of the market. A combination of price scenario and the threshold scenario could deepen the analysis and give hints, how much the formal recyclers have to increase in efficiency, to receive subsidies for environmental sound recycling and to profit from high metal prices. Formal recycling will only increase if the sector dramatically lowers the cost for recycling.

- What do we learn from model calculation about the design of a data collection scheme for future studies?

Obviously, the focus on data collection in future should be on parameter values for the most sensitive parameters discussed above: gold and copper content per PC, metal prices and threshold values.

In addition, future research should aim at better covering some important issues that our model application excluded explicitly. As general system understanding was the goal, some important parameters for monitoring or management purposes were not looked at. These are as follows.

First, some spatial parameters should be included to apply the model to a specific region. The model application presented in this paper depicts the whole PC market in India, but excludes collection and transport parameters. The sheer size of India as well as experiences for WEEE recycling systems in Europe indicate that collection and transport are important elements while setting up a recycling system. Therefore, spatial data on WEEE generation as well as data on collection patterns should be included in a future analysis.

Second, reuse is an important characteristic of the PC use in emerging economies. Reuse of appliances means the use for which they were conceived, including the continued use of the equipment or components thereof which are returned to collection points, distributors, recyclers or manufacturer. Such processes have been described for the recycling of cathode ray tubes from televisions and PC monitors in India (Jain and Sareen 2006). In our model, reuse has not been explicitly considered. Reliable data of PC reuse numbers would enable researcher to model two consumer stocks: first users and second users.

Third, the recycling volumes for PCs in our model are very high. Not only the return rates of obsolete PCs are set at 90%, also the minimum of material recycling that happens without any gold and copper recycling was set at 70%. Both levels contribute to this very high recycling rate. The system characteristics on which these high return rate are based on, are the effective waste collection services in India, which delivers services especially to social higher strata having the potential to buy own ICT equipment. But to make an accurate estimate how much of materials are in fact recycled and how much material is lost during the process, separate studies are necessary.

## Conclusions

With a model requiring a very limited amount of data, it was possible to get a quantitative understanding of the system PC consumption and WEEE in India. In particular, the key parameters representing the so called driving forces could be identified and quantified as well as the data gaps which should be closed. This is crucial in order to focus on collecting data which is really needed, instead of wasting human power and money with exorbitant unnecessary measuring campaigns. Such studies should focus on a better description of the use and reuse phases. By means of more specific PC stock data, individual stock development can be included in the calculation. If additionally recycling data of an emerging formal recycling sector is collected, let us assume, by a regulating authority, the presented model can be transformed into a powerful study and monitoring tool.

The study has revealed that at the present situation the formal PC recycling will not be able to squeeze informal recyclers out of the market. Also in the future formal recyclers have either to reduce dramatically their costs, or to benefit from continuous high metal prices for gold and copper. The calculation showed that even with doubling the metal prices, or lowering the threshold values for formal recycling by 50%, no substantial share of the waste volume was overtaken by the formal sector.

Informal recycling will attract more and more businesses as the amount of obsolete PCs will dramatically rise. This is even the case if only the historical sales data for PCs are taken into account, as the sales have increased exponentially. This will result logically in an exponential increase of PC waste in less than 8 years. The conservative prognosis we have made of the PC stock development until 2050 shows that presently there are far too little recycling capacities to deal with the waste.

If we assume that the informal sector will expand its activities as much as shown in the scenarios, urgent action is needed to upgrade and improve this recycling sector. Strategies which focus to improve the informal sector seem to be more suitable that investing in expensive infrastructure. One can be that the informal sector is shifting to towards pre-processing and sorting. But such initiatives have to be well coordinated and backend up with an appropriate legislation. It has to be also ensured that unproblematic pre-processing and separation processes are handing on the waste fractions to final material recovery or energy recovery processes which should be assiduously be monitored. Otherwise an upgrading or improving of informal recycling would only shift the problem. Some first interventions in this direction from development cooperation organisations are already happening. Additional studies on informal recycling are needed in order to confirm the first results and monitor the improvements of material recovery in the informal sector. What the study clearly showed is that the informal sector must become more sustainable, both in environmental and health terms, in order to enable the WEEE sector to attain higher environmental standards.

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