One laptop per child, local refurbishment or overseas donations? Sustainability assessment of computer supply scenarios for schools in Colombia

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ABSTRACT

With the intention of bridging the 'digital divide' many programmes have been launched to provide computers for educational institutions, ranging from refurbishing second hand computers to delivering low cost new computers. The fast and economical provision of large quantities of equipment is one of the many challenges faced by such programmes. If an increase is to be achieved in the sustainability of computer supplies for schools, not only must equipment be provided, but also suitable training and maintenance delivered. Furthermore, appropriate recycling has to be ensured, so that end-of-life equipment can be dealt with properly. This study has evaluated the suitability of three computer supply scenarios to schools in Colombia: (i) 'Colombian refurbishment', -refurbishment of computers donated in Colombia, (ii) 'Overseas refurbishment', -import of computers which were donated and refurbished abroad, and (iii) 'XO Laptop', -purchase of low cost computers manufactured in Korea. The methods applied were: Material Flow Assessment, -to assess the quantities-, Life Cycle Assessment, -to assess the environmental impacts, and the application of the Multiple Attribute Utility Theory, -to analyse, evaluate and compare different scenarios. The most sustainable solution proved to be the local refurbishment of second hand computers of Colombian origin to an appropriate technical standard. The environmental impacts of such practices need to be evaluated carefully, as second hand appliances have to be maintained, require spare parts and sometimes use more energy than newer equipment. Providing schools with second hand computers from overseas and through programmes such as 'One Laptop Per Child' has the disadvantage that the potential for social improvements – such as creation of jobs and local industry involvement – is very low.

1. Introduction

Information and Communication Technologies (ICT) have rapidly changed the dynamics of business and everyday life. The role of ICT in sustainable development strategies is widely discussed (Hilty et al., 2006; Hilty, 2008). The benefits and range of ICT applications seem boundless. Yet not all parts of the world profit equally from the high pace of this technological development. Since the mid-1990s, the gap between those who have, and those who don't have access to digital communication systems has been labelled the 'digital divide', and has become an issue on the political agendas in developing countries. Several studies have shown that there is no generic solution to overcome the 'digital divide' (Mansell, 1999; Tipson and Frittelli, 2003).

Many countries have realised that great progress can be made when the younger generation is given access to ICT and educated in the use of such equipment. Nevertheless, one of the main hurdles which schools in developing countries have to overcome remains the difficulty of providing physical access to ICT equipment (Pelgrum, 2001; Hawkins, 2004). Several international and national initiatives have been launched to specifically provide ICT equipment to schools or to educate pupils in the use of such tools. Although the intentions of the initiatives are similar, the means they choose to achieve this end vary widely (James, 2001, 2002).

In 2005, the initiative 'One Laptop Per Child' (OLPC) announced its US $100 laptop project at the World Economic Forum in Davos (OLPC, 2008). The vision of this initiative was to produce laptops exclusively designed for children, the so-called 'XO Laptop', and make them in

huge quantities affordable to the governments of developing nations. Since then, the price of the 'XO Laptop' has increased several times, *inter alia* due to the fact that sales have not yet achieved the expected levels (Arstechnica, 2008; OLCP News, 2008).

A different approach is taken by ICT reuse programmes launched in industrialized countries, such as the UK based 'ComputerAid', the Belgium founded 'Close the Gap' or the US based 'World Computer Exchange' (close-the-gap, 2008; Computer Aid International, 2008; World Computer Exchange, 2008). Under these programmes, obsolete computers from industrialized countries are collected, checked, refurbished and sold to developing countries. The organisations are non-profit and sell the equipment at a price that just covers their expenses.

In developing countries themselves many national initiatives have been launched to promote ICT use at schools. The majority of the programmes rely on refurbished second hand computers, low cost computers or both as their supplies of hardware. In Latin America the Chilean initiative "Enlaces" fosters ICT supported education jointly with the comprehensive educational Web site of the Chilean government (Hepp et al., 2004; EducarChile, 2008; Enlaces, 2008). In a complementary manner, the 'Todchilenter' programme refurbishes donated computers from public and private institutions (Steubing, 2007). In Costa Rica the Fundación Omar Dengo similarly promotes the educational, social and economic development by means of ICT (FOD, 2008). The Mexican based 'RedEscolar' provides schools with computers, Internet connectivity, a TV set and a wide range of educational resources (RedEscolar, 2008). In 2000, Colombia launched the refurbishment programme 'Computadores Para Educar' (CPE). CPE is a governmental initiative managed by the 'Ministerio de Comunicaciones' in partnership with the 'Ministerio de Educación' and the 'Servicio Nacional de Aprendizaje'. The programme was founded with the aim of supplying public educational institutions (mainly schools) with ICT through the refurbishment and maintenance of computers, and promoting the use and benefits of ICT during the education process (CPE, 2008). The programme 'Computers for Schools Kenya' is an adaptation of the similarly named Canadian programme, which intends to provide low cost ICT equipment to educational institutions, to maintain and service the equipment and to educate the participants in the use of the appliances (CFSK, 2008).

An initiative of an entirely different type is the 'hole in the wall' project, launched in 1999 in India (Mitra et al., 2005; HiWEL, 2008). Free access to computers was provided by placing them behind a window in unsupervised computer kiosks with access to a keyboard and a mouse through a slit, mainly designed for children. The successful project was replicated in many rural places in India and other Asian countries and also enabled the learning process of users to be monitored.

When decisions have to be made concerning the type of computers which should be supplied to schools for educational purposes, governments and policy makers are caught in the dilemma of whether to put more emphasis on educational aspects or the supply of hardware. There is no doubt that the fast and economical supply of ICT equipment is a necessary condition for the spread of computer literacy; but the problem is not solved by only providing the equipment. Several studies have shown that constant support, continuous staff training and local involvement are crucial if ICT tools are to be effectively integrated into education programmes (Hayes and Allison, 1998; OECD, 2003; Hepp et al., 2004). Lastly, local conditions – such as the ability to maintain and repair equipment and appropriate facilities for treating end-of-life equipment – also need to be considered. Inappropriate handling of waste from electronic equipment (or e-waste for short) can have a detrimental effect on the environment and one's health (Sepúlveda et al., in press).

Several methods have been applied to assess at least one of the three sustainability dimensions (economic, ecological and social) of ICT introduction to schools.

Life Cycle Assessment (LCA), as a standard methodology to assess environmental aspects, has been applied to ICT equipment (Zumbühl, 2006; Eugster et al., 2007). The advantage of LCA is that material and energy flows can be jointly evaluated by linking them to predefined categories of detrimental effects on the environment and human health.

Life Cycle Costing has been applied to evaluate the economic aspects along the life stages of the ICT goods (Kang and Schoenung, 2006; Nakamura and Kondo, 2006). In contrast to traditional LCA studies, these studies combine environmental with economic assessment, but most of them have a clear focus on the end-of-life treatment of ICT (Huisman, 2003; Atlee and Kirchain, 2006; Park et al., 2006; Scharnhorst et al., 2006).

Material Flow Assessment (MFA) models combined with an economic evaluation of the material flows have been developed to study the driving forces for material recycling processes from ICT equipment (Streicher-Porte et al., 2007).

In order to assess the overall sustainability of the use of ICT equipment, *Multiple Attribute Utility Theory (MAUT)* has been applied in the field of ICT (Zumbühl, 2006). MAUT assessments are particularly suitable when decisions have to take incommensurable dimensions into account – such as economic, social, and environmental impacts, stakeholder preferences and national or regional conditions. The present study has applied this method to the supply of computers to schools in Colombia through the above-mentioned programme CPE by evaluating three different supply scenarios. The study introduces this comprehensive sustainability assessment method as one possible tool for decision makers. Taking a look at the entire life span of the hardware provided, indicators relevant for sustainability are evaluated and aggregated to a single numeric value.

2. Methods

In this study, a combination of the three methodologies mentioned above was used to cover the majority relevant aspects of the system under study.

2.1. Material Flow Assessment (MFA)

In order to determine the exact material flows within the CPE programme, a Material Flow Assessment (MFA) was conducted. An MFA is a systematic assessment of the flows and stocks of materials within a system defined in space and time. It determines, describes and analyzes the metabolism of industries, regions or materials. "Metabolism" here refers to the transfer, storage and transformation of materials within the system and the exchange of materials with the system's environment (Brunner and Rechberger, 2004). The results of an MFA deliver data to be used in the subsequent research steps. The smallest entity traced through our system is a desktop PC with a cathode ray tube monitor (CRT), a keyboard and a mouse. In order to evaluate the environmental impacts of these units, an average material composition was assumed. The detailed MFA was carried in 2007 by Marthaler (2008) and can be found in the 'Swiss e-waste guide (2008)'.

2.2. Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) was applied in order to evaluate the environmental performance of the supply of computers to schools. The methodology followed the international standard procedure for LCA (ISO, 2000) and used the Eco-indicator'99 (H/A v203) (Goedkoop and Spriensma, 2001) as its aggregation and evaluation

method. The reason for this was the fact that Eco-indicator'99 uses so-called damage categories: Human Health, Ecosystem Quality and Resources (mineral and fossil), which reflect the three attributes chosen for the environmental assessment.

The 'Hierarchist' perspective of Eco-indicator'99 was chosen for weighting the dimensionless normalised values per damage category.

The collected inventory data was complemented with data from the database 'Ecoinvent v2.0' (ecoinvent, 2007) and analysed with the software product 'Simapro' (PRé Consultants, 2008).

The entire production – in the case of the OLPC-, or some refurbishing steps, -in the case of donations from overseas – are performed outside Colombia. Some of the production or refurbishing processes are even performed in middle or high income countries such as Korea and the UK. In addition to the difficulty of collecting data on all production steps, it is also hard to compare the costs of production with Colombian prices. Therefore, the mass based LCA was given preference over LCC. Another reason for the choice of LCA was the need to evaluate the environmental impacts stemming from material losses and the benefits of recycling.

2.3. Multiple Attribute Utility Theory (MAUT)

MAUT is a case evaluation method used for analysing, evaluating and comparing different alternatives. The objective of a MAUT assessment is "…to obtain a conjoint measure of the attractiveness (utility) of each outcome of a set of alternatives", which usually are different scenarios (Scholz and Tietje, 2002). The utilities of the scenarios can be compared with each other. The utilities calculated in this study are additive utilities with linear value functions as introduced by von Winterfeldt and Edwards (1986) and Fishburn (1988). The theory itself goes back to Keeney and Raiffa (1976).

The user of the MAUT methodology has to define a set of attributes intended to reflect the overall attractiveness (utility) of each scenario. In a further step each scenario is evaluated according to the list of attributes. With the normalised attribute values an overall utility of each scenario can be calculated. Additionally, each attribute can be given a weighting factor usually determined by stakeholder consultation. In the following subsection, the calculation steps for the utility values are briefly introduced. The attributes used in our study are discussed in Section 3.3.

2.3.1. Normalisation of attributes

Due to different units and scales of the attributes, their values have to be normalised in order to make them comparable. This can be achieved by normalising the values of a single attribute overall the scenarios. The resulting range for the values of a_n is between zero and one.

For the attributes, for which the values are proportional to their utility, the formula is as follows:

$$a_n = \frac{a_i}{\sum_{j=1}^{m} a_j} \tag{1}$$

If the values are reciprocally proportional to their utility, the formula is:

$$a_n = 1 - \frac{a_i}{\sum_{j=1}^{m} a_j} \tag{2}$$

a_n being the normalised and a_i the original value of an attribute of a certain scenario S_i.

2.3.2. Weighting factors

The weighting of the attributes was realised through stakeholder interviews with representatives of CPE, of the national directorate at the 'Ministry of Communication', of the 'Universidad Nacional' and of 'ComputerAid'. A total of 12 individuals were consulted for their preferences. All participants held leading positions in management. The participants were asked to allocate an importance between 0 and 4 to each attribute. 0 implied 'no importance', and 4 'very high importance'. A total of seven preferences were completed. The weighting factors of all attributes were normalised using formula (1).

2.3.3. Utility of the scenarios

Once the measured values have been normalised, the unweighted or additive utility for each scenario can be calculated as the sum of all utilities.

$$u_i = \sum_{j=1}^{n} a_j \tag{3}$$

where $a = (a_1, a_2, a_j, ..., a_n)$ is the set of attributes.

In order to obtain the total weighted utility for each scenario, the additive utility per attribute is multiplied by the normalised weighting factor. Formula (4) gives the total normalised weighted utility of a scenario. Other studies have used similar approaches to assess the utility of scenarios (Sutter, 2003; Hajkowicz, 2006; Zumbühl, 2006).

$$U(S_i) = \sum_{j=1}^{m} w_j u_j \tag{4}$$

where $U = (u_1, u_2, u_j, ..., u_n)$ is the set of utilities, $S = (S_1, S_2, S_i, ..., S_m)$ the set of scenarios and $W = (w_1, w_2, w_j, ..., w_n)$ the set of importance weights.

3. System and scenario description

3.1. System description

'Computadores Para Educar' was founded in 2000 by the Colombian government with the aim of supplying public educational institutions (mainly schools) with ICT. Since then CPE has supplied more than 10 000 public schools all over Colombia. An estimated 3 000 000 students have benefited from the programme (data from 2008).

The cores of the programme are the five 'Centros de Reacondicionamiento' (CRs, refurbishment centers) suited in the major towns of Colombia Barranquilla, Bogotá, Cali, Cúcuta and Medellin. These centres are at present delivering a total yearly output of 20 000 refurbished computers.

Lately the Colombian government defined the goal of reducing the ratio of 'pupils per computer' between 2006 and 2010 from 48:1 to 20:1 and to supply 70 percent of the public schools, while 45 percent of all computers are to stem from CPE. This requires the delivery of 46 000 refurbished computers per year. Since the output of the CRs will not be able to meet this demand, alternatives that could be incorporated into the programme of CPE had to be evaluated. CPE considered buying computers from refurbishment programmes overseas or from the OLPC initiative, which was a reason to include these options in our study. In order to receive overseas refurbished computers the 'Centro de Ensamble de Equipos del Exterior' (CEEX, assembly centre of overseas donated equipment) was supposed to be implemented, but has not been. Nor has the Colombian government yet ordered any XO Laptops.

In order to provide CPE with an appropriate treatment of the accumulated e-waste, the 'Centro Nacional de Aprovechamiento de Residuos Electrónicos' (CENARE, centre of e-waste recycling)

started operating in 2007. CENARE dismantles end-of-life equipment only manually. The recovered components and pure material fractions are sold to recycling facilities or smelters. Complex material fractions such as printed wiring boards or batteries are exported for appropriate treatment. A characteristic of the CENARE is the storing and reuse of some components in a subprogramme called 'Robotic', which aims to sensitize students for possible applications of ICT components and to spark their interest in science and technology in general. CENARE designs kits out of computer components to teach the students various applications such as an *electronic door*, a *fotomobile*, a *weather vane* and a *tetrapod*. The material flow into and from the subprogramme 'Robotic' was taken into account. Fig. 1 gives an overview of the entire life span of a computer in a generic form including the particular processes, institutions and units within the system boundary of Colombia. The four units of the CPE programme are highlighted in white.

3.2. Scenario description

We defined three scenarios of the supply of computers: 'Colombian refurbishment', 'Overseas refurbishment' and 'XO Laptop'. The supply of *50 000 computers for a five-year usage period at schools* was selected as functional unit. This corresponds roughly to the targeted amount and targeted life span of refurbished computers under the CPE programme. The scenarios were calculated as 'extreme' scenarios: In each scenario, there was only one source of computers (i.e. Colombian donations, overseas donations or OLPC purchase). This allowed us to determine clearly the pros and cons of each attribute per scenario. In reality a mixed supply strategy was followed. An overview and description of the scenarios are given in Table 1.

For the two scenarios 'Colombian refurbishment' and 'Overseas refurbishment' the computers provided consist of a desktop PC equipped with a CRT monitor, a keyboard and a mouse. For the 'XO Laptop' scenario, it is assumed that the laptop is self-contained and does not require any peripherals.

3.3. Attributes used in the MAUT assessment

In order to evaluate the sustainability of the scenarios, a set of attributes which represent the economic, environmental and social characteristics of the scenarios was compiled. Guidance for the choice of attribute was given by the commonly accepted definition of sustainability, which refers to a development that "…*meets the needs of the present without compromising the ability of future generations to meet their own needs.*" Sustainable development is today widely accepted as social, economic and environmental developments which "*can and should be mutually reinforcing*"

(World Commission on Environment and Development, 1987). Keeping this in mind, the authors initially defined the attributes in discussions with experts from the 'Sustainable Technology Cooperation' Group at Empa and CPE; later the definitions were further adjusted during the research.

3.3.1. Economic performance

Net costs and technical value were chosen as economic attributes. The technical value falls under economic attribute as the widespread need for the latest equipment directly influences the price for both, new and refurbished equipment.

3.3.1.1. Net costs. A detailed cost analysis for CPE was realised based on the financial results of the years 2006 and 2007. The costs at the CRs, CEEX, CENARE and for maintenance services were all calculated separately. For the refurbishment process the production costs were differentiated into direct labour costs, indirect labour costs, direct material costs and indirect material costs. Further costs included promotion, maintenance, monitoring, transport to disposal, and disposal.

The total costs are calculated per year and per computer unit.

Low net costs imply high utility, as the programme seeks to supply as many schools as possible with computers.

3.3.1.2. Technical value. This attribute was introduced in order to meet concerns about the different technical levels of the computers delivered. It is reviewed semi-quantitatively and ranked between 1 and 4. The choice of this attribute was based on our assumption that a higher technical standard would promote broader application and a better education to users. It would therefore create a higher value for the national economy. For each scenario the percentages of computers having a processor equivalent to 'Pentium I or lower' (1), 'Pentium II' (2), 'Pentium III' (3) and 'Pentium IV and higher' (4), were calculated.

A high technical value implies high utility.

3.3.2. Environmental performance

The assessment of environmental performance is indicated in Table 2 as the evaluation of the three attributes: 'use of energy', 'use of resources', 'amount of toxic emissions'. These attributes are best reflected in the damage categories of Eco-indicator'99: 'Resource Depletion', 'Ecosystem Quality' and 'Human Health'. The life cycle stages investigated were production, use, refurbishment, transport, recycling and (final) disposal. The demand for material resources and the energy consumption during these stages are related to the damage category 'Resource depletion'. The volume of all wastes and emissions of toxic substances overall stages is reflected in the categories 'Ecosystem Quality' or 'Human Health'.
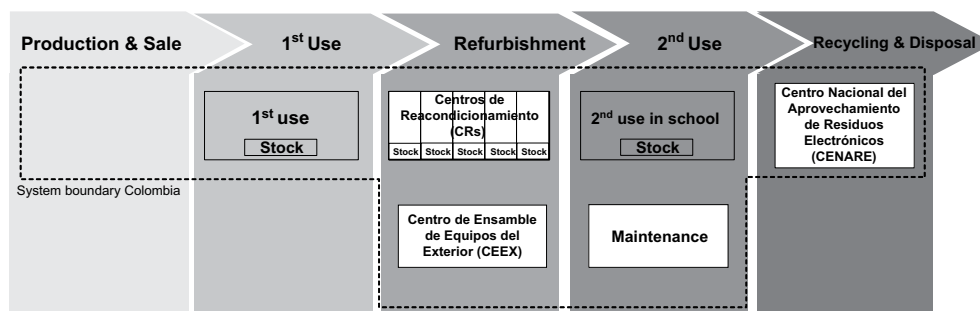

Fig. 1. 'Computadores Para Educar' (CPE), five 'Centros de Reacondicionamiento' (CRs) refurbish computers donated in Colombia. The 'Centro de Ensamble de Equipos del Exterior' (CEEX) is a foreseen part of CPE and deals with donations from overseas. This project part is not yet in operation. The 'Centro Nacional de Approvechamiento de Residuos Electrónicos' (CENARE) recycles the end-of-life equipments from CPE.

Table 1
Overview and description of supply scenarios.

Scenario	Description
Colombian refurbishment	All computers stem from Colombian donators. They are refurbished in one of the five refurbishment centres throughout Colombia and distributed from there to the schools. Maintenance takes place after two-years usage at schools.
Overseas refurbishment	Computers are being refurbished at a programme overseas and then transferred to the CEEX. At the CEEX a last check up and software installation takes place before distribution. Maintenance takes place after three-years usage at schools.
XO Laptop	The supply is guaranteed by purchasing the XO laptop. Neither computers are being refurbished nor is maintenance necessary.

The results are normalised Eco-indicator'99 points, indicating the 'sum of environmental losses and environmental benefits'.

Environmental benefits can occur when raw materials are saved due to recycling. Earlier studies have shown that these benefits can reduce the impacts considerably, under the condition that environmental standards are fulfilled (Hischier et al., 2005). For assessing the benefits, a classical LCA allocation problem had to be answered: Which share of avoided impacts from production should be taken into consideration? In order to test the sensitivity of different allocation schemes, three options were considered: 'Complete recycling', 'Allocated recycling' and 'Allocated production and allocated recycling'. 'Allocated recycling' was chosen for the calculation of the sustainability results of this study. The different allocations schemes are described in section 4.4, followed by analysis of the effects on the overall results when choosing a different scheme.

3.3.3. Social performance

Manhart and Grießhammer (2006) investigated the social impacts of the production of notebook PCs. They subdivide the impacts into three levels: 'employee', 'local community' and 'society'. The 'employee' level refers mostly to standard contracting rules, such as the 'use of child labour' and 'social security'. The level 'local community' relates to corporate and domestic policy domains such as 'indigenous rights'. Since CPE is a governmental initiative, it can be assumed that working conditions meet the Colombian labour legislation (Código sustantivo del trabajo, 2008). Therefore no criteria regarding the 'employee' or 'local community' levels were considered. On the 'society' level Manhart (2007) looks at

impacts such as 'corruption', 'intellectual property rights', 'contribution to national economy and budget', and 'employment creation'. The 'employment creation' of CPE was considered through two attributes: the creation of low or semi-skilled jobs and the creation of high-skilled jobs. The impact on the national economy was considered by a qualitative assessment of the involvement and participation of the local economy.

Corruption and violation of intellectual property rights were not assessed. The reason for this is the relatively broad exposure and official character of the CPE programme as a government initiative, which allow us to assume that employees are less vulnerable to corruption and more likely to respect intellectual property rights.

3.3.3.1. Creation of low or semi-skilled jobs. This attribute reflects the number of jobs provided by a scenario that do not require a university degree. Only directly process-related jobs are considered, e.g. the job for a technician at one of the CRs is included, while the creation of a job as driver for a transport company is not included. A high number of jobs created imply high utility.

3.3.3.2. Creation of highly skilled jobs. This attributes reflects the number of jobs provided by a scenario that do require a university degree. A high number of jobs created imply high utility.

3.3.3.3. Involvement/participation of the local economy. The involvement/participation of the local economy was only assessed qualitatively taking into account the processes refurbishment (where applicable), maintenance, recycling as well as all transport processes. The existence of a particular local process increases the value of the attribute by 0.25. The involvement/participation is 1 in cases where all four processes are present or 0 if none of the processes occurs. A high involvement/participation of the local economy implies high utility.

4. Results

4.1. Material flows

The total demand for computers in each scenario is determined by the failure rate of the refurbishment activity (if applicable) and the average life span of a provided computer. The necessary

Table 2
Set of attributes used for the MAUT.

Attribute	Unit	Description	Weighting factor	Normalised weighting factor
Economic performance				
Net costs	$/computer	Costs for transport, labour, material, fabrication, promotion, maintenance, accompaniment, monitoring minus the revenues (material values out of recycling)/computer	3.33	0.14
Technical value	[1, 2, 3, 4]	Value is based on technical standard (processor generation) of the computers being supplied	2.83	0.12
Environmental performance				
Use of energy	Normalised Eco-Indicator'99 points (=sum of environmental losses and environmental benefits)	Energy needed during total life span/computer	2.67	0.12
Use of material resources		Material resources needed during total life span/computer	3.00	0.13
Amount of toxic emissions		Emissions through whole life span minus prevented emissions due to savings of raw materials/computer	2.00	0.09
Social performance				
Creation of low or semi-skilled jobs	Number of jobs/computer provided for schools	Providing of low and semi-skilled jobs within Colombia	2.50	0.11
Creation of highly skilled jobs	Number of jobs/computer provided for schools	Providing of highly skilled jobs within Colombia	3.33	0.14
Involvement/participation of local economy	[0, 0.25, 0.5, 0.75, 1]	Share of local economy involved into implementation	3.33	0.14

donations, the number of laptops produced, and the number of components required during refurbishment and maintenance were calculated using material flow analysis.

The failure rates for computers, CRTs, keyboards and mice of Colombian donations were calculated based on data of the CPE programme. The total amounts donated, the number of refurbished computers, the purchased parts, the stocks and the internal use of equipment are documented since the year 2000. The specific failure rates of the three scenarios are summarised in Table 3.

The average life span of a donated computer is determined by the failure rate and affects the demand. As the functional unit chosen requires a five-year usage period at schools, computers which function less than five years have to be replaced by others. Experience has shown that Colombian donated computers have a two-year life span on the average, which can be extended with maintenance to a total of four years (Ricaurte, 2007). The necessary amount of Colombian donations is, therefore, higher by a factor of 1.25 than the original amount required. It is assumed that continuous maintenance is provided during the five-year usage period at schools.

For the 'Overseas refurbishment' scenario a three-year usage period was confirmed (Fairweather, 2008). The computers under this scenario are provided in a refurbished condition. As the technical value of the overseas donated computers is higher than the Colombian donations, it was assumed that another two-year usage could be expected under the condition that the computers be maintained during this time. In order to compensate for possible damage during transport, 'ComputerAid' adds 28 additional computers to a 40-foot container with 450 computers (Computer Aid International, 2008). This explains why 6 percent more computers are imported than provided to schools by CEEX.

The average age of a computer before entering the CPE system is of some importance, as possible benefits out of the recycling are allocated to a scenario by relating the computer's time spent in the system relative to its total life span. Computers donations of Colombian origin are on average five years old according to investigations of CPE. Provided that these computers are refurbished and maintained, a second use phase of four years can be achieved (Ricaurte, 2007). Therefore 4/9 of the benefits from appropriate recycling at CENARE for a Colombian donated computer are allocated to the 'Colombian refurbishment' scenario. Computers donated overseas are four years old and can remain functional for another five years with maintenance. Accordingly, 5/9 of the benefits from recycling are credited to the 'Overseas refurbishment' scenario. For the scenario 'XO Laptop' a five-year usage period without maintenance was assumed, based on the information provided by the OLPC project (Jepsen, 2007).

The computers are dismantled at CENARE. Plastic and cables are sold to a local recycler for further treatment. Metals (e.g. steel, copper, aluminium) are sold on the local market. Ceramics and other waste are disposed of in landfills. At present there exists no solution within Colombia for treating the printed wiring boards (PWBs), the funnel glass or the liquid crystal display of the 'XO Laptops'. CPE reuses some parts of the PWBs for 'Robotic' platforms. We therefore assume that the funnel glass and the LCD module are exported for state-of-the-art treatment, whilst 50 percent of a PWB is separated for 'Robotic' platforms before the rest is exported.

In Fig. 2 the three scenarios are illustrated graphically. All flows are related to the functional unit of supplying 50 000 computers for a usage time of five years at schools.

4.1.1. Colombian refurbishment

93 122 computers per year would need to be donated exclusively of Colombian origin (Fig. 2A) to reach the functional unit targeted. One third of the donated computers would need to be directly recycled at CENARE. Two thirds of the computers (62 500) would be refurbished at one of the five refurbishment centres of CPE and then distributed to the schools.

4.1.2. Overseas refurbishment

The total numbers of computers donated to 'ComputerAid' is shown in Fig. 2B. The refurbisher collects donated computers in an industrialized country and refurbishes them locally. From abroad they are shipped to a developing country. 'ComputerAid' provides 53 000 computers to CEEX. Six percent are directly recycled due to transport damage or technical failure. With maintenance the 50 000 computers have a second life span of five years.

4.1.3. 'XO Laptop'

Under this scenario 50 000 'XO Laptops' are purchased and provide service for five years without maintenance (Fig. 2C).

4.2. Performance of the scenarios

4.2.1. Economic performance

4.2.1.1. Net costs. Table 4 gives an overview of the overall costs for each scenario (in US$).

We assume similar administration expenditures on a national level for all scenarios. No overhead costs of the national directorate are therefore included.

Production costs for computers refurbished in Colombia and all further costs are based on the budget 2006 and 2007 of CPE (Camacho, 2007). Overhead costs of the CRs are included. The costs per unit already include the adjustment factor 1.25. For the production costs of computers provided through the CEEX an average price of a computer was based on declarations of 'ComputerAid' on their homepage in June 2007 (Computer Aid International, 2008). The price for the 'XO Laptop' is based on the corresponding market price in 2007 for the sales of 'XO Laptops' to Uruguay (OLCP News, 2008; OLPC, 2008).

The differences in the promotion costs are due to the relatively high costs needed to reach Colombian donors under the 'Colombian refurbishment' scenario. Five US$ per computer are the average expenditure for providing the ICT support of schools within Colombia. In the case of the 'XO Laptop' no costs during the support phase are included due to the autonomous learning process of the children. This explains the difference for the accompaniment and monitoring costs. Maintenance does take place in the 'Colombian refurbishment' and 'Overseas refurbishment' scenarios. Material revenues (negative costs) through recycling are of minor importance for the overall costs.

From a total purchasing standpoint, an 'XO Laptop' is the most economical option. Buying an overseas refurbished computer is almost 30 percent more expensive. A computer refurbished in Colombia results in almost double the price.

4.2.1.2. Technical standard. Our baseline consisted of data on the percentage of the value of second hand computers donated to CPE comprised by the processor in the donations in 2006 and 2007 and in production in 2006 at the Refurbishment Centre in Bogota.

Table 3
Failure rates for individual components for each scenario in percent of the total donations or purchases (Computer Aid International, 2008; CPE, 2008; OLPC, 2008).

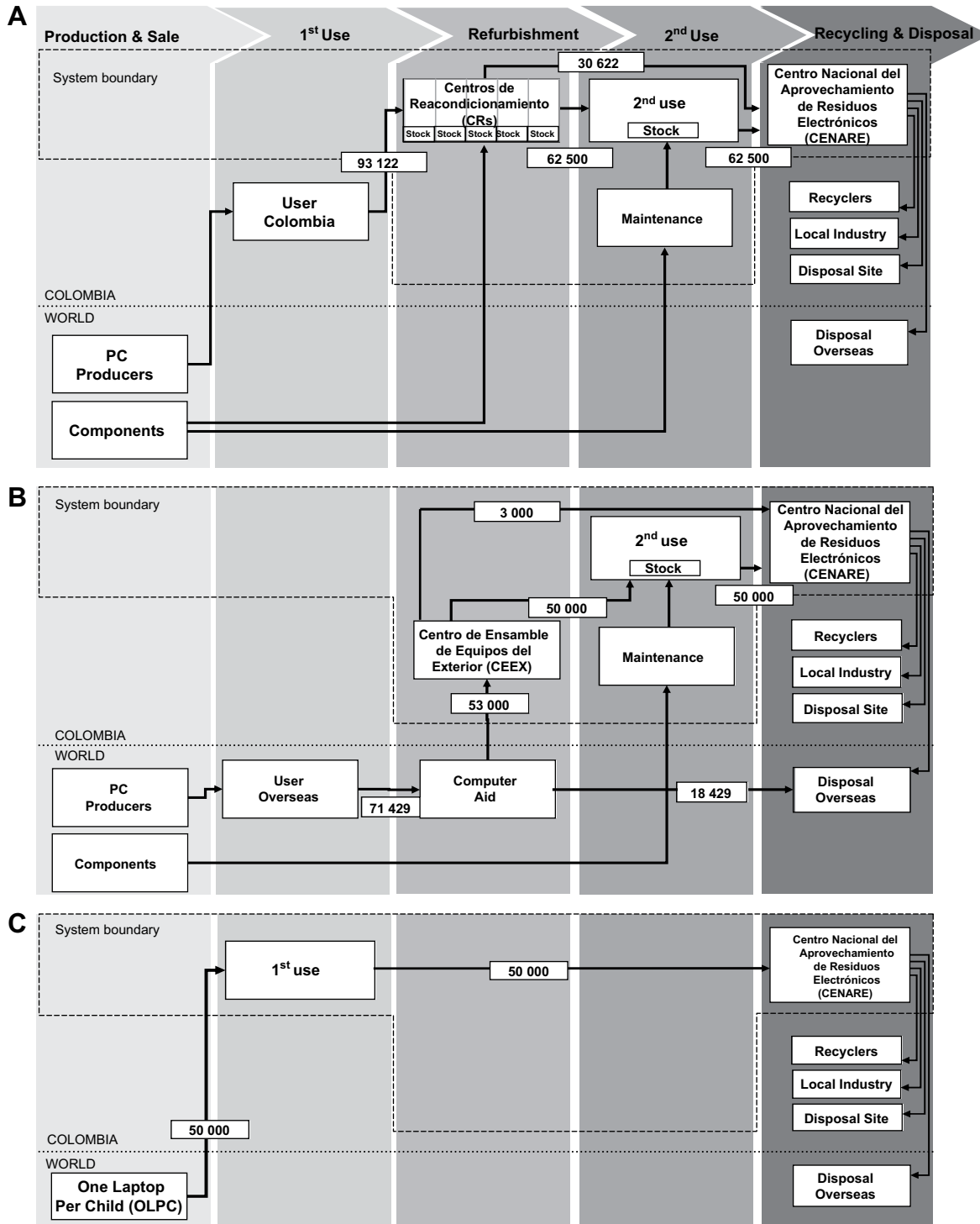|	Desktop PC	CRT monitor	Keyboard	Mouse
'Colombian refurbishment'	33	47	37	50
'ComputerAid'	6	6	6	6
'XO Laptop'	<1	–	–	–

Fig. 2. Material flows of scenarios. A: 'Colombian refurbishment'. Computers are provided exclusively by Colombian users. Note: the supply of 65 000 computers is necessary to meet the demand of one functional unit (adjustment factor 1.25). B: 'Overseas refurbishment'. Computers are provided exclusively from abroad. C: 'XO Laptop'. The supply is guaranteed by purchasing 'XO Laptops'.

The technical standards for computers originating from 'ComputerAid' are based on their declarations. At present (2008) 'ComputerAid' guarantees a share of 60 percent 'Pentium III' and 40 percent 'Pentium IV' for their deliveries (Computer Aid International, 2008). The 'XO Laptop' was assumed to meet the latest technical standards. Table 5 gives an overview of the technical standards applied, their share in each scenario and the values

given in this study. The CPE classification of technical standards for refurbished computers is compatible with the classification of 'ComputerAid'.

The highest technical standard is achieved with the 'XO Laptop' followed by computers originating overseas. If supply were provided through the CRs exclusively, the technical standard would be the lowest of all.

Table 4
Overview of the overall costs (in US$) for each scenario.

Scenario (source)	Colombian refurbishment (Camacho, 2007)		Overseas refurbishment (Computer Aid International, 2008)	XO Laptop (OLCP News, 2008)
Type of cost	Total	Per unit	Per unit	Per unit
Production costs	12 468 168	249	154	188
Promotion	2 862 169	57	5	5
Accompaniment & Monitoring	9 182 802	184	156	87
Maintenance	3 781 250	76	56	0
Transport (includes distribution and take back to CENARE)	2 500 000	50	40	40
Costs CENARE	−15 541	−0.31	−0.13	−0.03
Total	30 794 389			
Total per unit		616	410	320

4.2.2. Environmental performance

In order to calculate the environmental performance of each scenario, we assessed the production, transport, use, electricity consumption and the disposal of all included materials necessary to provide one functional unit based on the results of the MFA.

Our first step was to derive data on production from the 'Ecoinvent v2.0' database. Adjustments had to be made for the 'XO Laptop', for parts used for the 'Robotic' platform and for the components microphone, loudspeaker, alkaline battery and lithium button cell.

Transport into, out of and within the system borders was taken into account. Data for transport in Colombia regarding the collection of donations, transport between the CRs and distribution to the beneficiaries, stem from two Colombian carriers (Rodarcarga, 2008; Surenvios, 2008). For overseas transport, distances were obtained from an international carrier (IMA, 2008).

CPE has a close collaboration with the 'Universidad Nacional' being responsible for the monitoring at the schools. According to their investigations 30 percent of the schools derive their electricity directly from a generator and 70 percent from the grid. Table 6 gives an overview of the computer usage times at schools.

The electricity consumption of a PC with CRT monitor depending on its technical standard is based values given in Bray (2006), Cremer et al. (2003) and 'Ecoinvent v2.0' (2007). Table 7 gives an overview of the applied values. It was assumed that computers with Pentium III or newer processors refurbished at the CRs were equivalent to computers being refurbished overseas and classified as 'new'. Older processors were classified as 'old'. Hence, 78 percent of the computers of Colombian origin were classified as old, and 22 percent as new (see also Table 5).

At the disposal stage metals (e.g. copper, steel, and aluminium), plastics and cables that could be sold on the local market or to another recycler as well as the parts being reused for the 'Robotic' platform were evaluated in 'Simapro' assuming that they replace new materials. The lower quality of recycled materials was taken into account to the extent that 'Ecoinvent v2.0' contains data for different grades of raw materials.

The funnel glass and the PWBs of a computer as well as the liquid crystal display (LCD) of the 'XO Laptop' were assumed to be exported since no adequate treatment in Colombia was available. For the panel glass of a CRT monitor, there is a state-of-the-art treatment according to European standards in Colombia, as the lead free glass can be used in industrial processes. For batteries we assumed that an appropriate treatment would be put in place in Colombia in the near future. The data were obtained from 'Ecoinvent v2.0'. In order to map the final destination of ceramics, the disposal of glass to inert material landfill served as an approximation. In the case where it was not possible to identify that for a minor waste volume (less than 0.4 percent of the weight of a CPU and 0.1 percent of a CRT monitor) a disposal of municipal solid waste to sanitary landfill was assumed. Table 8 shows the results of the LCA of each scenario in Eco-indicator'99 points.

4.2.3. Social performance

The assessment of social performance was subdivided into three attributes 'creation of low and semi-skilled jobs' and 'creation of highly skilled jobs' and 'involvement/participation of the local economy'.

4.2.3.1. The creation of low or semi-skilled jobs and of highly skilled jobs.
The number of jobs was linearly extrapolated for the production of each scenario based on the production and number of jobs of the year 2007. The creation of jobs at the CRs, CEEX and in maintenance services was taken into account.

For the CENARE a different approach was chosen due to the fact that a complete regular dismantling process was not yet in place. Therefore, the times for dismantling a PC case with its contents, a CRT monitor, a keyboard, a mouse and the 'XO Laptop' were calculated separately. The calculations for the number of jobs were then based on the assumption that a year has 220 working days with 8 h each.

It was only possible to create one highly skilled job and 14 low and semi-skilled jobs at CENARE under the 'XO Laptop' scenario. Overseas refurbished computers would create additional jobs at

Table 5
Share of computer units delivered per technical standard of each scenario. Since 2006 no computers lower than Pentium I have been refurbished anymore at the CRs. The sum of the scale/unit multiplied with the share results in the average technical value for each scenario.

Technical standard applied at CPE	Scaling factor	Colombian refurbishment	Overseas refurbishment	XO Laptop
		Share	Share	Share
Pentium I or lower, Windows 95, Office 97	1	0.545	0.00	0.00
Pentium II, Windows 98 SE, Office 97	2	0.235	0.00	0.00
Pentium III, Windows 2000, Office 2000	3	0.187	0.60	0.00
Pentium IV or higher, Windows 2000, Office 2000, or equivalent	4	0.033	0.40	1.00
Technical value		1.71	3.4	4

Table 6
Usage times at school depending on the supply of the electricity (Source: CPE, Universidad Nacional).

Mode	Generator	Grid
Active	4 h	8 h
Standby	2 h	3 h
Off	18 h	13 h

CEEX, and with maintenance totals of 16 highly skilled and 166 low and semi-skilled jobs would be possible then. The majority of jobs could be created during the refurbishment processes at the CRs. Therefore, the totals of 63 highly skilled and 666 low and semi-skilled jobs could be created under the 'Colombian refurbishment' scenario.

Since the number of centres stays the same for all scenarios, the number of highly skilled jobs such as the director of plant, the directors of the centres, the maintenance coordinator and the CENARE coordinator were assumed to be identical for all scenarios.

4.2.3.2. The involvement of the local economy. In order to make a semi-quantitative judgement of how strong the local economy was involved, 0.25 points were given for the processes present under each scenario: refurbishment, maintenance, recycling and transport.

Under the 'XO Laptop' scenario only transport and recycling processes took place (score 0.5). Refurbished computers from abroad were transported, maintained (CEEX or related institution) and recycled at CENARE (score 0.75). The 'Colombian refurbishment' scenario comprises all processes, as refurbishment takes place at the CRs, the computers are transported and maintained and finally recycled at CENARE. The score is therefore the highest possible (see Table 8).

4.3. Application of the MAUT

The actual values assessed – as presented in the previous section – and the utilities of each individual attribute are listed in Table 8. The additive utility is the sum of the normalised un-weighted utilities. The additive utility ranges between 0 and 6, as six attributes were evaluated (three environmental attributes were aggregated to one attribute using the Eco-indicator'99 method). The normalised weighted utility is the sum of the normalised utilities multiplied with the normalised weighting factors. The values range between 0 and 1. Fig. 3A and B illustrates graphically both utilities.

With the assumptions, stakeholder judgements and allocations made, the 'Colombian refurbishment' scenario is the most sustainable solution to provide computers to schools in the case of Colombia. This result emerges clearly despite the shortcomings of this scenario, which are the relatively high net costs and a low technical standard of the computers provided. The greatest shares of costs arise from refurbishment, promotion and accompaniment

and monitoring. Further research on how to decrease these costs might reduce the high net cost under this scenario.

The second best solution is the 'Overseas refurbishment' scenario. The least sustainable scenario is the 'XO Laptop'. Both scenarios have the disadvantage that job creation and the involvement of local industry are relatively low. The 'XO Laptop' scenario also gets the lowest environmental performance. Under the 'allocated recycling' allocation scheme applied, the environmental impacts from production of the newly produced laptops are not sufficiently compensated for by the credits earned from materials recycling. It has to be considered that this result is highly influenced by the allocation scheme used (see also Section 4.4). The refurbishment scenarios have the advantage that impacts from production are not accounted for, whereas benefits from recycling are credited. Fig. 3A illustrates the additive utility results.

This trend becomes slightly less accentuated when the normalised weighted utilities shown in Fig. 3B are calculated. The stakeholder weights do not have a great influence on the utility results due to the fact that they are almost equally distributed over the three sustainability dimensions.

4.4. Discussion and sensitivity analysis

The most debatable part of our analysis is certainly the allocation of the impacts originating from production and recycling. It is easy to understand why the environmental impacts from a newly produced computer must be accounted for: the hardware simply has to be produced somewhere. It is also easy to understand that appropriate recycling – which recovers materials – is credited, as the primary production of these materials can be avoided. Matters become more difficult when recycling credits have to be given to second hand computers. Should recycling benefits be credited to the first use, the second use or proportionally over the entire life span? The same problem arises when production impacts must be allocated to a first and second use phase. One could state that obsolete computers are waste, which is turned into products by refurbishment programmes such as CPE. Following this line of thought, environmental impacts from production should be allocated entirely to the first use. But we could also argue that a ratio of the environmental impacts should be allocated to the second use. A simple rate per year could be the time spent in the system divided though the entire life span of the computer. Three different allocation schemes have been analysed for purposes of comparison:

- 'Complete recycling' credits all benefits out of the recycling process (raw materials savings) to the corresponding scenario for all computers entering the system. Environmental impacts from the production of a refurbished computer are not taken into account.
- 'Allocated recycling' credits benefits proportionally to the relative length of the second use phase. The ratio 'time spent in the system/whole life span' in years determines the proportion of benefits credited to our scenario. (E.g. a four-year old computer is refurbished abroad and is used another five years

Table 7
Electricity use of a PC without monitor, a CRT monitor and the 'XO Laptop' in Watt (W). Data for PC without monitor cited in Bray (2006), data for CRT monitor from indicated sources. The share of CPUs 'Old'/'New' technical value was also applied for the share of CRT 'Old'/'New'.

Mode	PC without monitor		CRT monitor		XO Laptop
	'Old': technical value 1 and 2	'New': technical value 3 or higher	'Old'	'New'	
Active	55 W	70 W	90 W	67 W	2.5 W
Standby	25 W	9 W	20 W	12 W	0.3 W
Off	1.5 W	3 W	3 W	3 W	0.3 W
Source	(Kawamoto et al., 2001; Kawamoto et al., 2004)	(Roberson et al., 2002)	(ecoinvent, 2007)	(Cremer et al., 2003)	(OLPC, 2008)

Table 8
Measured results, utility normalised and utility weighted for each attribute and each scenario.

Criteria	Unit	Colombian refurbishment			Overseas refurbishment			XO Laptop		
		Value as measured	Normalised utility	Weighted utility	Value as measured	Normalised utility	Weighted utility	Value as measured	Normalised utility	Weighted utility
Economic performance										
Net costs	$/computer	616	0.54	0.08	397	0.70	0.10	328	0.76	0.11
Technical value	[1, 2, 3, 4]	1.71	0.19	0.02	3.40	0.37	0.05	4.00	0.44	0.05
Environmental performance										
Use of energy	Eco-indicator'99 points	2.15	0.82	0.27	3.13	0.74	0.25	6.71	0.44	0.15
Use of resources										
Amount of toxic emissions										
Social performance										
Creation of low and semi-skilled jobs	Number of jobs	666	0.79	0.09	166	0.20	0.02	14	0.02	0.00
Creation of highly skilled jobs	Number of jobs	63	0.79	0.11	16	0.20	0.03	1	0.02	0.00
Involvement of local economy	[0, 0.25, 0.5, 0.75, 1]	1.00	0.44	0.06	0.75	0.33	0.05	0.50	0.22	0.03
Additive utility			3.57			2.54			1.89	
Normalised weighted utility				0.64			0.49			0.35

in a Colombian school. Therefore 5/9 of the recycling benefits at the end of life are credited to the scenario 'Overseas refurbishment'). Environmental impacts from the production of a refurbished computer are not taken into account.

• The 'Allocated production and allocated recycling' approach includes the environmental impacts from production and

benefits from recycling. Both are allocated to the scenario proportionally to the relative length of the second use phase.

Fig. 4 shows the environmental performance in Eco-indicator'99 points of the three allocation schemes. Low points indicate low environmental impacts, negative points environmental benefits
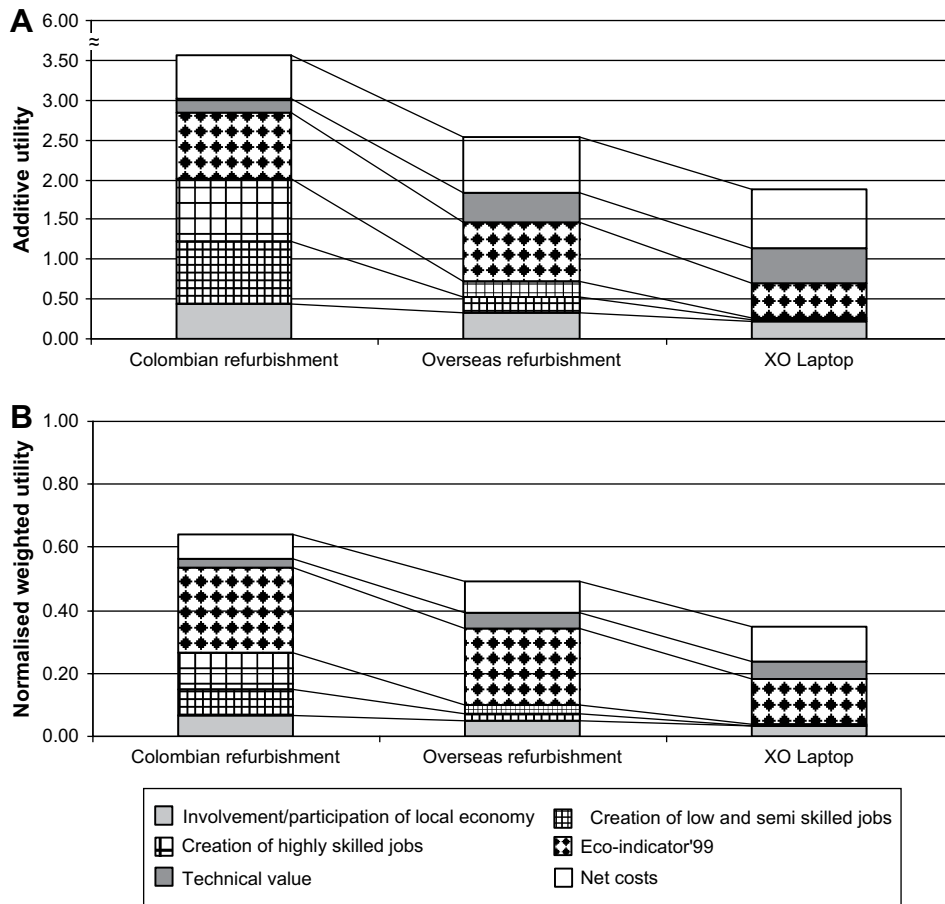

Fig. 3. A: individual utilities of attributes and additive utility. B: individual weighted utilities of attributes and overall sum of normalised weighted utility. Note: The maximum score of the additive utility is 6, because six attributes are combined. The three environmental attributes are summed up as 'Eco-indicator'. The normalised weighted utility ranges between 0 and 1, directly proportional to the sum of the actual values measured of one attribute overall scenarios.
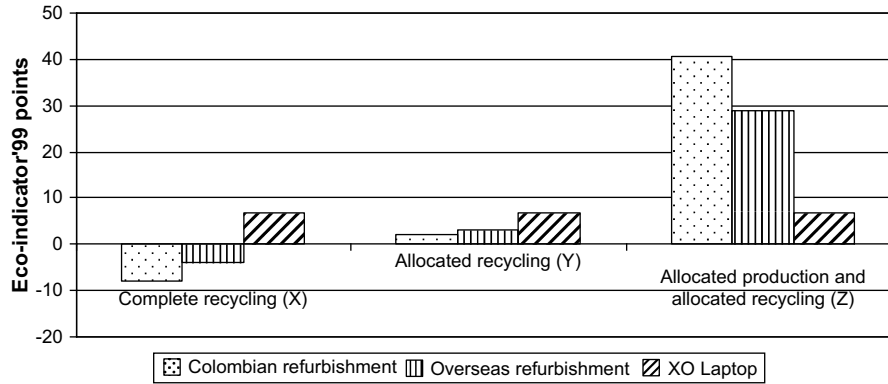
Fig. 4. Eco-indicator'99 points for the three allocation schemes. The complete production of a XO Laptop is included in all allocation schemes.

(avoided impacts). It can be seen that the inclusion of impacts from production and recycling can turn the results around. In case only recycling is credited, the refurbishment scenarios are more advantageous (Fig. 4 X and Y). Under the 'Allocated production and allocated recycling' scheme, the environmental impacts of a desktop computer (both refurbishment scenarios) are much higher than the one of a 'XO Laptop' (Fig. 4 Z). The reason for the considerable high impact of the entire production of a computer under the refurbishment programmes is the fact that the production of a desktop PC with CRT monitor, keyboard and mouse is grave compared to the production of the 'XO Laptop'.

To calculate the results shown in the previous section, the 'Allocated recycling' allocation scheme was applied. However, if the 'Allocated production and allocated recycling' scheme is used, the results still show the same ranking – despite the fact that, apart from the attributes 'net costs' and 'technical value', the 'XO Laptop' now also shows the best environmental performance. Due to the low score of the 'XO Laptop' in the social attributes, the scenario 'Colombian refurbishment' still has the highest utility.

During refurbishment and maintenance new components are needed. The environmental impacts of the production of spare parts have to be allocated to the respective scenario. Therefore, the influence of increased refurbishment and maintenance under the scenario 'Colombian refurbishment' has been evaluated.

Fig. 5 illustrates the impact on environmental performance if the effort to produce the required parts for the refurbishment/maintenance process at the CRs is increased by 10, 20 and 50 percent, now again under the allocation scheme 'Allocated recycling'. The environmental performance of scenario 'Colombian refurbishment' equals that of scenario 'Overseas refurbishment' if refurbishment/maintenance increases by 10 percent. 50 percent increase in

refurbishment/maintenance results in equal environmental performance to that of scenario 'XO Laptop'.

Second hand computers need refurbishment and maintenance. Additionally, desktop PCs consume more electricity during the use phase than small laptops do, especially if they are still equipped with CRT monitors. Extensive replacement of components of second hand appliances and using them for a few additional years can result in a higher environmental impact than buying small sized new appliances. These drawbacks from second hand appliances have to be carefully monitored when measuring environmental impacts.

4.5. Further strategies

CPE and 'ComputerAid' as overseas refurbishers cannot individually guarantee a sufficient supply. At present CPE produces 20 000 refurbished computers per year. 'ComputerAid' as the biggest refurbisher of its kind has shipped a little over 100 000 computers during the past nine years. It is unlikely that 'ComputerAid' would provide 50 000 computers per year to only one contractor. It is also unlikely that the Colombian government would order 50 000 'XO Laptops' per year.

We therefore calculated three strategies – as combinations of the three scenarios – which could provide a sufficient number of computers. The MAUT results for these supply strategies were calculated and compared to the three 'pure' scenarios discussed above.

- Strategy 1 combines Colombian and overseas refurbishment. 20 000 computers are provided by Colombian donations and 30 000 computers are imported from 'ComputerAid'.
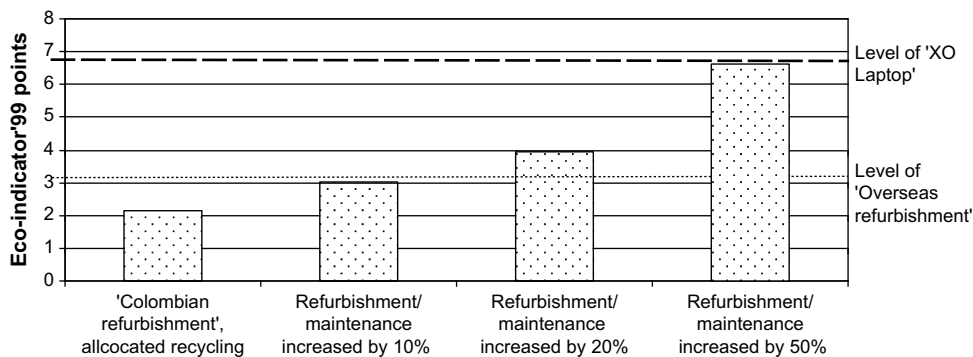

Fig. 5. Sensitivity analysis of environmental impacts under the scenario 'Colombian refurbishment', using the allocation scheme 'Allocated Recycling'. Increase of the refurbishment and maintenance activities implies an increased use of new components and hence an increase in the environmental impacts.

- Strategy 2 combines 'Colombian refurbishment' and 'XO Laptop'. 20 000 computers are Colombian donations, 30 000 'XO Laptop's are purchased.
- Strategy 3 combines 'Overseas refurbishment' and 'XO Laptop'. Each scenario provides half of the required amount of 50 000 computers.

Fig. 6(A) summarizes the additive utility of the scenarios and the described supply strategies, Fig. 6(B) shows accordingly the normalised weighted utility of the scenarios and supply strategies.

The utilities for the supply strategies are only a combination of the scenarios. None of the strategies achieve, therefore, a higher utility than the scenario 'Colombian refurbishment'. Due to the low utility of the 'XO Laptop' scenario all the combined strategies containing the 'XO Laptop' also have relatively low utilities (Fig. 6).

5. Conclusions

This study shows that local refurbishment of second hand computers is currently the most sustainable solution to supply computers to schools in Colombia. Financially, the overall net costs associated with local refurbishment are higher than the costs when buying low cost new computers. In contrast, the social benefits of local refurbishment programmes outnumber the financial drawbacks, as jobs are created and the local economy is involved. The environmental impacts are ambivalent. While 'XO Laptops' create the lowest impacts in the production process and the use phase compared to desktop computers, it is debatable if the production process needs to be accounted for in the second use phase of a computer. The answer given to this question has a relevant influence on the results.

The study has shown that the costs of refurbishing used computers are often considerably higher than those of buying new equipment. The cost for refurbishment, promotion as well as accompaniment and monitoring of second hand computer refurbishment programmes are the biggest cost drivers of such activities. Another drawback of second hand computers is the fact that they are not technically up-to-date, as they are equipped with e.g. smaller Random Access Memory cards or older software versions. New computers are often equipped with the latest hard- and software products, providing them with a competitive edge over second hand equipment.

The social contribution of second hand computer refurbishment programmes is certainly positive, as a whole range of jobs are created during which the employees are educated and trained in the use and maintenance of ICT equipment. Another positive social effect is the involvement of the local economy. These findings are supported by studies, which have shown that the involvement of the community is a mandatory condition for such programmes to be successful, nevertheless it remains often being neglected (Hayes and Allison, 1998; OECD, 2003; Hawkins, 2004; Hepp et al., 2004). Identification with, and involvement in, an ICT project creates the necessary willingness to integrate the technology into everyday life.

Environmental impacts of the different scenarios have to be evaluated carefully. This study considered impacts of the entire life span of computers: production, electricity consumption during usage, and impacts or benefits of recycling processes. Earlier studies of the energy consumption of computers showed that either of the two stages production (Williams, 2004) or use (Schischke and Kohlmeyer, 2005) have the greatest environmental impacts in the entire life cycle. The exact share depends on
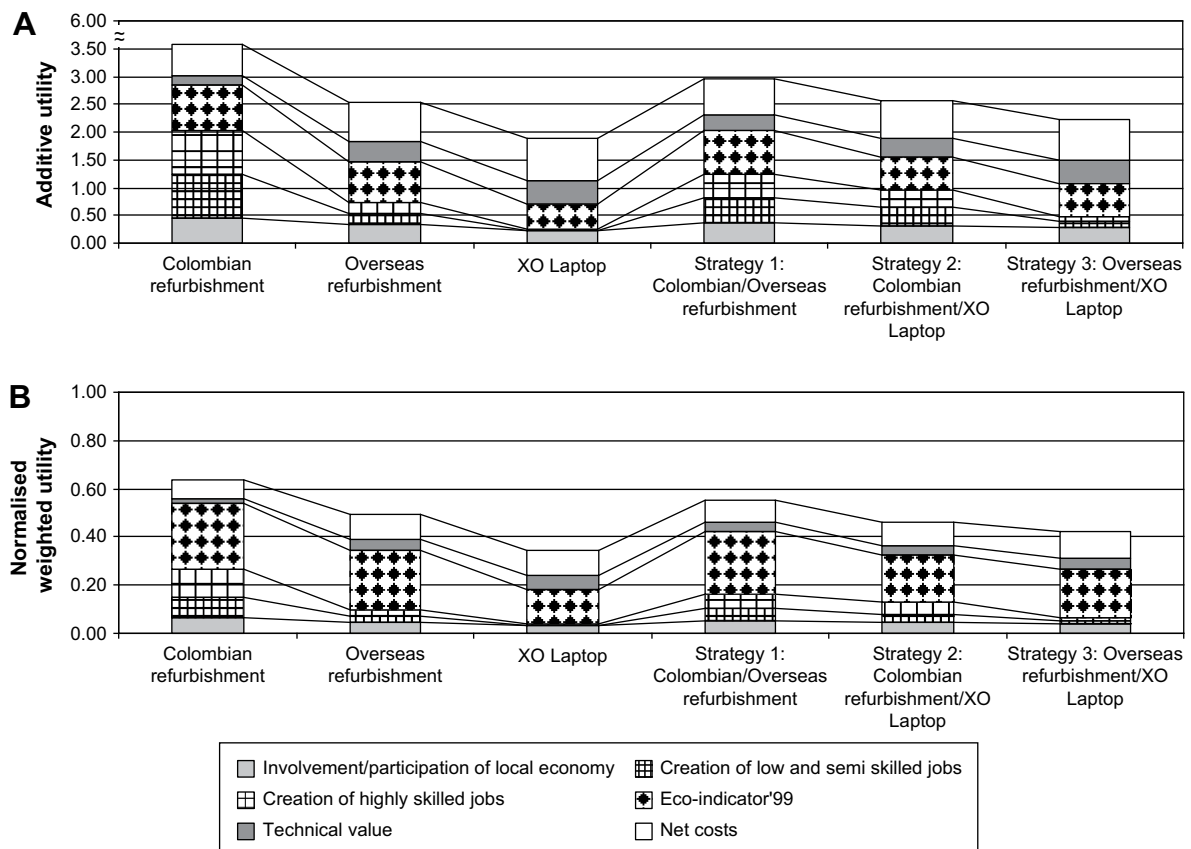

Fig. 6. A: additive utility of scenarios and strategies. B: normalised weighted utility of scenarios and strategies.

longevity, as environmental impacts from production can be exceeded by the impacts of electricity consumption, the longer the appliances live (Eugster et al., 2007; Duan et al., 2009). Apart from this trade-off, the study also showed that the allocation of environmental impacts from production and recycling influences the outcome of the results considerably.

The sensitivity analysis showed that excessive refurbishments involving the replacement of larger electronic components do not make sense. The impacts from the production of spare parts can eat up all the benefits gained from extending the life span of an already produced good, and from appropriate recycling at the end of its life.

6. Recommendations

The provision of hardware still remains a limiting factor when it comes to educating scholars in the use of ICT equipment in developing countries. At the same time, low cost computer offers are available from an increasing number of producers, and the XO Laptop announced in 2006 by the OLPC initiative is only at the tip of this iceberg-development. However, the study showed that stakeholders involved in the provision of computers to schools in developing countries value not only the fast and economical purchase of hardware. They also consider it important to 'embed' the provided equipment in a surrounding which assures continuous maintenance, training and adequate end-of-life treatment.

When policy makers evaluate their options in providing computer for schools, the first option should be basic refurbishment of second hand computers of a high technical standard donated to recipients in the countries where they are needed. This is particularly advantageous if programmes create employment and enable involved persons to educate themselves in using and understanding the technology. As this strategy is more costly than importing low cost computers it might be feasible to further professionalise such programmes in order to make refurbishment of second hand computers economically more competitive. Imports of second hand refurbished computers or the purchase of low cost computers in large numbers can reduce costs, but this alternative should only be chosen when the domestic supply of second hand computers would not satisfy the demand by itself.

In addition to this, the choice of software is an important element of the supply strategies for computers – an issue which was not part of this study, but should be looked at in more detail during further investigations.

The study showed that financial burden and technical up-to-datedness are only a few of the aspects to be considered when designing programmes to provide computer for schools. Social or environmental benefits are also valued by stakeholders and can counterbalance the downside in trade-offs. These observations underline the fact that a comprehensive approach from a life cycle perspective is advantageous when evaluating one's strategy for supplying ICT equipment to schools in developing countries.

Acknowledgement

References

Arstechnica, 2008. http://arstechnica.com/news.ars/post/20080515-former-security-director-blasts-olpc-suggests-new-strategy.html (accessed July 2008).
Atlee, J., Kirchain, R., 2006. Operational sustainability metrics assessing metric effectiveness in the context of electronics-recycling systems. Environmental Science & Technology 40, 4506–4513.
Bray, M., 2006. Review of Computer Energy Consumption and Potential Savings. Dragon Systems Software Limited (DssW).
Brunner, P.H., Rechberger, H., 2004. Practical Handbook of Material Flow Analysis. Lewis Publishers, Boca Raton, FL.
Camacho, A., 2007. Personal Communication: Angel Camacho, Computadores Para Educar, Confidential Information on Budget 2006/2007. Bogota.
CFSK, 2008. Computer for Schools Kenya. www.cfsk.org (accessed August 2008).
close-the-gap, 2008. http://www.close-the-gap.org/pages/frontend/Home.aspx?menuitem=17 (accessed July 2008).
Código sustantivo del trabajo, 2008. http://www.lared.com.co/kitdeherramientas/casoslaborales/codigolaboral/codigolaboral.asp?titulo=N (accessed July 2008).
Computer Aid International, 2008. www.computeraid.org (accessed June 2008).
CPE, 2008. www.computadoresparaeducar.gov.co (accessed July 2008).
Cremer, C., Eichhammer, W., Friedewald, M., Georgieff, P., Rieth-Hoerst, S., Schlomann, B., Zoche, P., Aebischer, B., Huser, A., 2003. Der Einfluss moderner Gerätegenerationen der Informations- und Kommunikationstechnik auf den Energieverbrauch in Deutschland bis zum Jahr 2010-Möglichkeiten zur Erhöhung der Energieeffizienz und zur Energieeinsparung in diesen Bereichen., Karlsruhe/Zürich.
Duan, H., Eugster, M., Hischier, R., Streicher-Porte, M., Li, J, 2009. Life cycle assessment study of a Chinese desktop personal computer. Science of the Total Environment 407, 1755–1764.
ecoinvent, 2007. ecoinvent data v2.0. Online-Database. Swiss Centre for Life Cycle Inventories, St. Gallen, Switzerland.
EducarChile, 2008. http://www.educarchile.cl/ (accessed August 2008).
Enlaces, 2008. Red Enlaces. Centro de Educación y Tecnología. http://www.enlaces.cl/index.php?t=44 (accessed August 2008).
Eugster, M., Huabo, D., Jinhui, L., Perera, O., Potts, J., Yang, W., 2007. Sustainable Electronics and Electrical Equipment for China and the World, a Commodity Chain Sustainability Analysis of Key Chinese EEE Product Chains. International Institute of Sustainbale Development, IISD, Winnipeg.
Fairweather, J. 2008. Personal communication: James Fairweather, general production manager at 'ComputerAid'.
Fishburn, P.C., 1988. Nonlinear Preference and Utility Theory, vol. 5. The Johns Hopkins University Press, Baltimore. Johns Hopkins Series in the Mathematical Sciences.
FOD, 2008. Fundación Omar Dengo. http://www.fod.ac.cr/ (accessed August 2008).
Goedkoop, M., Spriensma, R., 2001. The Eco-Indicator 99. A damage Orientated Method for Life Cycle Impact Assessment. Methodology Report, Amersfoort.
Hajkowicz, S., 2006. Multi-attributed environmental index construction. Ecological Economics 57 (1), 122–139.
Hawkins, R.J., 2004. Ten Lessons for ICT and Education in the Developing World. The World Bank Institute.
Hayes, J., Allison, C.W., 1998. Cognitive style and the theory and practice of individual and collective learning organizations. Human Relations 51, 847–871.
Hepp, P., Hinostroza, J.E., Laval, E., Rehbein, L., 2004. Technology in Schools: Education, ICT and the Knowledge Society. World Bank Education Advisory Service.
Hilty, L.M., 2008. Information Technology and Sustainability. Essays on the Relationship between Information Technology and Sustainable Development. Norderstedt, Germany, (Books on Demand), ISBN: 9783837019704.
Hilty, L.M., Arnfalk, P., Erdmann, L., Goodman, J., Lehmann, M., Wäger, P., 2006. The relevance of information and communication technologies for environmental sustainability – a prospective simulation study. Environmental Modelling & Software 11, 1618–1629. doi:10.1016/j.envsoft.2006.05.007.
Hischier, R., Wäger, P., Gauglhofer, J., 2005. Does WEEE recycling make sense from an environmental perspective? The environmental impacts of the Swiss take-back and recycling systems for waste electrical and electronic equipment (WEEE). Environmental Impact Assessment Review 25, 525–539.
HiWEL, 2008. Hole-in-the-Wall Education Ltd. http://www.hole-in-the-wall.com/ (accessed June 2008).
Huisman, J., 2003. The QWERTY/EE Concept, Quantifying Recyclability and Eco-Efficiency for End-of-Life Treatment of Consumer Electronic Products. Ph.D thesis, Delft University of Technology, Delft, Netherlands.
IMA, 2008. http://www.imadxb.com/home.php (accessed July 2008).
ISO, 2000. International Standard Organization. 14040 Series: Environmental Management – Life Cycle Assessment – Principles and Framework. ISO 14040 Series. International Standard Organization. www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm? csnumber=23152 (accessed July 2008).
James, J., 2001. Bridging the digital divide with low-cost information technologies. Journal of Information Science 27 (4), 211–217.
James, J., 2002. Low-cost information technology in developing countries: current opportunities and emerging possibilities. Habitat International 26, 21–31.
Jepsen, M.L., 2007. Personal communication Mary Lou Jepsen, former chief technology officer of OLPC.
Kang, H.Y., Schoenung, J.M., 2006. Economic analysis of electronic waste recycling: modeling the cost and revenue of a materials recovery facility in California. Environmental Science & Technology 40, 1672–1680.
Kawamoto, K., Koomey, J.G., Nordman, B., Brown, R.E., Piette, M.A., Ting, M., Meier, A.K., 2001. Electricity Used by Office Equipment and Network Equipment in the US: Detailed Report and Appendices, LBNL-45917. Lawrence Berkeley National Laboratory, California. http://enduse.lbl.gov/projects/InfoTech.html (accessed August 2008).
Kawamoto, K., Shimoda, Y., Mizuno, M., 2004. Energy saving potential of office equipment power management. Energy and Buildings 36, 915–923.

Keeney, R.L., Raiffa, H., 1976. Decisions with Multiple Objectives: Preferences and Value Tradeoffs. Wiley, New York. Wiley Series in Probability and Mathematical Statistics. Applied Probability and Statistics.

Manhart, A., 2007. Key Social Impacts of Electronics Production and WEEE-Recycling in China. Öko-Institut e.V., on behalf of Empa (Federal Institute of Materials Testing and Research) and SECO (State Secretary of Economic Affairs), Freiburg.

Manhart, A., Grießhammer, R., 2006. Social Impacts of the Production of Notebook PCs, Contribution to the Development of a Product Sustainability Assessment (PROSA). Öko-Institut e.V., Freiburg.

Mansell, R., 1999. Information and communication technologies for development: assessing the potential and the risks. Telecommunications Policy 23, 35–50.

Marthaler, C., 2008. Computers for Schools: Sustainability Assessment of Supply Strategies in Developing Countries. A Case Study in Colombia. Master thesis, Swiss Federal Institute of Technology (ETHZ)/Swiss Federal Laboratories for Materials Testing and Research (Empa), Zurich/St. Gallen Switzerland.

Mitra, S., Dangwal, R., Chatterjee, S., Jha, S., Bisht, R.S., Kapur, P., 2005. Acquisition of computing literacy on shared public computers: children and the "hole in the wall". Australasian Journal of Educational Technology 21 (3), 407–426.

Nakamura, S., Kondo, Y., 2006. A waste input–output life-cycle cost analysis of the recycling of end-of-life electrical home appliances. Ecological Economics 57, 494–506.

OECD, 2003. Providing Low-cost Information Technology Access to Rural Communities in Developing Countries: What Works? What Pays? OECD Development Center.

OLCP News, 2008. http://www.olpcnews.com/sales_talk/price/olpc_uruguay_205_dollars_laptop.html (accessed July 2008).

OLPC, 2008. One laptop per child – OLPC. http://laptop.org/ (accessed July 2008).

Park, P.-J., Tahara, K., Jeong, I.-T., Lee, K.-M., 2006. Comparison of four methods for integrating environmental and economic aspects in the end-of-life stage of a washing machine. Resources, Conservation & Recycling 48, 71–85.

Pelgrum, W.J., 2001. Obstacles to the integration of ICT in education: results from a worldwide educational assessment. Computers & Education 37, 163–178.

PRé Consultants, 2008. SimaPro, Version 7.1, LCA Software Tool. PRé Consultants, Amersfoort, the Netherlands.

RedEscolar, 2008. http://redescolar.ilce.edu.mx (accessed August 2008).

Ricaurte, G., 2007. Personal communication: German Ricaurte, 'Coordinador Mantenimiento', 'Computadores Para Educar'.

Roberson, J.A., Homan, G.K., Mahajan, A., Webber, C.A., Nordman, B., Brown, R.E., McWhinney, M., Koomey, J.G., 2002. Energy Use and Power Levels in New Monitors and Personal Computers, LBNL-48581. Lawrence Berkeley National Laboratory, California. http://enduse.lbl.gov/Projects/OffEqpt.html (accesses August 2008).

Rodarcarga, 2008. http://www.rodarcarga.com.co/ (accesses July 2008).

Scharnhorst, W., Hilty, L.M., Jolliet, O., 2006. Life cycle assessment of second generation (2G) and third generation (3G) mobile phone networks. Environment International 32, 656–675. doi:10.1016/j.envint.2006.03.001.

Schischke, K., Kohlmeyer, R., 2005. Regionale Netze für die Wieder- und Weiterverwendung elektronischer Geräte, Umweltbewertung des ReUse von PCs. (Regional Reuse and Recycling of electrical equipment, environmental evaluation of ReUse of PCs). Berlin Center of Advanced Packaging, BeCAP, Technical University Berlin.

Scholz, R.W., Tietje, O., 2002. Embedded Case Study Methods: Integrating Quantitative and Qualitative Knowledge. Sage Publications, Inc., California, USA.

Sepúlveda, A., Schluep, M., Renaud, F., Streicher-Porte, M., Kuehr, R., Gerecke, A., Hagelueken, C., A review of environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: examples from China and India. Environmental Impact Assessment Review, in press, available online 9 May 2009.

Steubing, B., 2007. e-Waste Generation in Chile, Situation Analysis and Estimation of Actual and Future Computer Waste Quantities Using Material Flow Analysis. Master thesis, Swiss Federal Institute of Technology (EPFL)/Swiss Federal Laboratories for Materials Testing and Research (Empa), Lausanne/St. Gallen Switzerland.

Streicher-Porte, M., Bader, H.-P., Scheidegger, R., Kytzia, S., 2007. Material flow and economic analysis as a suitable tool for system analysis under the constraints of poor data availability and quality in emerging economies. Journal of Clean Technology and Environmental Policy 9, 325–345.

Surenvios, 2008. http://www.surenvios.com.co/ (accessed July 2008).

Sutter, C., 2003. Sustainability Assessment of Energy related Projects under the Clean Development Mechanism of the Kyoto Protocol. Dissertation, Swiss Federal Institute of Technology, Zurich, Switzerland.

Swiss e-waste guide, 2008. http://ewasteguide.info (accessed August 2008).

Tipson, F.S., Frittelli, C., 2003. Global Digital Opportunities National Strategies of "ICT for Development".

von Winterfeldt, D., Edwards, W., 1986. Decision Analysis and Behavioral Research. Cambridge University Press, Cambridge, UK.

Williams, E., 2004. Energy intensity of computer manufacturing: hybrid assessment combining process and economic input–output methods. Environmental Science & Technology 38, 6166–6174.

World Commission on Environment and Development. 1987. Our Common Future: Report of the World Commission of Environment and Development, Chapter 2: Towards Sustainable Development. Geneva.

World Computer Exchange, 2008. http://www.worldcomputerexchange.org/ (accessed July 2008).

Zumbühl, D., 2006. Mass Flow Assessment (MFA) and Assessment of Recycling Strategies for Cathode Ray Tubes (CRTs) for the Cape Metropolian Area (CMA), South Africa. Master thesis, ETH Zurich/Empa St. Gallen, Switzerland.

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