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The Best-of-2-Worlds philosophy: Developing local dismantling and global infrastructure network for sustainable e-waste treatment in emerging economies

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ABSTRACT

E-waste is a complex waste category containing both hazardous and valuable substances. It demands for a cost-efficient treatment system which simultaneously liberates and refines target fractions in an environmentally sound way. In most developing countries there is a lack of systems covering all steps from disposal until final processing due to limited infrastructure and access to technologies and investment. This paper introduces the ‘Best-of-2-Worlds’ philosophy (Bo2W), which provides a network and pragmatic solution for e-waste treatment in emerging economies. It seeks technical and logistic integration of ‘best’ pre-processing in developing countries to manually dismantle e-waste and ‘best’ end-processing to treat hazardous and complex fractions in international state-of-the-art end-processing facilities. A series of dismantling trials was conducted on waste desktop computers, IT equipment, large and small household appliances, in order to compare the environmental and economic performances of the Bo2W philosophy with other conventional recycling scenarios. The assessment showed that the performance of the Bo2W scenario is more eco-efficient than mechanical separation scenarios and other local treatment solutions. For equipment containing substantial hazardous substances, it demands the assistance from domestic legislation for mandatory removal and safe handling of such fractions together with proper financing to cover the costs. Experience from Bo2W pilot projects in China and India highlighted key societal factors influencing successful implementation. These include market size, informal competitors, availability of national e-waste legislation, formal take-back systems, financing and trust between industrial players. The Bo2W philosophy can serve as a pragmatic and environmentally responsible transition before establishment of end-processing facilities in developing countries is made feasible. The executive models of Bo2W should be flexibly differentiated for various countries by adjusting to local conditions related to operational scale, level of centralized operations, dismantling depth, combination with mechanical processing and optimized logistics to international end-processors.

1. Introduction

E-waste covers a wide spectrum of electrical and electronic products incorporating both valuable (e.g. non-precious metals: iron, steel, copper, aluminum, etc.; precious metals: gold, silver, palladium, platinum, etc.; plastics) and hazardous substances (e.g. lead-containing glass, mercury, cadmium, batteries, flame retardants, chlorofluorocarbons and other coolants with heavy potential of environmental impact) (EC, 2003; Tsydenova and Bengtsson, 2011). It has the potential to generate significant negative environmental impacts if handled improperly (Robinson, 2009; Lim and Schoenung, 2010). During the last decade, large amounts of e-waste have been rapidly piling up in emerging economies both from growing domestic consumption as well as imports. A UNEP report forecasts that obsolete computers in China and South Africa will rise by 500% in 2020 compared to their 2007 levels (Schluep et al., 2009). Apart from domestic generation, additionally about 50–80% of e-waste from developed countries is exported to regions such as China and Africa (Puckett et al., 2002; Hosoda, 2007; Huisman et al., 2008; SBC, 2011). This is driven by the demands of second-hand electronic products and secondary resources by refurbishment and dismantling as an income-generating opportunity for the local people (Hicks et al., 2005; Schwarzer et al., 2005; Schmidt, 2006; Cobbing, 2008). However in most of these destinations, e-waste treatment is

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dominated by backyard/informal recyclers using intensive manual dismantling of equipment. This is usually followed by primitive processes for material recovery like acid-leaching of printed wiring boards (PWBs) or burning of cables and residues without basic working protection regarding health and safety (Puckett et al., 2002; Chi et al., 2011). Sampling of heavy metals and toxic organics sediments in e-waste recycling sites such as Guiyu (China) and Bangalore (India) showed that heavy contamination from backyard recycling brings severe damage to the local environment and leads to human health risks (Ha et al., 2009; Sepúlveda et al., 2010). In addition, informal recovery of valuable materials like precious metals has low yields and thus leads to the loss of resources (Rochat et al., 2008), resulting in an increased demand for mining and extraction capacity. Therefore, establishing environmentally sound treatment systems in developing countries is essential to reduce the impacts from rapidly increasing quantities of e-waste.

Collection and treatment of e-waste is a highly intricate system, in which the flow of materials includes a great variety of stakeholders connected (Sagar and Frosch, 1997; Huisman et al., 2003; Gregory and Kirchain, 2008; Rousis et al., 2008). This complexity can be divided into two sub-systems: (1) the technical system applying treatment technologies and innovations in industrial infrastructures; and (2) the societal system responsible for adoption of innovations and management of the technical system under treatment standards and legal requirement (Fig. 1) (Schluep et al., 2009). The technical system is formed by a cluster of pre-processors, refiners and final disposers in different treatment stages, fulfilling the tasks to recycle secondary materials and enable toxic control over hazardous substances (Castro, 2005; Castro et al., 2007; Meskers et al., 2009). Its performance mainly depends on available technologies, processing equipment and facilities. Meanwhile, the societal system provides a conditional framework, which influences the selection of technologies and performances of the technical system through domestic take-back policies, economic rules, market dynamics and environmental standards (Osibanjo and Nnorom, 2007). There is an apparent geographic and socio-economic division for e-waste handling patterns across the globe. Legislation, separate collection channels and sophisticated treatment are (in the process of being) established in developed countries, while unregulated repair and reuse with substandard informal recycling prevails in developing countries (Ongondo et al., 2011). Therefore, introduction of innovative technologies and development of e-waste treatment systems should be combined systematically with the socio-economic context.

Scientific reviews of state-of-the-art e-waste treatment technologies include: comparison of pre-processing options based on the recycling rate of precious metals (Chancerel et al., 2009; Meskers et al., 2009), treatment technologies for capacitors containing polychlorinated biphenyls (Eugster et al., 2008), PWBs (Cui and Zhang, 2008), flame retardant plastics (Nnorom and Osibanjo, 2008; Wäger et al., 2011), CRT (cathode ray tube) glass (Mostaghel and Samuelsson, 2010; Nnorom et al., 2011) and LCD (liquid crystal display) monitors (Böni and Widmer, 2011). Dynamic modeling of various e-waste recycling processes is established to predict and monitor their technological, environmental and economic performances (Huisman, 2003; Huisman et al., 2003; Mathieux et al., 2008; van Schaik and Reuter, 2010). Meanwhile, the majority of research work towards developing countries emphasizes the investigation of pollution and ecological damages from informal recycling (Wong et al., 2006; Shen et al., 2008; Ha et al., 2009). Most research concentrates either on technological details of the industrialized context like treatment processes for a specific product or part of the treatment chain, or on impacts from informal activities. While providing valuable inputs in their respective areas, these studies often do not directly provide the systematic treatment solutions targeting more optimal balances in environmental, economic and social performance.

The fundamental contribution of this paper lies in the introduction of a novel philosophy, which proposes an innovative approach for e-waste treatment in developing countries. It seeks a technical and logistic integration of suitable and available technologies in different treatment stages to form a complete recycling chain for

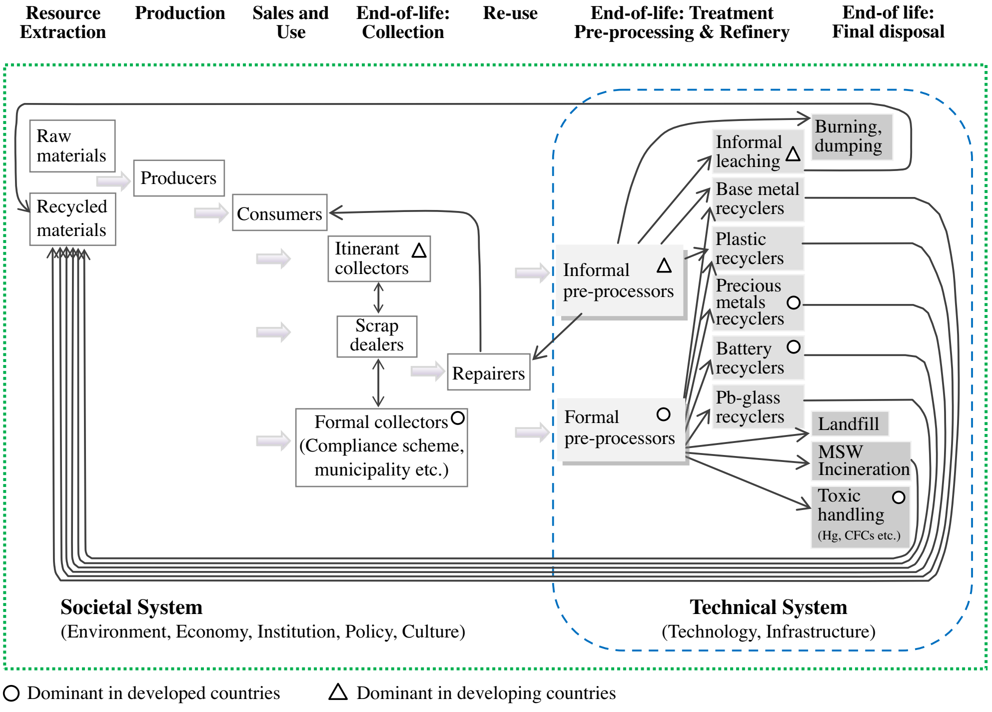


Fig. 1. Technical system of e-waste treatment and its external societal boundary for implementation.

all materials. A geographical distribution of carrying out treatment processes in both developing and industrialized regions offers competitive advantages in terms of environmental impact and resource recovery efficiency, which provides a better alternative for the current regionally focused activities in developing countries (mostly low performing practices). This philosophy is titled the Best-of-2-Worlds (Bo2W), originated at StEP Initiative (Solving the E-waste Problem) and the United Nations University. Several literature sources have analyzed the political framework, implementing approach and trade issues related to parts of this philosophy (Schluep et al., 2009; Sepúlveda et al., 2010; Manhart, 2011), but they have not elaborated on its comprehensive reasoning, objective and implementing experience. This paper systematically summarizes the concept, fundamental rationales, executive models and first-hand experience of developing the Bo2W philosophy, based on the results from literature reviews, dismantling trials and pilot projects.

This paper is further organized as follows. Section 2 summarizes the key stages of e-waste treatment chain. A case study of gold recovery from computer demonstrates the complexity and diversity of the treatment chain. The Bo2W philosophy is introduced based on the analysis of the most efficient treatment approach envisaged for developing countries. Section 3 describes a series of e-waste dismantling trials in a pilot plant in Taizhou China. It validates the Bo2W recycling approach by comparing eco-efficiency results with other existing recycling scenarios. Section 4 briefs the Bo2W pilot projects in China and India, summarizing the implementation experience from practical field work. Section 5 analyzes key policy and organizational conditions for the success of the Bo2W philosophy. Section 6 presents a roadmap for further implementing this philosophy in other countries and regions.

2. E-waste treatment chain and the Best-of-2-Worlds philosophy

This section summarizes four sequential stages in the e-waste treatment chain and explores the best recycling scenario with the case study of gold recovery from computer recycling. Based on the findings, the Best-of-2-Worlds philosophy is introduced.

2.1. Stages of e-waste treatment chain

With the two objectives of material recycling and detoxification simultaneously, e-waste treatment requires subsequently connected steps to liberate target materials and further refine them separately. The entire treatment chain can be divided into the following stages (Schluep et al., 2009):

Stage 0, Collection is a crucial stage to aggregate and divert the e-waste streams to the desirable treatment facilities. Collection of e-waste is not the focus of this paper but regarded as part of the socio-economic settings.

Stage 1, Toxic removal is an essential step to primarily single components containing hazardous substances out of the equipment for de-pollution (i.e. batteries, mercury lamps, CRT glass and PWBs, as listed in Annex II of EU WEEE Directive 2002/96/EC). It can guarantee these parts are segregated at the early phase of treatment, which eliminates dispersion, contamination and loss of target materials into undesirable streams (Salhofer and Tesar, 2011).

Stage 2, Pre-processing applies physical techniques to liberate and upgrade desirable materials (from the feedstock out of stage 1) into relatively homogeneous streams, which are used as inputs for end-processing in stage 3. The most common automatic pre-processing method is mechanical size reduction and sequential sorting, while human labor is widely used for non-destructive disassembly. Comparatively, manual dismantling achieves higher liberation rates without breaking the original form of components and materials, which is easier to sort and improves re-usability. Selective dismantling and mechanical separation can be optimally combined to have the most cost-effective liberation result under certain economic conditions.

Stage 3, End-processing is the final stage to refine and detoxify various outputs liberated from stage 2, through chemical, thermal and metallurgical processes to upgrade materials and reduce impurities as well as final disposal. A wide spectrum of materials contained in e-waste demands diverse and separate treatment processes and considerable investment in advanced technologies (especially metallurgical recovery) is required to reach high recovery rate and low environmental impact. For instance, a typical aluminium smelter in Europe requires a minimum input of 50,000 tons of aluminum scrap per year to run a plant, and the investment cost is approximately 25 million Euro (Schluep et al., 2009). For precious metal refinery, there are only a few companies in the world equipped with technical know-how, sophisticated flow sheets and sufficient economy of scale (e.g. Aurubis AG in Germany, Boliden in Sweden, DOWA in Japan, Umicore in Belgium, Xstrata in Canada), which can fulfill the technical and environmental requirements. For instance, the integrated smelter-refinery of Umicore Precious Metal Refining in Belgium has the capacity of producing 2400 tons of silver, 100 tons of gold, 25 tons of palladium and 25 tons of platinum per year (investment cost on the metallurgical processes was more than 500 million Euro). About 25% of the annual production of Ag and Au and 65% of Pd and Pt originates from e-waste and end-of-life catalysts (Umicore, 2005).

2.2. Diversity of e-waste treatment chain: a case study of gold recovery from computer

Within each stage of the treatment chain, there are alternative processes for specific equipment and material. Various treatment scenarios can be configured by interlinking different pre-processing and end-processing options, which consequently produce distinct results. For instance, Fig. 2 illustrates the loss of gold in six representative recycling scenarios of a computer. Gold is used as an indicative element to track the performances of liberation and refining because it exists in trace concentration but can contribute 12–65% of the total value in different e-waste samples (Cui and Zhang, 2008). The first two scenarios represent two pre-processing options in West-Europe, demonstrating that disassembly of the motherboards and contacts yields 80% of the gold content, while further dismantling towards power supply and drives can yield 17% extra; whereas mechanical treatment can only yield 70% recovery due to losses to dust and ferrous fractions. This implies that separation efficiency can improve as a function of dismantling depth and can be higher than mechanical methods. Scenario 3 applies an optimized shredding setting tailored for homogeneous ICT equipment to maximize the capture of precious metal fractions (including the diluted mixture with other materials). Scenario 4 includes general shredding settings for mixed e-waste feeds. These two scenarios show that different mechanical configurations can lead to liberation results varying from just 11% up to 74% loss of gold. This implies there is differentiation within advanced treatment technologies, and logically, technical settings need to be adjusted for the specific waste stream processed. In the stage of end-processing (scenarios 3, 5 and 6), gold recovery from an integrated smelter is more than 90%, surpassing the example of a copper smelter (50%) and informal leaching (31%).

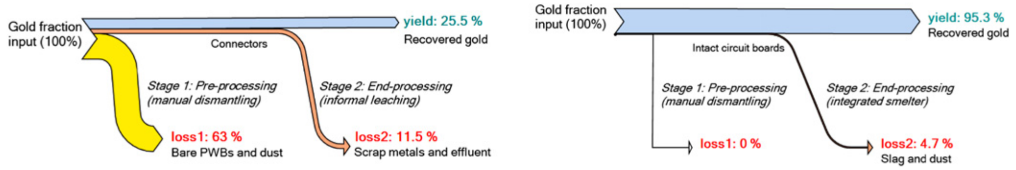
It can be concluded that the current practices are very diverse with alternatives in both pre-processing and end-processing stages. In order to reach the highest recycling rate of gold, the best scenario is to combine full manual dismantling with state-of-the-art refining for gold-rich disassembly fractions. Similarly, other

1. Manual pre-processing trial (full dismantling) of PCs in Germany (Meskers, Hagelüken et al. 2009)

2. Mechanical pre-processing trial (coarse break-up and sorting) of PCs in Germany (Meskers, Hagelüken et al. 2009)

3. Optimized shredding for small IT equipment and refinery of copper smelter (Huisman, Magalini et al. 2008)

4. Shredding for mixed IT & consumer equipment and refinery of integrated smelter (Chancerel, Meskers et al. 2009)



5. Informal recycling of circuit boards in India (Keller 2006; Rochat, Rodrigues et al. 2008)

6.Trial of PC dismantling and refinery in China (Gmünder 2007)

Fig. 2. Gold loss and yield in six scenarios of desktop computer recycling.

precious metals (e.g. silver, palladium and platinum) and toxic elements contained in computers follow the same treatment rule (Chancerel et al., 2009; Meskers et al., 2009). This approach is costly in industrialized countries because of high labor costs in dismantling and not feasible in developing countries due to limited access to capital intensive technologies. Nevertheless, if geographically separating pre-processing (manual dismantling in developing countries) and end-processing (integrated smelting of gold in developed countries), a more optimal technical, environmental and economic outcome could be achieved (scenario 6).

2.3. Best-of-2-Worlds philosophy

Under the observation of integrating best geographically distributed treatment options, the Bo2W philosophy helps to achieve the most sustainable solution for developing countries: to locally pre-process their domestically generated e-waste by manual dismantling; and to deliver critical fractions to state-of-the-art end-processing facilities in a global market.

When the Bo2W philosophy is applied in developing countries specifically, manual dismantling can be retained locally because it generates fine material output with low technical requirements. When the critical output fractions are forwarded to global state-of-the-art facilities, then in theory overall detoxification and recovery of valuable materials is optimal. Sharing the existing end-processing infrastructures globally among dismantling facilities in developing countries is attractive in terms of economy of scale and avoiding high investment. Several studies (Gmünder, 2007; Rochat et al., 2008), for instance indicate that this approach can create positive revenues with low environmental impacts. From a social point of view, such configuration can improve the treatment standard in developing countries to prevent high environmental impacts. Meanwhile, the Bo2W philosophy adopts a labor-intensive approach under environment health and safety standards, which preserves abundant jobs for the informal sectors with improved working conditions.

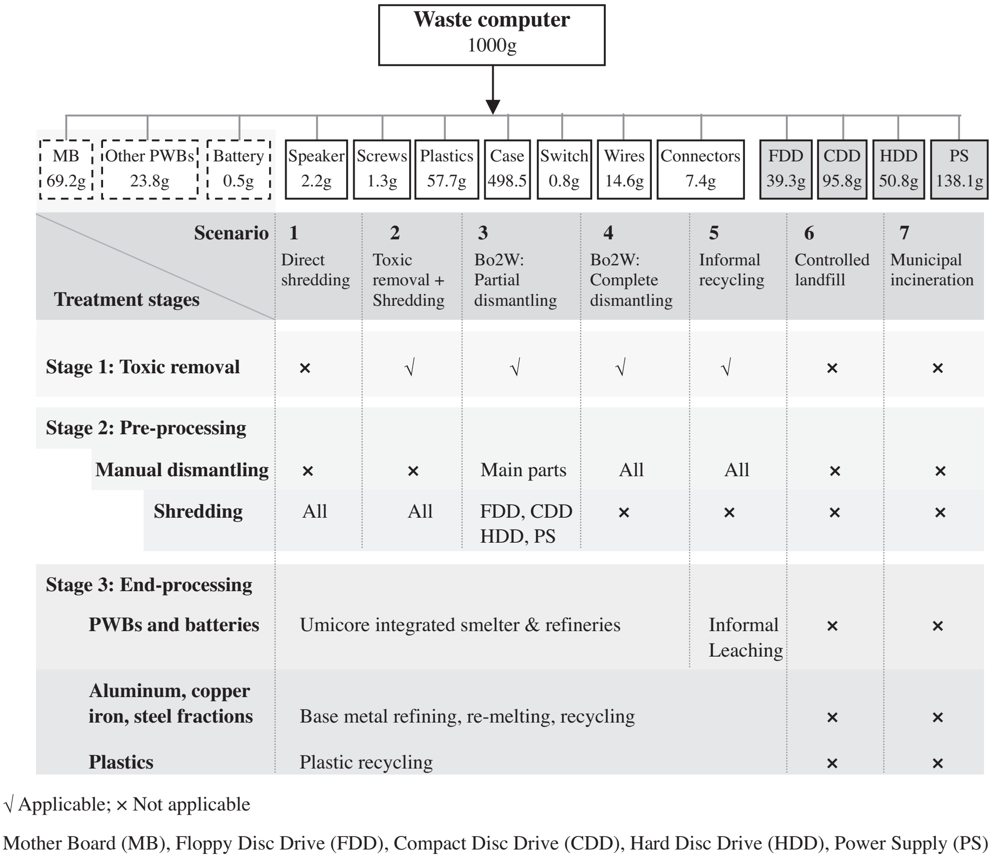
In order to further prove this philosophy, only the case of gold recovery from single IT products is not sufficient to justify it, so extensive dismantling trials were conducted for validation, including other types of equipment.

3. Further validation by dismantling trials

A series of dismantling trials were carried out and prototypes of dismantling configurations and plants were developed between 2006 and 2009. Various products were dismantled to track dismantling time and mass balances for different disassembly depths. Disassembled fractions were sent to respective facilities for chemical analysis. Process data were recorded per treatment scenario consisting of different pre- and end-processing options. Moreover, technical, environmental and economic performances were compared to identify the advantages and disadvantages of the Bo2W philosophy.

3.1. Comparative scenarios and evaluation methods

To illustrate the outcomes, two metric tons of obsolete mixed-brand desktop computers (excluding monitors) and other types of household equipment were collected and processed. The batch was dismantled by skilled workers in Taizhou China, and details about the settings of the dismantling sessions in the constructed pilot plant can be retrieved from (Gmünder, 2007; Wang, 2008). A selection of treatment scenarios is shown in Fig. 3. Re-use of components is not considered in this trial. From scenarios 1–4,



Treatment stages \ Scenario	1 Direct shredding	2 Toxic removal + Shredding	3 Bo2W: Partial dismantling	4 Bo2W: Complete dismantling	5 Informal recycling	6 Controlled landfill	7 Municipal incineration
Stage 1: Toxic removal	×	√	√	√	√	×	×
Stage 2: Pre-processing							
Manual dismantling	×	×	Main parts	All	All	×	×
Shredding	All	All	FDD, CDD HDD, PS	×	×	×	×
Stage 3: End-processing							
PWBs and batteries	Umicore integrated smelter & refineries				Informal Leaching	×	×
Aluminum, copper iron, steel fractions	Base metal refining, re-melting, recycling					×	×
Plastics	Plastic recycling					×	×

√ Applicable; × Not applicable

Mother Board (MB), Floppy Disc Drive (FDD), Compact Disc Drive (CDD), Hard Disc Drive (HDD), Power Supply (PS)

Fig. 3. Seven treatment scenarios of desktop computers by combining different options in each treatment stage.

the depth of manual dismantling increases while the level of mechanical separation declines and all liberated fractions are sent to the same end-processing destinations. Scenarios 3 and 4 represent approaches according to the Bo2W philosophy, which involve manual dismantling and the treatment of PWBs and batteries in state-of-the-art end-processing facilities abroad. Scenario 5 shares the same dismantling depth as scenario 4 but PWBs are treated in a local low-tech leaching process. Scenario 6 is landfill with leachate control, while scenario 7 is municipal waste incineration with energy recovery.

Material Flow Analysis was applied to model and visualize the mass balance of flows and stock in the sources, pathways and intermediate and final sinks of investigated processes within a defined space and time (Brunner and Rechberger, 2004). Life Cycle Assessment (LCA) was applied to evaluate the environmental impacts of the recycling processes (Guinée et al., 2002). Treatment of 1 kg of desktop computer was used as the functional unit to compare all scenarios. Eco-indicator'99 was used as a Life Cycle Impact Assessment (LCIA) indicator to interpret the mass flows into the overall environmental impact (Goedkoop and Spriensma, 2001). The inventory data was converted into environmental effects by assigning mass loads of specific material/energy/emission to the corresponding impact categories and weighting factors. A single end-point damage score (milliPoints/mPts) was applied to integrate three damage results from human health (HH), ecosystem quality (EQ) and resource damage (RD), with the 'Hierarchist' weighting method.

Process-based cost modeling (Gregory et al., 2006; Wang, 2008) was applied to analyze the costs during treatment, excluding the collection cost to obtain obsolete computers. Revenue from the processes was calculated from the market prices of primary and secondary materials; costs include variable costs which were subjected to the scale of processes and market dynamics (like labor, transport, storage, material and energy use etc.), and fixed costs (such as construction, machinery and overheads).

Eco-efficiency analysis was applied as a quantitative tool to measure the balance between economy and ecology of the specific scenarios (Huisman, 2003). It was projected in diagrams with economic gain or loss vertically and environmental impacts or avoided impacts horizontally.

3.2. Data

Material compositions of desktop computers and dismantling times were obtained during the trials, in which the equipment were ultimately separated into homogenous materials and components. Recycling efficiencies, material and energy consumption, emissions of shredding processes, plastic recycling, controlled landfill and municipal incineration were derived from the European empirical studies (Huisman, 2003; Huisman et al., 2008) and standard processes in database Eco-invent v2.2 (Ecoinvent, 2010), due to unavailable data in China. Information of base metal recycling was obtained from local copper, aluminium and steel smelters in China. Composition and recycling efficiency of PWBs were acquired from a state-of-the-art integrated smelter with precious metal refinery in Europe.

The environmental impact of a single process was modeled with SimaPro software (PRé, 2011). Cost analysis was determined for a pilot plant with an assumed annual treatment capacity of 1000 tons of obsolete computers. Average material prices of 2010 were used in this study, with primary metal prices retrieved from London Metal Exchange (LME, 2010), primary and secondary plastics, secondary metals and circuit boards trading data from mixed internet sources (ChinaWasteWeb, 2010; WorldScrap, 2010). labor cost for Chinese dismantling workers was set at 0.8€/h, and the energy price at 0.1€/kWh in 2010 (CNBS, 1996–2010). Fixed costs were estimated from the cost of building prototype plants and a mixed-metal scrap recycling yard in Taizhou China.

3.3. Result

3.3.1. Desktop computer

The results (Fig. 4) consistently show that the scenarios including state-of-the-art end-processing technologies (scenarios 1–4) generate more revenues as well as environmental gains and hence are environmentally and economically preferable. The scenario with complete dismantling following the Bo2W philosophy (scenario 4) has the best performance, but differs slightly from scenario 3. So shifting from complete dismantling to partial dismantling combined with mechanical processing seems to produce an almost similar result. The informal scenario 5 generates medium revenues but creates significant negative impact on the environment and is therefore not preferred, mainly due to the impacts of the acid leaching. Controlled landfill and incineration (scenarios 6 and 7) have scores close to zero, not having any environmental gains or substantial costs for disposal, but leading to a large loss of material value.

As can be seen by comparing scenarios 1 and 2, removing the critical components (PWBs and batteries) before mechanical separation leads to an additional 8% environmental gain and 14% increase of revenues. This affirms the significance to remove hazardous fractions prior to mechanical separation, in order to avoid cross-contamination. Examining scenarios 2, 3 and 4, it can be concluded that the eco-efficiency improves along with the dismantling depth. Net revenue increases 14% when major plastic and metal fractions are dismantled instead of separated via mechanical separation. A further 9% added value is generated when disc drives and power supplies are further manually disassembled. This demonstrates that in the pre-processing stage, full manual dismantling outpaces mechanical separation eco-efficiently under the trial settings, as the optimal dismantling depth.

The result of the 'informal sector' scenario 5 was roughly estimated, without first-hand ecological damage and financial data for China. Instead, basic settings from a similar study in India were applied, which indicated that gold yields in informal gold leaching processes are below 60% (Keller, 2006). Compared to a state-of-the-art integrated precious metal refinery in Europe, informal treatment results in 180 times higher metals emissions to water, three times higher CO_2, SO_X, and NO_X emissions to air, but 1.5–4 times lower water and energy consumption. In total, (scenario 5) causes substantial environmental damage and is less profitable due to loss of gold, silver and palladium. It confirms the finding that delivering PWBs to global state-of-the-art end-processing facilities prevents loss of resources and ecological damage.

To examine the economic distribution along the treatment chain, scenario 4 (Bo2W approach with complete dismantling) is used as an example to demonstrate the involved costs and revenues (Fig. 5). For pre-processing, the profit was calculated by the revenues from selling the liberated scraps (secondary materials in the trading markets) subtracting the fixed and operational costs (mainly labor cost). For end-processing, the profit was calculated by the revenues from the recycled materials (market price of primary materials multiplying the recycled mass) subtracting the purchase cost of secondary scraps, fixed and operational costs. The result suggests that the first step of removing the circuit board can create a profit of 0.31€ per kg desktop computer; when finishing the deep level dismantling of all components, it can bring a further profit of 0.25€ per kg; Eventually, when all the fractions are sent for refinery, the overall profit from the various end-processing treatment can add up to 0.22€ per kg. It is evident that dismantling of desktop computers can generate 72% of the whole profit through a recycling chain, with 40% coming from the removal of the highly valuable circuit boards. This can explain the phenomenon of intensive manual dismantling of e-waste in the low-labor cost countries. Despite of higher profit gained from pre-processing than end-processing, the cost of collection (or purchasing e-waste in the market) undertaken by the pre-processors has not been included yet. According to a survey done by the Bo2W project team in the local trading market in Taizhou in 2010, an obsolete desktop computer can value from 3.3€ up to 16.7€ per unit (0.3–1.49€ per kg), depending on the remaining reuse value from embedded components (e.g. mother boards, memories, PS, CDD, HDD etc.). If taking the minimal collection price of 0.3€ per kg into account, the profit of pre-processing can maximally be 0.26€ per kg, which is equivalent to the overall profit from the end-processing. If the collection price of computer exceeds 6.28€ per unit (0.56€ per kg), the pre-processing will not be economically feasible any more. Separating the reusable components can definitely bring extra profit to the dismantlers, but such high collection price will make recycling scenarios without reuse less profitable (e.g. crushing memory and HDD to destroy data, mechanical pre-processing etc.). Therefore,

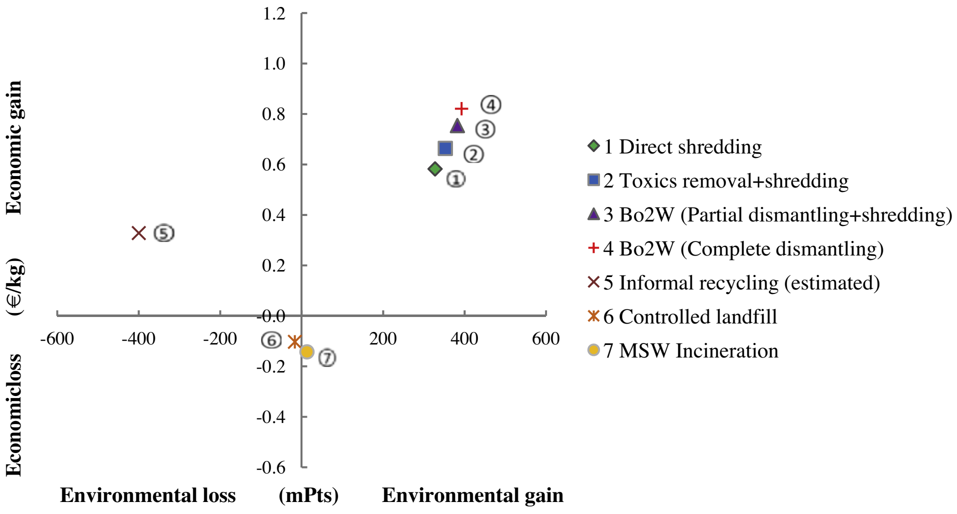


Fig. 4. Eco-efficiency scores of seven recycling scenarios for desktop computer (based on 2010 price level).

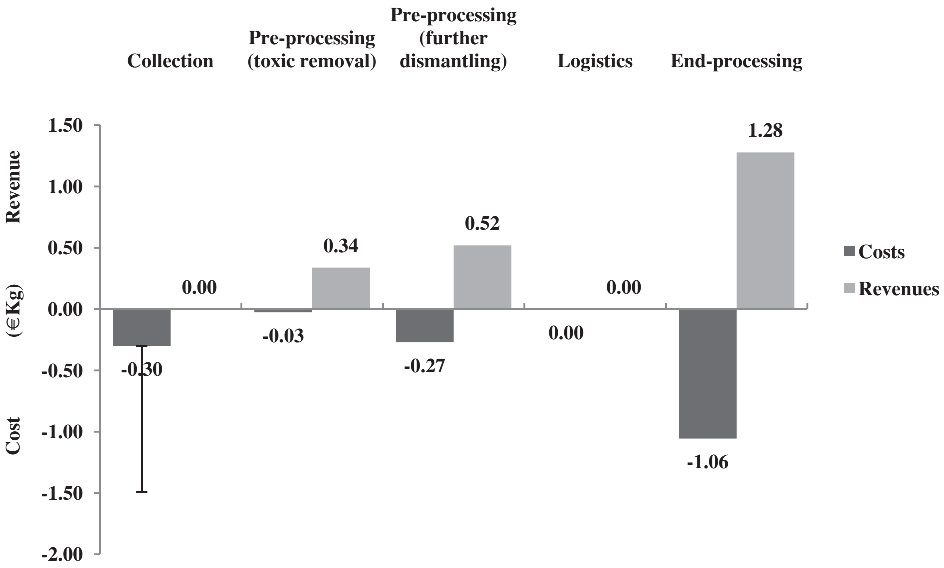


Fig. 5. Revenues and costs for different treatment stages of desktop computer applying the Bo2W philosophy (complete dismantling).

integrating reuse into the general recycling strategy will enable the overall economic model of formal sectors more competitive in developing countries. Meanwhile, applying the Bo2W philosophy by sending the circuit boards to Europe for better treatment has very low logistic cost (0.0012€ per kg), therefore is in theory feasible from the economic perspective.

3.3.2. Other types of equipment

Applying the same calculating method, the eco-efficiency scores for other types of equipment following the Bo2W treatment philosophy are plotted in Fig. 6. It can be directly observed that the material composition of products has direct influence on its profitability and environmental impact occurred during the same treatment processes. Products containing substantial amounts of metals (especially precious metals) have higher eco-efficiency scores than products dominant in plastics or other low value materials. In addition, according to the treatment results of a microwave oven, vacuum cleaner and washing machine, complete dismantling is more eco-efficient than the combination of partial dismantling and shredding of complex components (such as transformers, motors etc.) under the Chinese setting. However, the magnitude of difference between these two scenarios varies by product. Overall, the result suggests that the economic and environmental performances of the Bo2W philosophy are greatly determined by products' intrinsic characteristics (e.g. type, material composition, way of joints etc.), and recycling configurations shall be adapted to different treatment categories for the best outcome.

3.4. Sensitivity analysis of the results

As the dismantling trials are based on experimental data in China, the question is how eco-efficient the Bo2W philosophy is for other geographical settings and market conditions. To investigate this, this section analyses the sensitivity of the model towards

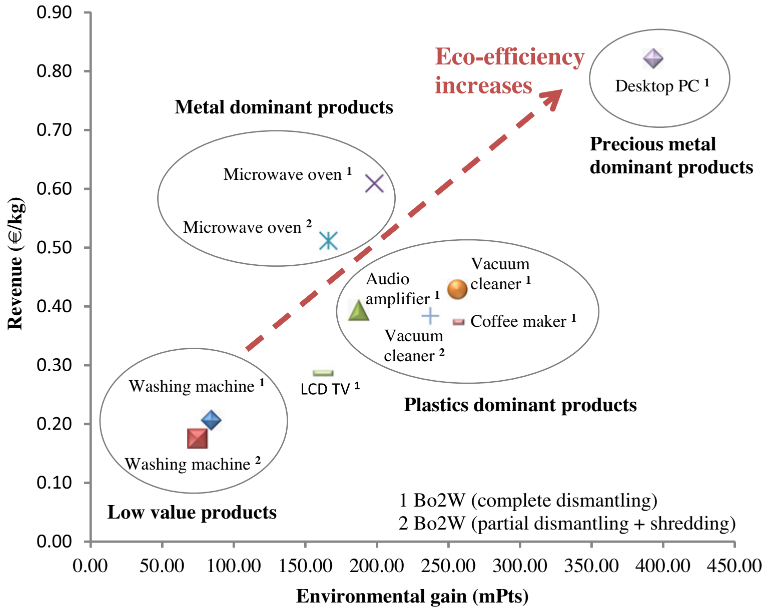


Fig. 6. Eco-efficiency scores of seven electrical and electronic products under the Bo2W recycling approach.

dynamic economic conditions of market prices and labor costs. The environmental results are primarily determined by market preferences and are more treatment configuration related. In addition, validity of the data collected in local plants of China and the restriction of the data availability are also discussed.

3.4.1. Market prices of resources

Material recovery from the secondary resources is one of the key drivers for global trading and recycling of e-waste, therefore the dynamics of material prices have direct influences on the recycling industries. Fig. 7 illustrates that from 2004 to 2010, the prices of copper and palladium have roughly doubled and the gold price increased by a factor 2.5 at an average annual growth rate of 14.5% (LME, 2010). When importing the price dynamics of metals and plastics into the economic calculation of scenario 4 (complete dismantling of computer with state-of-the-art refineries), revenues from treatment obviously follow the same trend as the resource prices. Meanwhile, there is a drastic drop in Cu and Pd prices in 2009 due to the global economic recession, causing the revenue of dismantling to decrease by 28% in contrast to the 2008 peak. Despite these fluctuations, the same economic order for the scenarios investigated in Fig. 4 is found.

Notwithstanding the downturn in 2009, resource prices have shown stable increase in the long term. External forces such as depletion of oil reserves, resource scarcity and rising industrial demand for materials also contributes to the steady increase of resource prices. Rising resource prices will consequentially provide opportunities for better recovery of materials in e-waste. Processes that enable better liberation and end-processing of the target materials are continuing to be encouraged by the global market in this case.

3.4.2. Labor costs

Rising labor costs will lower the profitability of manual dismantling and hence greatly influence the implementation of the Bo2W philosophy. In order to assess the impact of rising labor costs, net profit is used to compare three pre-processing scenarios of desktop computers as shown in Fig. 3: (A) complete manual dismantling, (B) partial dismantling with partial mechanical separation, (C) full mechanical separation. The net profit is calculated by subtracting the labor costs for dismantling from the material revenue (Eq. (1)). p_i is the market price for material i; m_i is the weight of recovered material from recycling; C_{labor} is the unit labor cost per hour, and t_j is the duration for dismantling step j.

$$\text{Net profit} = \text{Material revenues} - \text{Labor costs}$$
$$= \sum_{i=1}^{r} p_i m_i - C_{\text{labor}} * \sum_{j=1}^{s} t_j \qquad (1)$$

Fig. 8 presents the change in profitability of pre-processing methods measured by the net profit, in function of gradually rising labor costs from 2000 to 2035. The labor costs used in the analysis referred to Chinese manual workers' salary statistics (CNBS, 1996–2010), starting from 0.33€/h in 2000 with an annual growth rate of

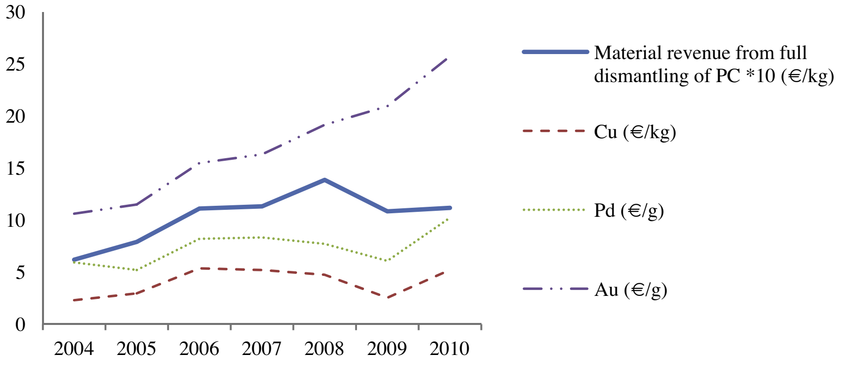


Fig. 7. Dynamics of material prices and corresponding revenues from computer dismantling (2004–2010).

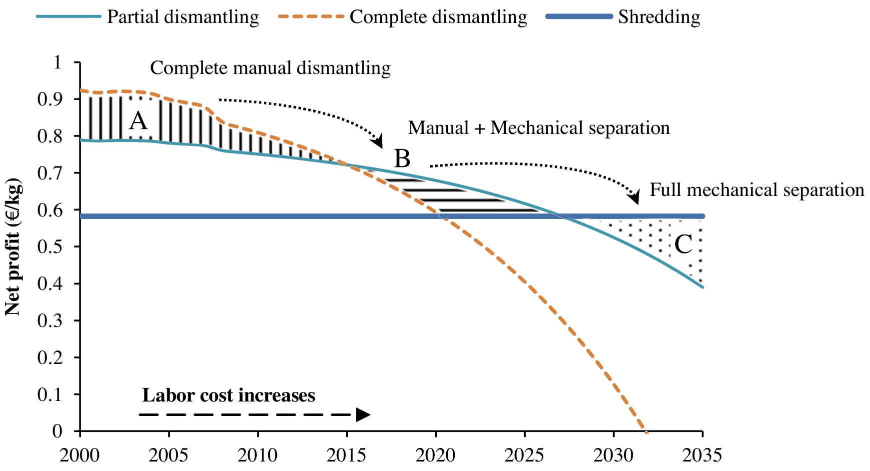


Fig. 8. Transformation of pre-processing methods for desktop computer influenced by increasing labor costs in China (2000–2009, statistic data; 2010–2035, forecast). When labor cost increases, mechanical separation gradually replaces manual dismantling, in order to gain profit (shift from zone A–B and finally C to be economically advantageous).

13.6% until 2009. An estimated annual growth rate of 8% was used to extrapolate the labor costs after 2009, considering a more modest economic growth in China compared to the last 10 years. It was assumed that material prices, energy costs and consequently the revenues from dismantling and mechanical separation stay constant at the level of 2010.

Results of this analysis imply that complete dismantling generates the highest profit until the labor costs reaches 1.26€/h in 2015. As labor costs continue to grow, partial dismantling of higher value components becomes more profitable and mechanization is introduced to selectively replace manual work for complex components (e.g. transformers, power supply and drives etc.). After reaching 2.95€/h in 2026, full mechanical separation becomes the most profitable pre-processing method by replacing all manual work. It is expected that based on the strong economic growth and intense industrialization, China will face a gradual transformation of labor-intensive work into more mechanized and automated processes (Wang, 2008). As this development is also expected for other developing countries, though at a slower pace, it is suggested that transitional change is anticipated by fostering local industries to transform from manual into mechanical processing gradually (Schluep et al., 2009). By doing so, countries can make sure they benefit from the efficiency of manual processes as long as socio-economic parameters prevail over mechanical processes and assuming material and energy costs will stay constant at the 2010 levels.

3.4.3. Data sources and availability

The dismantling session in Taizhou was carried out by trained dismantlers with pneumatic tools on specially designed working tables, and the arrangement of the dismantling activities was optimized according to the planned dismantling sequences. Different workers were arranged to specific fixed tasks along the dismantling chain, such as opening cases, dismantling hard disc/power supply/CD-ROM, taking aluminium sinks and components out of the circuit boards, sorting materials etc. The dismantlers did not switch work in order to improve proficiency and to save time, which helped to derive actual dismantling time for larger scaled operations. This needs to be compared with less optimized processes, in which one worker might dismantle whole appliances until the final level, and constantly switch tools and working positions for different parts (maybe even with incompatible tools). It would be less efficient than more sequentially optimized and realistic dismantling settings as applied in this section.

For the calculation of various scenarios, part of the data were replaced by generic database information because some processes were not installed in China yet (large scale shredding plant for e-waste), or the information about specific process is scarce (the efficiency and emissions of plastic recycling, landfill and municipal incineration in China). When European references were applied (mainly processes in The Netherlands and Switzerland), the environmental impact from the state-of-the-art processes can be substantially lower compared to the local facilities in China, due to higher environmental standards and emission control in the reference systems. Therefore, the overall environmental scores of the seven scenarios in Fig. 4 would have been lower if on-site Chinese data of plastic recycling were applied, and the scores of scenarios 6 and 7 would be significantly lower if there lacks of leachate control in the local landfill sites and off-gas control in the municipal incineration plants. Similar to the environmental scores, the economic performances of scenarios 1–4 would have been lowered when the shredding efficiency and the recycling rate of plastics were inferior to the reference systems. Relative distance between the Bo2W scenarios (3 and 4) versus the mere shredding scenarios (1 and 2) as well as the waste disposal scenarios (6 and 7) would further increase, due to better separation of valuable and toxic materials for the Bo2W scenarios under Chinese final treatment conditions. Future investigation into various end-processing and disposal options in China can make the assessment result more accurate.

3.5. Discussion

The dismantling trial demonstrated the advantage of manual dismantling over mechanical processing in China, and delivering circuit boards to international state-of-the-art is more eco-efficient than local informal treatment. Although there are alternative solutions for the precious metal fractions in developing countries (e.g. aqua regia and cyanide leaching), these approaches are either examined on laboratory level or not yet evaluated for its environmental standards, final destinations of waste and by-products as well as recycling efficiency (Sheng and Etsell, 2007; Cui and Zhang, 2008; Yamane et al., 2011).

Analysis conducted in this section so far was based on the recovery of valuable materials from IT, large and small household appliances. In most developing countries, informal recycling only focuses on the equipment or components with positive market values. The treatment of environmentally critical fractions and emission control are often ignored owing to additional detoxification costs without economic returns. This is especially the case for lead-containing CRT glass with fast-declining market value, mercury containing lamps and coolants from cooling and freezing equipment. Due to the absence of mandatory legislation and financial stimulation, removal and treatment of hazardous fractions is not widely adopted. Even when the toxic fractions are liberated and treated in responsible facilities abroad following the Bo2W philosophy, the added environmental gain does not reflect in an economic gain accordingly. So for these fractions, the application of the Bo2W philosophy is only environmentally advantageous unless combined with the necessary policy or economic interventions simultaneously. Considering the great variety of e-waste categories and diverse interpretations of e-waste scope in developing countries (Osibanjo and Nnorom, 2007), e-waste legislation and management shall set priority for equipment and substances with most environmental and resource impact. In this way, Bo2W philosophy can be better applied to reach an optimal eco-efficiency for most e-waste categories.

4. Pilot projects of Bo2W implementation

Results of the dismantling trials suggest that implementing the Bo2W philosophy in developing countries can be beneficial from an environmental and economic point of view. However, the assessment as presented above is confined within a pre-defined technical system. This section presents case studies where the Bo2W philosophy is implemented in pilot projects (China and India), to discuss challenges and lessons learnt from all relevant societal influences.

4.1. Pilot project in China: a comprehensive large-scale approach

In 2008 a project consortium was formed by the StEP Initiative including two electronic multinational producers, one refurbisher, one European precious metal refiner, various research institutes and one mix-metal scrap recycler. It aimed at setting up a large scale dismantling center in China while connecting to global state-of-the-art end-processing partners, in order to demonstrate the implementation value of the Bo2W philosophy. Personnel (dismantling workers and managers) and 2000 m^2 of industrial area were provided by a mixed-metal scrap recycler in city of Taizhou. Despite substantial technical know-how accumulated after 1.5 years' implementation, the original goal to set up a large scale infrastructure network was not fully reached and lacking commercial success.

The primary challenge was to collect sufficient e-waste at reasonable price levels. Although free batches (around 20 tons of ICT equipment) were provided by producers, such quantities are far from adequate to sustain the plant's daily operation. At the absence of national legislation to regulate e-waste treatment at that time, the informal sector dominated the collection, trading, re-use and recycling. In many developing countries, the collection price does not solely reflect the material value of the recyclables, but also the re-use value from the remaining equipment and components. The pilot project had to pay the integral value to acquire e-waste, even though it does not specifically focus on refurbishment before recycling due to lack of repair expertise (on hardware and software), official authorization from producers, standardization, quality control and guarantees. Together with the internalized cost for environmentally sound treatment, the pilot project was economically not competitive against its informal competitors.

Other challenges were found in business development and management issues, where responsibilities and expectations among the involved partners were not always clear. Herein a pivotal role in leadership was lacking. This adversely affected the planning of the technical routes and material exchanging network, evaluation of the financial feasibility and administration such as resolving issues regarding export taxes, custom notifications, transaction fees and overheads. Another challenge was the communication across cultural and language barriers, between the local dismantler and foreign end-processors and with authorities regarding permitting and export licenses. Lack of transparency, in-depth communication, tracking mechanisms and safeguard measures limited the cooperation between partners due to long distances and subsequent difficulty of continuous quality checks.

Using the global market for the treatment of critical fractions increases the administrative complexity for authorities as well. The environmental bureaus in China are concerned that tracking multiple disassembly fractions overseas is very difficult and the chances of fraud or toxic transfer is regarded significant. Together with increasing focus on strategic 'urban minerals', treating precious metal rich fractions overseas also gains political resistance.

4.2. Pilot project in India: a pragmatic small scale approach

A similar pilot project in India, where the Bo2W philosophy is also applied, resulted in more encouraging outcomes. Until now two batches of PWBs have been shipped to a European end-processor. This pilot project is carried out by the Swiss e-Waste Programme through EMPA involving the informal sector in Bangalore, in partnership with the local recyclers. The pilot project is based on the implementation of alternative business models to target the informal sector, in order to transfer informal wet chemical processes to state-of-the-art recycling technologies (Schluep et al., 2009). A win–win situation is created by encouraging the informal sector to concentrate on the preparation of the optimal fractions as input for the integrated smelter. While creating a financial incentive to pay back their dismantling activities, the environmental impact from improper recycling could be minimized.

The alternative business model allows the local recycling partners to establish themselves as innovation hubs enabling them to act as the key players between the informal and the formal sectors. However, there is a major financing barrier with the five-month delay between the shipment of disassembly fractions from India and the payment from the refiner in the EU (after treatment). This poses serious cash flow issues in the informal sector which usually works on a day-to-day basis. Possible solutions to this problem include a buffer model, where a potent, larger formal recycler (local or international) or an organization acts as an intermediate between the smaller semi-informal recyclers and the integrated smelter. The success of implementing this model was found to be a feasible approach for the safe participation of the informal sectors in the e-waste treatment chain. Despite that they are only involved for the pre-processing steps, their income is ensured, while the formal refiner gains access to higher e-waste volumes from emerging economies.

Although this project gains encouraging results from PWB recycling, it also creates a controversy because the alternative business model, contrary to the Chinese attempt, so far only aims at the valuables and does not address hazardous parts, such as CRT screens or other e-waste fractions with a negative value. A partial implementation of the Bo2W philosophy without taking care of all hazardous fractions can be regarded as 'cherry picking' when no solution is found for other critical fractions. Even though the participating end-processors are not in the position to set up a fully monitored material delivery system for all e-waste fractions, the general challenge remains to carefully examine the environmental and social correctness of the suppliers.

4.3. Summary

The implementation experience in China demonstrates that constructing a large-scale Bo2W recycling infrastructure can be successful when necessary framework conditions are in place, such as sufficient collection, fair access to waste material, legal clearance and financing. The Indian approach can be perfected if toxic control is installed with proper funding to cover all fractions. Implementing the Bo2W philosophy, starting from a small scale towards profitable fractions is more feasible than initiating ambitious plans with comprehensive solutions for all e-waste categories, specifically in case there is no considerable government or financing support. Trust among the waste providers, dismantlers and end-processors can be established when there is stable flow of materials and payment. Informal sectors shall be motivated through paying their collection and disassembly work rather than being excluded or ignored. In the long run, the solution to non-profitable hazardous parts and equipment still has to be addressed. This shall be enforced by 'systemic design' on national levels and local legislators ensuring pre-processors are behaving responsibly with hazardous fractions.

5. Validity of results and conditions for success

Based on the previous analysis, it is concluded that a comprehensive view of all framework conditions and in particular the societal prerequisites are indispensable for implementing the Bo2W philosophy.

5.1. Policy and financing

Establishment of environmental policies and treatment standards can prevent the improper recycling and encourage the environmentally friendly treatment of e-waste. According to the average costs of five long running e-waste management systems in the EU (Huisman et al., 2008), there is an inevitable economic limit for some e-waste categories and derived fractions which makes formal treatment not automatically break-even. Revenues from secondary materials are not sufficient to cover all costs occurring through the entire treatment chain, including taking back discarded equipment from end users (purchase, logistics and storage), toxic handling and material recovery. In respect to dynamic market prices and size of markets for downstream fractions in developing countries, the risks for stakeholders engaging in improper recycling are still high without a financing system as a safety net to cover the deficit.

In the societal system, environmental policy and recycling standards can facilitate the e-waste streams to the proper channels for safe treatment. In addition added environmental value from proper handling shall be encouraged by policies to avoid cherry picking. Without these preconditions practicing the Bo2W in developing countries will only have temporary success and lead to insufficient economic performance in limited treatment scale in the long run.

5.2. Mutual trust and transparency

As experienced in the pilot projects, a significant challenge to set up an eco-efficient treatment system is to establish trust between stakeholders, which takes time and effort. This is highly relevant for various end-processors towards the dismantlers, who are dominant in the recycling hierarchy and free to determine the destinations for their secondary streams. Alternative outlets in the informal market offer higher prices and inferior environmental performance at the same time. For dismantlers in developing countries, selling valuable fractions to the informal market can be rather attractive economically, and this could easily influence the implementation of a Bo2W treatment network. Meanwhile, long distance cooperation made it difficult to establish trust between pre-processors and end-processors through daily communication or field visits to track the relevant fractions and destinations. A key success for the Bo2W implementation is that dismantlers deliver the critical fractions to designated facilities without "cherry picking", thus a global treatment network can be formed for best eco-efficient performance. Lack of trust and experience from authorizations in developing countries (e.g. environmental bureau and customs) regarding outgoing waste shipment notifications also makes it difficult. A direct way to strengthen the cooperation is to file formal contracts between dismantlers and end-processors, with explicit stipulation of material delivery and treatment quality while excluding informal recipients for the same fraction. Additionally, if the critical materials are transferred inter-regionally and become less traceable, a common international platform for sharing knowledge and assessing the treatment quality and mass balance will help to monitor the treatment and improve the mutual trust.

5.3. Transboundary shipment

Increasing globalization and production outsourcing are two significant trends in the modern economy. The majority of labor-intensive production activities have shifted to developing countries to lower the manufacturing costs (Osibanjo and Nnorom, 2007). Along with this trend, a large percentage of the obsolete electronic equipment from the developed world is exported to developing countries for reuse, refurbishment and treatment. The high treatment costs in the exporting countries, growing demands for cheap second hand equipment and materials in developing countries, together with low labor costs and lax (or weakly enforced) environmental standards create strong economic incentives for this trade (Tsydenova and Bengtsson, 2011). However, such global transfer of e-waste has been labeled as "digital dump" because the environmental quality and resource efficiency of such home-grown recycling activities are rather low (Puckett et al., 2002; Brigden et al., 2005). From this perspective, "outsourcing" treatment of e-waste in developing countries cannot generate an equivalent treatment quality in the immediate future compared to developed countries and shall therefore be restricted.

Contrast to the prevailing activities to seek international destinations to reduce production or treatment costs, the Bo2W philosophy aims at a net stream of hazardous or precious metal fractions to the best state-of-the-art end-processing facilities available, in order to reach the best treatment performances from a global perspective. Transboundary shipment of such fractions has limited logistic and economic impacts due to relatively low volumes with only a small portion of the fractions going to advanced end-processing. It is not against the principles of the Basel Convention, which exclusively restricts the shipment of e-waste from OECD to non-OECD countries. Meanwhile, taking into account the mentioned social limitations, the philosophy should not be abused to support the export of e-waste from developed to developing countries. The industrial development and administration in the developing world is yet far from mature to treat all critical fractions with sufficient environmental and economic performance. Bo2W is therefore to be regarded as a transitional and complementary solution for developing countries lacking refineries or treatment facilities for locally generated hazardous waste.

6. Conclusions and recommendations

6.1. Fundamentals of the Bo2W philosophy

The fundamental rationale to apply the Bo2W philosophy in developing countries is:

(1) For the pre-processing stage, manual dismantling (low technology, low operational cost and higher yield of material liberation) is preferred over mechanical separation (high technology, high energy consumption, high investment cost and lower yield of material liberation). In developing countries the pre-processing step is often performed in the informal sector providing a minimal income source for the poor. Having this abundant workforce in mind, high levels of mechanization and automation in pre-treatment processes cannot be justified, due to high investment, increased energy consumption, leading to jobs loss for the poorest and a decrease in revenues because of lower-grade outputs.

(2) For the end-processing stage, technically advanced facilities (high technology with high environmental health and safety performance) are clearly preferred over informal refining techniques (low technology, high environmental, health and safety risks). In developing countries such facilities are usually not available locally for all fractions and it is not under all circumstances practical to locally establish a comprehensive cluster of an advanced infrastructure targeting the entire e-waste treatment chain. Under the limitations of economy of scale, access to global state-of-the-art end-processing facilities can be a pragmatic solution for the critical fractions in developing countries.

(3) Hence, combining the best techniques for manual pre-processing on a local scale with proper environmental, health and safety standards and for high-tech end-processing on a global scale allows achieving the most sustainable solutions for the treatment of e-waste in developing countries.

The Bo2W philosophy is novel to provide an alternative for conventional approaches adopted in e-waste management. It is more pragmatic and economic compared to the construction of a comprehensive recycling chain with all necessary pre-processing and end-processing facilities available locally. The net flow of environmentally critical materials to be treated in global state of the art facilities is an improvement to the current dumping of e-waste, which can overcome substandard processing in developing countries. This philosophy can be applied economically for e-waste categories with high material value (e.g. IT equipment and PWBs). For equipment containing substantial hazardous substances, it demands the assistance from legislations and financing to cover

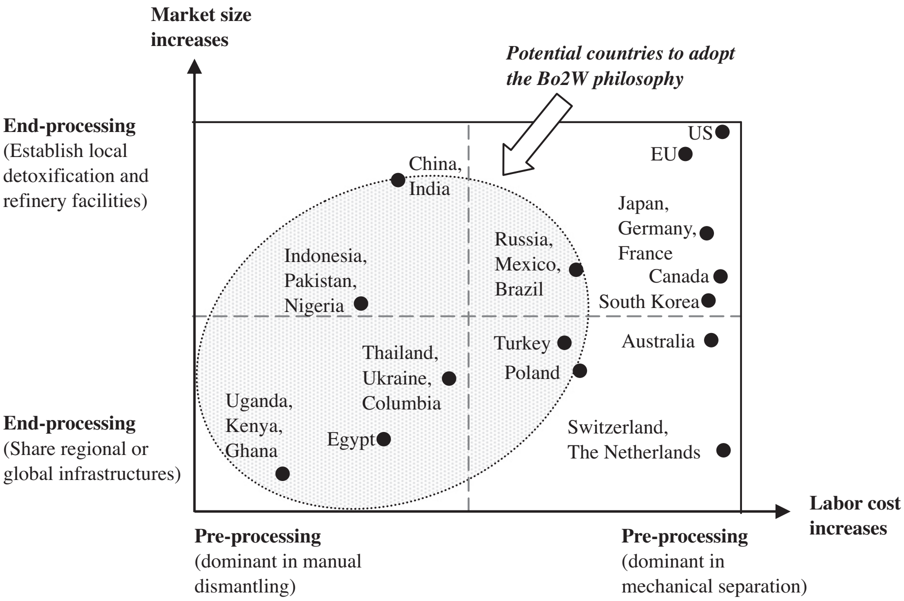


Fig. 9. Potential countries to adopt the Bo2W philosophy for e-waste treatment (estimated at 2010 level).

the costs from the service of detoxification. It is a solution-based approach that can serve as a pragmatic and environmentally responsible transition before establishment of end-processing facilities in developing countries is made feasible.

6.2. Roadmap for suitable implementing regions

Two major aspects determine the feasibility and approaches to implement Bo2W: firstly, the level of labor cost allowing manual dismantling; secondly, the economic and technical conditions (e-waste market size, technical know-how and investment) determining whether setting up advanced end-processes locally or delivering critical fractions to existing global state-of-the-art end-processing facilities. Among these factors, the most critical one is the market size of domestic e-waste, which is dependent on the total population and purchasing power (per capita) in the region (Huisman, 2010).

With these two conditions, a group of possible application countries are projected in Fig. 9 according to their labor costs and market size in 2010. On the right side of the figure, industrialized regions with high labor costs mainly apply mechanical separation. The other countries can fall into the Bo2W scope with different implementing models. Countries with low labor costs and limited market size are the best location to apply full dismantling and share end-processing facilities in global state of the art facilities (like Uganda and Egypt); for countries with medium level labor costs but large e-waste volumes (like China and India), they can practice full dismantling as a start and gradually mechanize processing and arrange international treatment of critical disassembly fractions in the short term before constructing local end-processes in the long run; for countries with relatively high income but limited e-waste generation (like Mexico and Turkey), they can combine dismantling and mechanical processing smartly and treat the critical liberated fractions internationally. It is a first rough sketch of possibilities to apply the Bo2W philosophy. More in-depth investigation into the local and global refining and toxic-handling industries is necessary when defining treatment solutions for one specific country.

The societal relevancy of the Bo2W philosophy approach is very high as this paper demonstrates that optimizing e-waste processing configurations on an international scale could yield substantial environmental and economic improvements. It is a transitional method that enables developing countries to improve the status of informal sector treatment without a leap into high-tech investments and cutting jobs for the poor. Through the implementation process, skills and technology transfer can be triggered to facilitate an industrializing process. By its comprehensive nature, it can assist in a better global optimization of e-waste treatment and faster development of highly desired sustainable take-back and recycling systems, in a world of rapidly growing supply and demand for materials used in and derived from electronics.

Future research should focus on mapping patterns and trajectories of developing e-waste recycling industries in emerging economies, from the informal recycling to formal/full-scale state-of-the-art treatment. This would enable the implementation of the Bo2W philosophy during the industrialization and formalization process. To further explore the feasibility of applying this philosophy, additional pilot projects towards processing of different equipment types containing hazardous fractions under different socioeconomic conditions are desirable. Identifying alternative financing models targeting the responsible handling of hazardous fractions can make the implementation of the Bo2W philosophy more feasible to solve the e-waste problem in developing countries.

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