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Computers for Schools: Sustainability Assessment of Supply Strategies in Developing Countries

A case study in Colombia

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MASTER THESIS

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computadores para educar

“Too poor not to invest in information and communication technology.”

Meles Zenawi Asres, Prime Minister of Ethiopia

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Abstract

The ‘digital divide’, commonly defined as the gap between those who have and do not have access to computers and the Internet, has been a central issue on the scholastic and political agendas of new media development. Several private and public initiatives have been launched since the late 1990s in order to overcome this gap and provide computers to schools in developing countries.
In 2000 Colombia initiated a refurbishment program called “Computadores para Educar” (CPE) in order to supply domestically donated computers to schools.

This study aims to assess the sustainability of the refurbishment program CPE and incorporate alternative supply strategies. The results should help to facilitate the decision making process, regarding the implementation of the most appropriate supply strategy for providing computers to schools.

A material flow analysis (MFA) of the program CPE was carried out. Alternative strategies were then identified, incorporated and assessed regarding their economic, environmental and social performance using the method Multi Attribute Utility Theory (MAUT).

The results of the MFA provided new data, regarding the benefits of a combined refurbishment-recycling system as compared to a recycling system. Taking the Eco-indicator’99 as reference this study concludes that a refurbished-recycled personal computer (PC) compared to a directly recycled PC has a 16.8% better environmental performance.

The MAUT assessment shows that the well-established program CPE sets a high standard that will challenge alternative solutions. This study concludes that the refurbishment of computers of Colombian origin is the most sustainable strategy. Furthermore it concludes that the ‘XO laptop’, representing a recent development, is the most cost efficient and second best environmental solution. However, the non-use of local human resources leads to a lower overall sustainability as compared to other strategies.

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Abbreviations

CEEX	Centro de Equipos del Exterior
CENARE	Centro Nacional del Aprovechamiento de Residuos Electrónicos
CIEN	Centro de Integración de Equipos Nuevos
CPE	Computadores para Educar, www.computadoresparaeducar.gov.co
CPU	Central Processing Unit
CRB	Centro de Reacondicionamiento de Bogotá
CRBQ	Centro de Reacondicionamiento de Baranquilla
CRC	Centro de Reacondicionamiento de Cali
CRCB	Centro Regional del Convenio de Basilea
CRCU	Centro de Reacondicionamiento de Cúcuta
CRM	Centro de Reacondicionamiento de Medellín
CRs	Centros de Reacondicionamiento (Refurbishment Centres)
CRT	Cathode Ray Tube
EEE	Electrical and Electronic Equipment
EMPA	Swiss Federal Laboratories for Materials Testing and Research, www.empa.ch
GDP	Gross Domestic Product
ICT	Information and Communications Technology
IDC	International Data Corporation, www.idc.com
LAC	Latin America and the Caribbean
LCD	Liquid Crystal Display
MAUT	Multi Attribute Utility Theory
MAVDT	Ministerio de Ambiente, Vivienda y Desarrollo Territorial, www.minambiente.gov.co
MFA	Material Flow Analysis
MIT	Massachusetts Institute of Technology, http://web.mit.edu
OECD	Organisation for Economic Co-operation and Development, www.oecd.org
OLPC	One Laptop Per Child, www.laptop.org, http://wiki.laptop.org
PC	Personal Computer
PWB	Printed Wiring Board
RoHS	Directive on the Restriction of the Use of Certain Hazardous Substances in EEE
SENA	Servicio Nacional de Aprendizaje, www.sena.edu.co
SUSTEC	Sustainable Technology Cooperation, www.empa.ch/sustec

Glossary

Assembling	Fitting together parts and pieces of a computer
Disassembling	Taking apart parts and pieces of a computer
Dismantling	Synonym for disassembling (see above)
E-waste	Waste of electrical and electronic equipment
Maintenance	Technical upkeep of a personal computer (PC) which includes servicing and repair. It usually takes place after a two year usage of a PC at schools and prolongs the lifespan for another two years
Normalizing	Bringing different scales into one standard or norm in order to make them comparable
Overseas	Synonym for North America and Europe
Recycling	Process that allows the reuse of material as secondary raw material after the disassembling of a product
Refurbishment	Renovation and restoration of a computer. Can include cleaning and technical maintenance. Allows a re-use of the computer
Utility	Attractiveness of a certain scenario/strategy. 1 implies the highest possible attractiveness, 0 the least.

Executive Summary

Introduction

Deployed in many different ways, technology is seen as one of the main sources of human prosperity, progress and rationalization. The benefits of technological development and its range of applications seem boundless. Yet due to lack of access and competence not all profit equally from new technologies. Since the mid-1990s this gap between those who have, and do not have access has been labelled as the 'digital divide'.

An extended research has been carried out to identify the reasons it exists (Pinkett 2003; Chinn and Fairlie 2006; van Dijek 2006) and to offer advice regarding which policies would be best implemented in order to narrow the gap (Mariscal, 2005). For all conducted studies the cost seemed to be a crucial element in bridging the gap. Once the reasons were identified, possible solutions were suggested. James (2000) stated that *"…costs of computers used in developing countries can be reduced in two main ways, the first of which is by extending the lives of existing models and the second of which is by designing entirely new products".* He anticipated what has become reality today.

'One Laptop Per Child' (OLPC) designed a low cost laptop, the so-called 'XO laptop' in order to supply huge quantities to schools in developing countries. Refurbishing programs like 'ComputerAid', 'Close the Gap' or 'World Computer Exchange' ship computers from developed to developing countries for reuse. All with the vision of bridging the digital divide.

But what happens after the solutions are implemented? Or as Smith (2004) put it *"…the issues is not whether we should or should not use computers for educational purposes, rather, the issue is how computers are manufactured, used, and ultimately disposed of."*.

He brings up what has been an open question and idle research field. Once the delivered computers reach their 'end-of-life' they turn into 'e-waste'[1]. According to Widmer et al. (2005) 'e-waste' contains hazards such as lead, mercury, arsenic or flame retardants, to name only a few and can cause damage to the environment and human health if not treated in an appropriate way. It is therefore of crucial importance to investigate the environmental sustainability of different strategies aiming to bridge the 'digital divide'.

In 2000 Colombia took the matter of narrowing the gap into its own hands by launching the refurbishment program 'Computadores para Educar' (CPE). CPE is a governmental organization that refurbishes domestically donated computers and distributes them to schools all over the country.

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[1] E-waste is *"any appliance using an electric power supply that has reached its end-of-life"* as defined by the Organisation for Economic Co-operation and Development (OECD 2001).

Objective of the study

This study aims to investigate the sustainability of different strategies to supply computers to schools in Colombia. New findings regarding the benefits of refurbishing a personal computer (PC) should be acquired additionally. Cooperation with CPE was established and the following research questions defined:

A *What are the exact material flows of the refurbishment program CPE?*

B *What are possible alternative scenarios to provide a sufficient supply of computers to schools in Colombia?*

C *What are the involved costs of each of these scenarios?*

D *What are the critical stages during the life cycle of a refurbished and recycled computer regarding the environmental impact?*

E *Which of the scenarios has the best performance regarding its economic, environmental and social impacts?*

Methods

A material flow analysis (MFA) has been used as the method to estimate the material flows of CPE. The flows of a CPU, CRT monitor, keyboard and mouse were investigated. Parts and components during the refurbishment were quantified, as well as the resulting materials after the dismantling process.

In order to assess the sustainability of different scenarios, the Multi Attribute Utility Theory (MAUT) was chosen as the default method. The MAUT requires a set of attributes (see also figure 2) encompassing the desired aspects of the problem being assessed. To allow subjective preferences they undergo a stakeholder weighting. Once all scenarios have been rated according to each of the attributes, the MAUT composes the ratings and realizes a synthesis resulting in a one-dimensional utility measure.

Within the MAUT the environmental performance was assessed with a Life Cycle Analysis (LCA) and further evaluated with the Eco-indicator'99 (figure 3). This allowed the identification of critical life cycle stages. Stages are: the production, use, refurbishment, transport, recycling and disposal (figure 1).

Results

As the **functional unit** for all scenarios the supply of 46'000 computers, for a usage time of five years at schools, was defined. The number is based on the Colombian government's goal to reduce the ratio of pupils per computer to 20:1 from the present ratio of 40:1.

Five scenarios with two sub scenarios were defined.

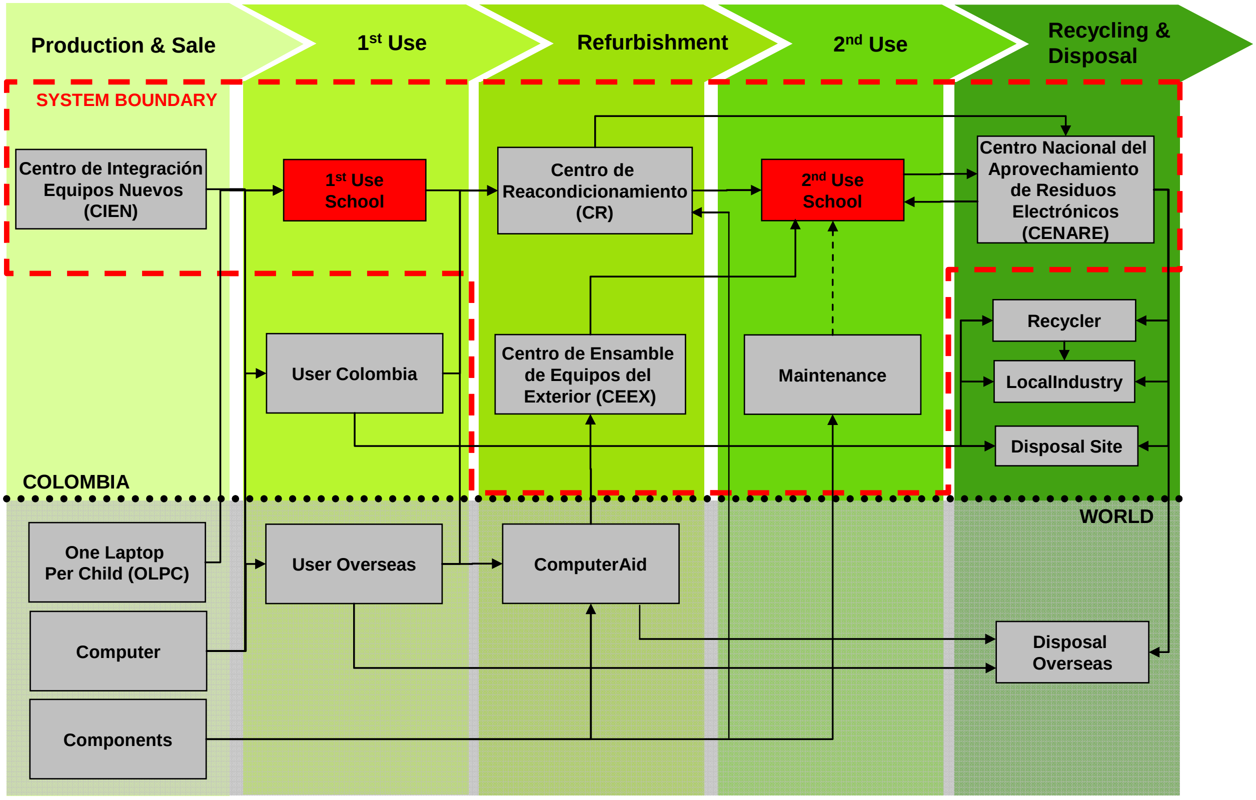

Figure 1: Model scheme of the MFA illustrating possible scenarios.

Scenario I "100% Colombian refurbishment": This scenario was based on the actual situation in 2006. Computers are exclusively of Colombian origin and refurbished at one of the five refurbishment centres (CRs) of CPE. A sub scenario which does not include maintenance was defined.

Scenario II "Colombian/overseas refurbishment and local assembling": This scenario reflects the situation at present (2007). Computers are provided either by the CRs, assembled newly at the Centro de Integración de Equipos Nuevos (CIEN) or arrive from a refurbisher overseas (in this study 'ComputerAid') to the Centro de Ensamble de Equipos del Exterior (CEEX).

Scenario III "Overseas refurbishment": Computers are mainly provided by 'ComputerAid'. For the refurbished computers at the CRs a technical threshold ('Pentium III' or higher) was defined.

Scenario IV "Overseas donation for Colombian refurbishment": Computers are guided directly from the users overseas to the CRs. For refurbished computers of Colombian origin a technical threshold ('Pentium III' or higher) was defined.

Scenario Va "XO laptop", Vb "Purchase PC (new)": For refurbished computers of Colombian origin a technical threshold ('Pentium III' or higher) was defined. The remaining computers were replaced by purchasing the 'XO laptop' (scenario Va) or a new computer (scenario Vb).

Application of the MAUT

The MAUT assessment shows that scenario I is the most sustainable solution for supplying computers to schools in Colombia (Figure 2). Most of the work is done within Colombia. Furthermore this scenario incorporates the highest amount of computers whose lifespan was prolonged. The second most sustainable solutions are scenario II, scenario III and IV. Taking only the economic and environmental performance into account scenario Va proves to be the most sustainable solution. Due to the production abroad, reduced Colombian refurbishment and a diminished effort for the recycling of an 'XO laptop' the scenario has a relatively low positive social performance. Scenario Vb is the least sustainable solution.

Note: Figure 2 illustrates the weighted utilities. 1 is the maximum utility, 0 the minimum.

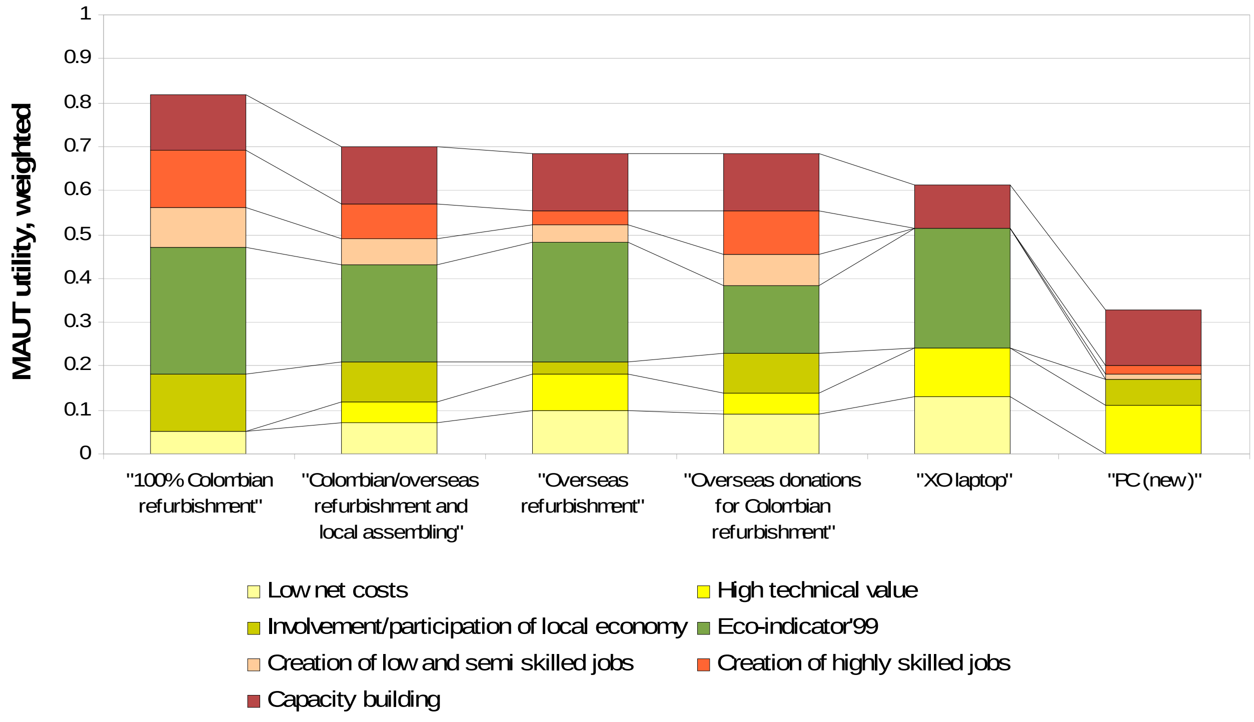

Figure 2: Weighted MAUT results subdivided into the applied attributes

The benefits of refurbishment

Independent from the scenarios and the MAUT the MFA data collected at the CRs allowed a comparison of the environmental performance of the life cycles of PCs being refurbished, refurbished and maintained, directly recycled and the 'XO laptop'. The estimated lifespan for refurbished PCs is seven years, if maintained nine years. For a directly recycled PC and the 'XO laptop' the lifespan is estimated at five years. All calculations were made for a total usage time of ten years.

The data was processed with the software ‘Simapro’ and evaluated with the Eco-indicator’99.
With a total environmental performance of 14.3 Eco-indicator’99 points the ‘XO laptop’ has approximately 90% less negative environmental impact than a PC which scores in the best case 163.6 Eco-indicator’99 points (figure 3).
If a PC is being refurbished and maintained it results in a 16.8% better environmental performance than if the PC is directly recycled. The same computer not being maintained has still a 6.9% better environmental performance compared as when recycled directly.

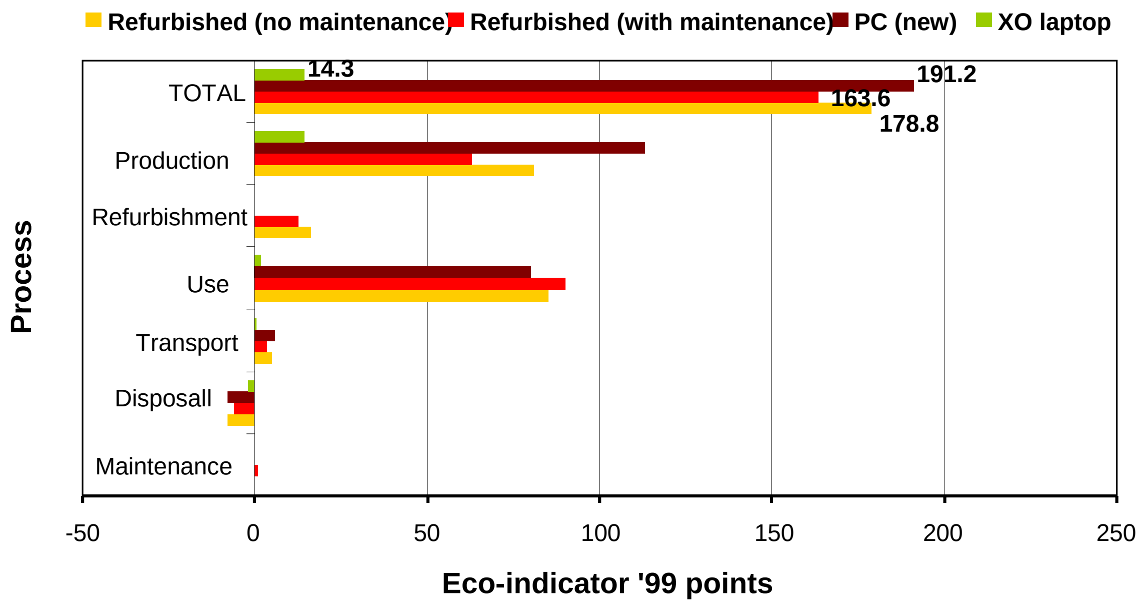

Figure 3: Comparison of the total environmental performance (Eco-indicator’99 points) of a refurbished PC (with/without maintenance), a directly recycled PC and the ‘XO laptop’.

Conclusion

Although not the most cost efficient solution, scenario I “100% Colombian refurbishment” proved to be the most sustainable. This is mainly due to utilizing of the local resources which results in a high positive environmental and social performance.
Scenario II, III and IV are ranked nearly equally as second most sustainable solutions.
In scenario II the CIEN plays a major role. The production of new parts for assemblage leads to high costs and a relatively low positive environmental performance. Scenario III has a low positive social performance since the refurbishment takes place abroad. In scenario IV, the OFF flow (computers that would normally enter the system) combined with a high quantity of PCs to be refurbished within Colombia lead to a relatively low environmental performance.
Next most sustainable solution is scenario Va “XO laptop”. Although it has the best environmental performance if pictured individually (Figure 3) and is the most cost efficient scenario, the ‘XO laptop’ does not utilize local human resources and results in a lower overall sustainability than other strategies. However, OLPC envisages implementing local assembling which would increase social performance. Additionally, countries that do not have such a well established refurbishment

program the situation would have to be assessed differently. Further research has to be done regarding small scale refurbishment in combination with the ‘XO laptop’.

1 Introduction

Technological development is the embodiment of modern society. Deployed in many different ways technology is seen as one of the main sources of human prosperity, progress and rationalization. Enthusiasm over its anticipated benefits appears boundless.

The technological development runs parallel with the modernization of our society and is considered as the dynamic element of its development. It offers an endless range of new possibilities and conveniences and the scope of its applications is growing daily. Yet due to lack of access and competence not all profit equally from new technologies. This gap between those who have and do not have access is labelled as the ‘digital divide’.

1.1 The digital divide

The term ‘digital divide’ came into regular usage in the mid-1990s and referred initially to the discrepancy in the ownership of personal computers (PCs) between groups. According to a definition by the OECD (2001) ‘digital divide’ refers to *“…the gap between individuals, households, business and geographic areas at different socio-economic levels with regard both to their opportunities to access information technologies (ITs)*[2] *and to their use of the Internet for a wide variety of activities”.*

Since the birth of the term, extended investigations were dedicated to analyse the structure of and reasons for the ‘digital divide’ (Pinkett 2003; Chinn and Fairlie 2006; van Dijek 2006).

Until recently research in this field predominantly focussed on the imbalances of material access, lately the main focus was also put on the imbalances in resources, skills and motivational access (van Dijek, 2006). However, the following study assesses strategies aiming to overcome the material (physical) access.

Many of the studies identified a strong positive relationship between technology use and income, across and within countries (OECD, 2001; US Department of Commerce, 2002). According to Chinn et al. (2006) the differences in income explain approximately 50% of the penetration gap (except for Europe and Central Asia). Other reasons are telecommunication infrastructure, human capital (measured by the years of schooling) or regulatory quality (Chinn, 2006; Dasgupta, 2001).

[2] IT (information technology) is a term that encompasses all forms of technology used to create, store, exchange, and use information in its various forms (business data, voice conversations, still images, motion pictures, multimedia presentations, and other forms, including those not yet conceived). It's a convenient term for including both telephony and computer technology in the same word. It is the technology that is driving what has often been called "the information revolution".
See also http://searchdatacenter.techtarget.com/sDefinition/0,,sid80_gci214023,00.html

Requests for the providing of low-cost information technology already arose at the beginning of the new millennium. A summary report of the International Millennium Conference on information technology and development held in India 2000 recognized that,

"…while there have been very significant advances in telecom-related science in recent decades, most of these in developed countries have focussed on providing better services and greater bandwith to the user at a constant cost which is affordable to most in these countries. The requirement in developing countries is, however, significantly different: to provide lower-cost basic access".

There is no consensus among the academic literature, regarding the appropriate policy to implement in order to achieve higher IT penetration in developing countries. While some argue that the market alone will take care of any perceived disparities, others think that governments should implement policies that subsidize access in some fashion (Mariscal, 2005).

1.2 Bridging the digital divide with computers

James (2000) stated that *"…costs of computers used in developing countries can be reduced in two main ways, the first of which is by extending the lives of existing models and the second of which is by designing entirely new products".*

In 2005, the initiative 'One Laptop Per Child'[3] (OLPC, see also chapter 3.1.3), founded by the Massachusetts Institute of Technology (MIT), introduced its project of a US $100 laptop at the World Economic Forum in Davos. The vision of the initiative is to produce laptops designed for children, the so-called 'XO laptops' and make them affordable to the governments of developing nations in huge quantities.

A different approach to bridging the 'digital divide' was chosen by 'ComputerAid'[4] (see also chapter 3.1.2), 'Close the Gap'[5] or 'World Computer Exchange'[6]. Both collect obsolete computers (in England and North America respectively), and select still operating equipment before selling them to developing countries. They work as non-profit organizations and sell the equipment at a price that just covers the expenses.

Due to a constantly growing population, affordable prices and shorter lifespan of electronic and electrical equipment (EEE) including PCs, sales figures are growing exponentially. In 2007 the

[3] See also www.laptop.org or wiki.laptop.org
[4] See also www.computeraid.org
[5] See also www.close-the-gap.org
[6] See also www.worldcomputerexchange.org

International Data Corporation (IDC) estimates that worldwide over 200 million PCs will be sold. Under these circumstances the potential of such initiatives seem boundless.

Developing countries on the other hand are facing a different reality. The reuse of computers is carried out within the country's borders. The growing demand of new or reused EEE from the private as well as the public sector in combination with low labour costs in these nations, allows a certain degree of maintenance, the so-called refurbishment.

The Colombian government initiated in 2000 a program called 'Computadores Para Educar' (CPE[7], see also chapter 3.1.1). CPE refurbishes domestically donated computers and distributes them to schools all over the country.

1.3 Problem outline

One important aspect that has not been mentioned but comes into play while bridging the 'digital divide', is the fact that once EEE reaches its end-of-life it turns into 'e-waste'[8]. Or as Smith (2004) put it *"…the issues is not whether we should or should not use computers for educational purposes, rather, the issue is how computers are manufactured, used, and ultimately disposed of."*.

According to Widmer et al. (2005) 'e-waste' contains hazards such as lead, mercury, arsenic or flame retardants, to name only a few and can cause damage to the environment and human health if not treated in an appropriate way.

That an appropriate recycling of 'e-waste' is *"…clearly advantageous from an environmental perspective."* was proven by a study conducted by Hischier et al. (2006). Hischier compares the environmental impacts of a recycling scenario of 'e-waste' to a baseline scenario of incineration of all 'e-waste', and its corresponding primary production of raw materials. He shows that the recycling of 'e-waste' not only decreases the environmental impacts, but also contributes further to the preservation of natural resources.

Prolonging the lifespan can be another solution, improving the overall environmental performance of a computer. Williams (2004), who calculated the energy consumption of the production phase (81%) in contrast to the use phase (19%) in the average lifespan of a computer, supports these kinds of activities. Nevertheless it is important to mention that he did not take into account the final disposal or recycling.

Schischke and Kohlmeyer (2005) had different calculations but a similar conclusion. According to them the production phase uses up only 25% of the total energy consumption. At the same time they observed a constant increase of energy consumption during the use phase of recently

[7] See also www.computadoresparaeducar.gov.co

[8] E-waste is *"any appliance using an electric power supply that has reached its end-of-life"* as defined by the Organisation for Economic Co-operation and Development (OECD 2001).

released computers. Contrasting a computer with an average lifespan of four years to a computer being reused (life prolonging of two years), they calculated a decreased energy consumption of 11% (or 900 kWh) over the period of 12 years (two lifespan of a reused computer). However, the study of Schischke and Kohlmeyer (2005) does not mention a technical maintenance for the reuse.

At present Smith (2004) conducted the only study known to the author, that investigates computer based education from an environmental point of view. However, he only compared traditional (pen and paper) with digital (computer) learning at the small scale of a classroom, applying the ‘ecological footprint’[9].

This study takes the topic of how sustainable computer based education is to a complete new level. By analysing the refurbishment program CPE in Colombia the study provides new findings regarding the benefits of extending the lifespan of a computer. Furthermore the study aims to fill the gap of research assessing the sustainability of different strategies recently being launched and traditional ideas of how to supply schools in developing countries with computers.

1.4 Research objective

The aim of the present study is to investigate and analyse different strategies for providing computers to schools in Colombia and assess their economic, environmental and social impacts. A final statement about the sustainability of each scenario will be made at the end. Main focus lies on the refurbishment process of CPE.

In order to do so, a comprehensive Material Flow Analysis (MFA) regarding the program CPE was executed. An assessment of the environmental, economic and social contribution to the sustainability of this combined refurbishment-recycling system was realized.

Furthermore alternative scenarios of providing computers to schools in Colombia have been identified. This includes: the importation of donated computers, the local assembling of new computers, the refurbishment abroad, the purchase of the ‘XO laptop’, the purchase of a new computer. Data regarding their economic, environmental and social performances were gathered for each scenario and further assessed with the Multi Attribute Utility Theory (MAUT). This allowed the ranking of the overall sustainability of each scenario.

As a common output for all of the scenarios a yearly supply of 46’000 computers to the schools was assumed. The number is based on the declaration of the Colombian Ministry of Education who aims to supply 70% of all public schools with computers until 2010. This was stated regarding the objective to diminish the ratio of pupil per computer to 20:1.

[9] The ‘Ecological Footprint’ analysis attempts to measure human demand on nature. It compares human consumption of natural resources with planet Earth's ecological capacity to regenerate them and estimates the amount of biologically productive land and sea area required in order to do so (Rees, 1992).

To take into account the different lifespan of a computer in a certain scenario the supply of a school for a usage time of five years was hypothesized for all scenarios. The **functional unit** therefore is defined as the usage of 46'000 computers during five years at a school.

The results shall primarily give an evaluation of different strategies (separate or combined) for the supply of computers to schools and serve as the foundation to determine the contribution of the refurbishment process to sustainability. Additionally they should give an understanding of the advantages and shortcomings of CPE or the OLPC initiative. Different ideas regarding the support accompanying of such programs or the educational effects will only be discussed qualitatively.

1.5 Research questions

The following research questions have been investigated in order to achieve the aim of the study:

A *What are the exact material flows of the refurbishment program CPE?*
(Assessment of the present system)

The material flows of the actual situation which guarantees a supply of computer for the schools has been analysed. Therefore cooperation with CPE was established and the necessary data of the program was collected.

B *What are possible alternative scenarios to provide a sufficient supply of computers to schools in Colombia?*
(Investigation for alternative solutions)

Possible alternatives of supplying schools with computers were identified and illustrated graphically. Some are related to future plans of CPE.

C *What are the involved costs of each of these scenarios?*
(Cost analysis)

For each of the scenarios a cost analysis was conducted. While some scenarios do not have to include paying for the computers other have to purchase new equipment.

D *What are the critical stages during the life cycle of a refurbished or recycled computer regarding the environmental impacts?*
(LCA assessment)

For each of the scenarios a Life Cycle Analysis (LCA) of a computer was conducted. This shows the environmental impacts of each stage during the life cycle of a computer. Stages are the production, the use, the transport, possible processes to enable reuse and the final disposal of the computer.

E Which of the scenarios has the best performance regarding its economic, environmental and social impacts?
(Sustainability and best case assessment)

Each of the scenarios has been assessed with the Multi Attribute Utility Theory (MAUT). This method allows a comparison of the sustainability of the scenarios. It was applied in order to gain information about which strategy has the best sustainability performance and give future advice of how schools in Colombia could be supplied with computers in the most sustainable way.

1.6 Case study region

As a case study region, Colombia was selected. This was due to the well established refurbishment program CPE, the biggest of its kind in Latin America.

1.6.1 General information

Capital:	Bogotá
Surface:	1'141'748 km^2
Population:	44'065’000
GDP (PPP):	US $3,245.859 (2008)
Currency:	Colombian Peso
Literacy:	92.5%

Figure 1: Locating Colombia on the world map

Colombia is the fourth-largest and second-most populated country in South America. In the West it borders the Pacific Ocean and in the North the Atlantic. Neighbouring states are Panama in the North-West, Venezuela in the North-East, Brazil in the South-East, Peru in the South and Ecuador in the South-West. It is politically subdivided into 32 departments and a federal district with the capital Bogotá (Distrito Capital).

Colombia's main exports include manufactured goods (41.32% of exports), petroleum (28.28%), coal (13.17%), and coffee (6.25%). Moreover it is the largest provider worldwide of cut flowers and the third largest of plantains. Unofficially illegal drugs are also a major export.

Due to internal conflicts there exists a huge amount of displaced people. This increases the effect of the migratory movements from the rural to urban areas. While in 1951 around 54% of the population lived in an urban area it is estimated to be around 77% at present.

In Santa Fe de Bogotá, the biggest city, live around 1/6 of the population. Other big cities are Medellín (2.4 million) and Cali (3.1 million).

Since 1985 the population grew from 32 million habitants to more than 44 million at present. The average population growth per year is an estimated 1.43%.
The Gross Domestic Product (GDP) is anticipated to be US $156.690 billions in 2008. This corresponds to a GDP per capita of US $3'246. Therefore Colombia is defined as a "lower middle income" country by the World Bank. According to the Colombian government 14.7% (2005) of the population live below the poverty line.

Figure 2: Geographical coordination and map of Colombia. (Source: www.wikipedia.com)

1.6.2 School system

The education in Colombia is divided into a preschool education, basic primary schooling, secondary schooling and university. Many schools are private. The primary schooling lasts five years and is compulsory for children between 6 and 12 years of age. Secondary schooling lasts six years of which the first four years are compulsory and called basic secondary education and the last two years vocational media education. Despite the compulsory nine years of school the net enrolment for secondary school in 2001 was 53.5%. The completion rate for children attending primary school totalled 89.5%. The ratio of pupils to teachers in 2001 in primary school was 26:1 and in secondary school 19:1 according to a 2003 estimate[10].

The total public spending on education as a percentage of the GDP was 4.4% in 2001 as compared with 2.5% at the end of the 1980s. This is one of the highest rates in Latin America and shows the high priority education has in Colombia.
The literacy increased continuously throughout the years and today is more than 93% in urban areas but only 67% in rural areas.

[10] Source: CIA World Factbook (2006 edition)

The ratio of pupil to computer at present is 48:1[11]. In its four year plan between 2006 and 2010 the Colombian government[12] formulated the goal to bring this ratio down to 20:1. The specifications are to provide a supply of computers for 70% of all public schools by the year 2010. 45% of the schools will be supplied through CPE. This requires an increase of the turnaround of 18'000 computers (2006) at CPE to a yearly amount of 46'000 computers between 2007 and 2010.

1.6.3 ICT usage

In 1999 the 'Ministry of Communication' launched a program called 'Compartel'. The initiative aims to improve the accessibility of telecommunication services to rural zones and low social stratums. Steps to achieve this aim are the expanding of basic telephone services, building community access centres and providing internet connections to schools and hospitals. CPE is among others one wing of the initiative.
The following chapter describes and illustrates the need for these activities.

According to a study by CompTIA, Colombia is ranked in the middle of the development and usage of information and communication technology (ICT) within Latin America.
As illustrated in Table 1 Colombia has a low computer penetration of 5% per capita compared to the average of 16.1% in Latin America. The same accounts for broadband connections where the total penetration is only 1.3%. Though, according to the latest IDC report (2007) the Colombian broadband subscribers have increased by 93% in 2007 which represents the highest growth rate in Latin America. But mobile phones show a different image. Colombia lies with a penetration rate of over 60% not only above average in Latin America but also worldwide.

Table 1: Indicators of the ICT development of Colombia and selected countries/regions**.**

	Colombia	Chile	LAC	Switzerl.	USA	World
Computers per 100 habitants	5.0	20.1	16.1	86*	76.2*	19.8
Broadband connections per 100 habitants	1.3	6.8	3	26.2*	19.2	5.7
Mobile phones per 100 habitants	63.6	77.7	53	92*	77.22	45.3

Source: World Banc (2007), *2005; Colombia: CCIT, ASOCEL, SIUST 2006.

The results shown in Table 1 are confirmed by analysing the investments spent for ICT per capita of selected countries within Latin America. Even though Colombia has the lowest investments

[11] Source: Ministry of Education, www.mineducacion.gov.co
[12] See also www.dnp.gov.co

compared to Argentina, Brazil, Chile, Mexico and Venezuela it is the only one that shows a continuing increase between 2001 and 2006 (Figure 3).

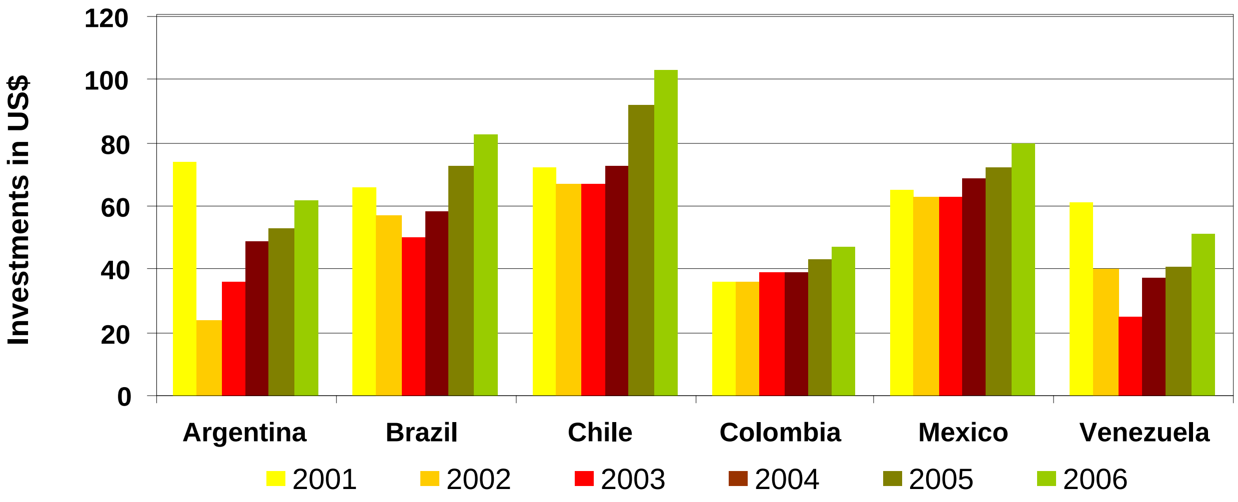

Figure 3: Investments per capita in ICT of selected countries in Latin America (Source: IDC)

Figure 3 illustrates e.g. that a Colombian in 2006 spent an average of US$ 47 on ICT while a Chilean spent more than double, US $103.

Analysing the development of the penetration rate of computers per capita between 2001 and 2006 (Figure 4) one observes a total increase of a little more than 2% for Colombia. In the same time period countries like Brazil, Chile or Mexico could increase their penetration between 4% and 5%. Note: More recent estimations of the penetration rate indicate almost a doubling since 2001 of computers per capita for Colombia.

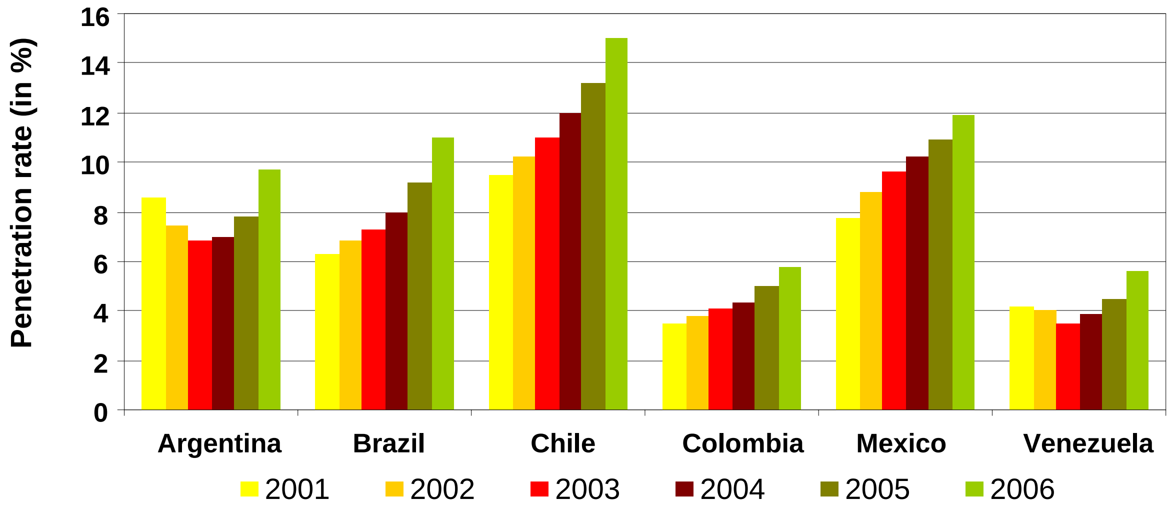

Figure 4: Development of the penetration rate between 2001 and 2006 of computers per capita for selected countries in Latin America (Source: IDC).

As illustrated in Figure 4, Colombia does have a lower increase of the penetration compared to Brazil, Chile or Mexico. If one compares the penetration rate of Colombia with the rest of Latin

America the gap has increased since 2001 from 3.1% to an actual 4.8% (Figure 5). This signifies that an instant installation of more than 2.1 million computers would be required to reduce the gap to the level of 2001 (Ott, 2008).

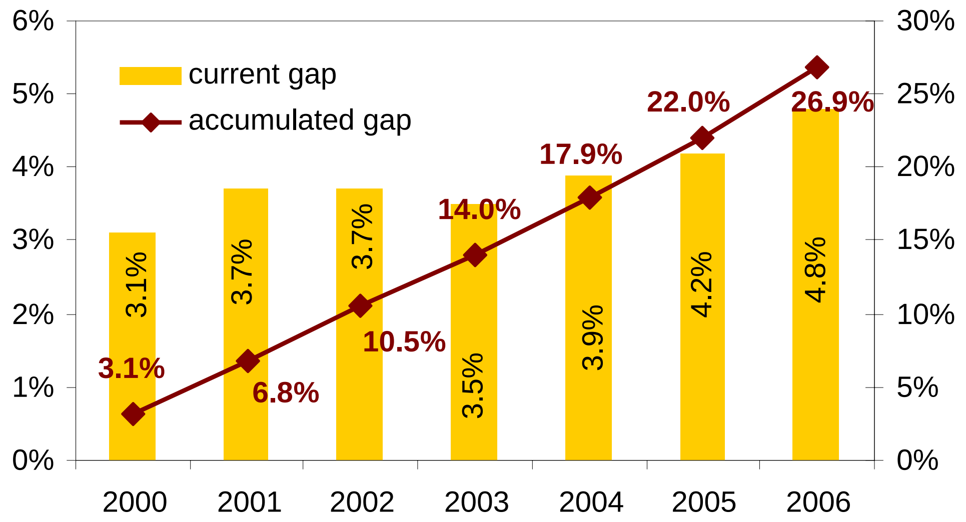

Figure 5: Penetration gap of Colombia compared to Latin America (Source: IDC, 2008)

Analogue to Figure 4 the installed base of computers since 2000 has increased from 1.5 million computers to more than double in 2007. A recent jump from 2006 to 2007 can be identified (Figure 6). The biggest share is installed in households, followed by the private and public sector.

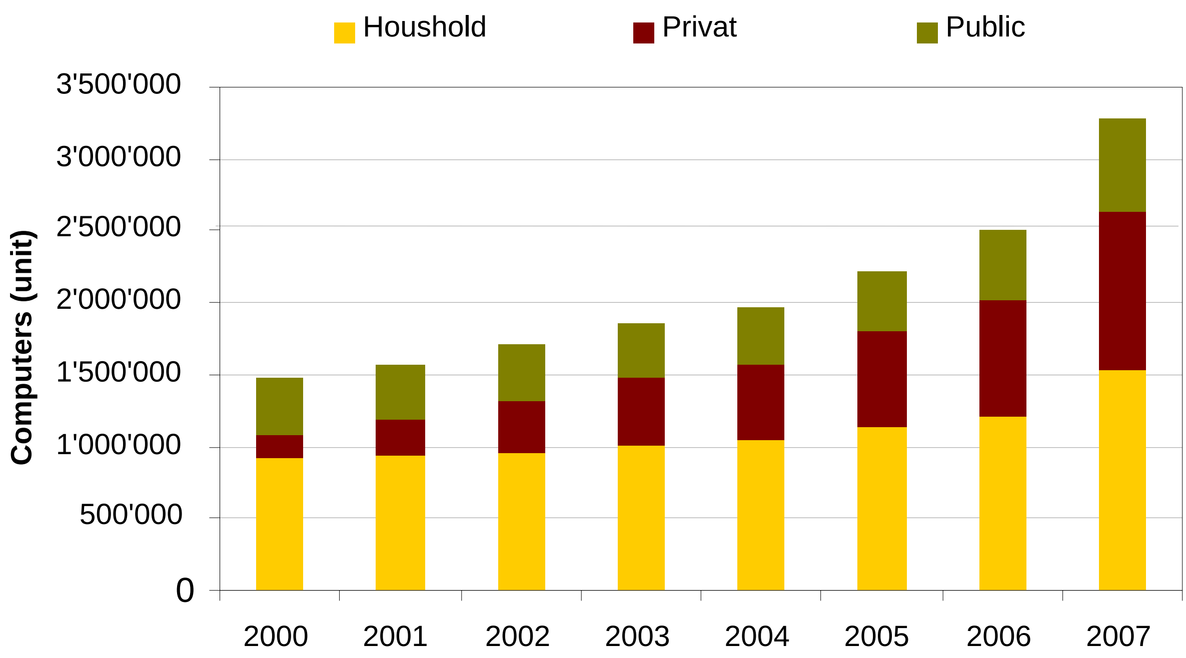

Figure 6: Development of the installed base of computers between 2000 and 2007 (Source: IDC, 2008)

Although the figures illustrate a recent jump in the increase of computers in Colombia the country is still far below the average in Latin America. Due to lack of data no comparison could be drawn of the IT penetration rate in schools.

1.6.4 E-waste management

Juan Lozano Ramirez, the 'Minister of Environment' declared the sustainable management of e-waste and the ban of transboundary movements[13] of 'e-waste' into Colombia as a priority to his ministry[14].

However, at present there is no specific legislation regarding the handling or recycling of 'e-waste' in Colombia.

At the moment Costa Rica is the only state in Latin America which prepared a draft law regarding 'e-waste'. The draft has not yet been put into force.

Nevertheless in Colombia, a campaign for the collection of used mobile phones was launched in August 2006 in collaboration with the three biggest providers. Earlier initiatives were addressing the recuperation and recycling of refrigerators.

At present the 'Ministry of Environment' (MAVDT, Ministerio de Ambiente, Vivienda y Desarrollo Territorial) is negotiating with the industry to sign a contract which aims to develop a collection and recycling system for obsolete computers and peripheral devices. A pilot project with four collection centres in Bogotá is planned during the first quarter of 2008. People are encouraged to bring back their obsolete computers. Participants receive a small reward. The project will be partly financed by the Centro Regional del Convenio de Basilea (CRCB) and CPE, which will take care of the collected computers. Technical and operative support will be provided by the MAVDT and the EMPA. The whole project will be documented and should serve as an example for entire South America.

[13] In order to avoid the exportation of hazardous waste and prevent the developed world to use developing countries as a dumping ground, the Basel Convention (see also www.basel.int) was put into force in 1992. This UN Convention is a multilateral entered environmental agreement that aims to regulate and control the transboundary movements of hazardous waste and their disposal. In 1995 the Parties agreed to incorporate a "Ban Amendment" which prohibits the export of waste intended for final disposal, recovery and recycling from Annex VII countries (EU, OECD, Lichtenstein) to all other Parties to the Convention. Until today the "Ban Amendment" has not yet into force (Secretariat of the Basel Convention, 2007). Colombia is one of the countries that have not yet ratified it.

[14] See also http://ec.europa.eu/environment/waste/weee/index_en.htm

2 Methods

2.1 Material Flow Analysis (MFA)

The material flow analysis (MFA) is a systematic assessment of the flows and stocks of materials within a system defined in space and time. A MFA determines, describes and analyzes the metabolism of industries, regions or materials. The metabolism of a system stands for the transfer, storage and transformation of materials within the system and the exchange of materials within its environment (Brunner und Rechberger, 2004). It therefore has to connect the sources, pathways and the intermediate and final sinks of a material. The results of an MFA can serve to identify theoretical possibilities for regulations (Baccini & Bader, 1996). It can be controlled by a simple material balance comparing all input, stocks and outputs of a process. This distinct characteristic of the MFA makes it an attractive method as a decision-support tool in resource management, waste management and environmental management (Brunner und Rechberger, 2004). Originally the MFA was developed for processes in industrialized countries but was recently applied in developing countries (Binder et al., 2001; Streicher-Porte, 2006) for the early recognition of the environmental impacts of human activities.

The working process contains the following four steps:

- System analysis: Defining the system boundaries, description of the system through processes and materials
- Data collection of the material flows
- Calculation of stock flows
- Schematic description and interpretation of the results

The practical execution of the MFA is often an iterative progress during the further understanding of the system.

2.1.1 Definitions

The following list defines the most important terms used for the material flow analysis in the context of this study. The definitions are carried out according to the Practical Handbook of Material Flow Analysis (Brunner and Rechberger, 2004):

Material

The term material includes substances and goods. Substances are defined as chemical elements, whereas goods are real life items, such as wood or a computer.
In this study, the term material refers to a computer including all parts and components.

Process

A process is defined as the transformation, transport or storage of materials. The processes used in the material flow analysis conducted in this study involve production (where additional), transport, refurbishment, storage and disposal of a computer. A process of storage includes a stock, where material is stored for a defined time.

Flow

A flow is defined as a mass flow rate. This is the ratio of mass per time that flows through a system or process e.g. the amount of computer material that flow from the refurbishment process to the recycling and disposal process during one year. The physical unit of a flow may thus be given in units of kg/year. In this study, a flow may also refer to a flow of goods. The flow is then given in units/year (which can easily be converted into a mass flow, multiplying the units by their mass).

Transfer coefficient (TC)

Transfer coefficients describe the partitioning of a material in a certain process. In the present study the transfer coefficient is determined by the failure rate during the refurbishment processes. These take place either at one of the CRs or at 'ComputerAid' and are expressed in percentages for material 'level one' (see Table 10) and units for material 'level two' (see Table 7). Furthermore a TC comes into effect during the recycling and disposal where a manual dismantling of material 'level one' and 'level two' is being processed. For the recycling and disposal the TCs are expressed in g and % (see also Table 11 to Table 15, chapter 4.2.3). Figure 7 illustrates the concept of a TC.

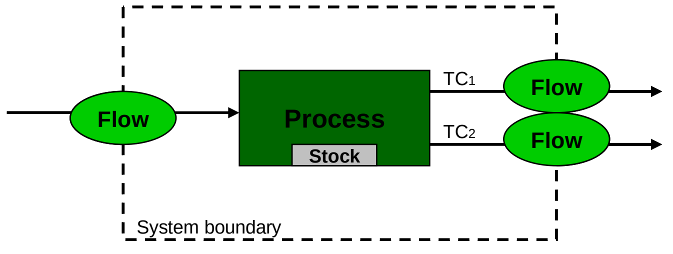

Figure 7: Schematic description of a Transfer Coefficient (TC). Added up all TCs have to result 1.

System and system boundary

A system is the actual object of the study and may be considered to be the sum of the interacting elements in the system. In the present study the program CPE is the object of investigation. Since the aim of the system is the supply of schools with computers alternative scenarios as well as the complete recycling processes are being integrated into the program CPE.

The system boundary defines the limits of the study in space and time.

2.1.2 Mathematical description

In order to describe a system mathematically a set of variables has to be found that reproduces the system in the most descriptive possible way. The set is complete when it enables calculating the material density as well as all material flows and storages at any time and any point of the system. Taking the principles of the mass conservation into account the principal equation of the material balance is as follows:

$$\frac{dM^{(j)}}{dt} = \sum_r A_{rj} - \sum_s A_{js} \qquad (1)$$

$M^{(j)}(t)$: amount of material in $V(j)$

$A_{rj}(t)$: material flow from $V(r)$ to $V(j)$

The partitioning of material flow through a process is modulated by transfer coefficients.
The transfer coefficients k indicate the (relative) fraction of the total input into balance volume V_r into the balance volume V_s, i.e. the flow V_{rs} that leaves the balance volume V_r.
The mathematical definition is as follows:

$$k_{rs} = \frac{A_{rs}}{\sum_j A_{jr}} \qquad (2)$$

Whereas $\sum_j A_{jr}$ represents the total V_r.

The principal steps involved in developing a mathematical model are:

- A complete description of the system and the involved variables (e.g. transfer coefficients)
- The determination of the mass balance equations which describe the interactions in the system
- The implementation of these in a model

2.1.3 System analysis

2.1.3.1 System boundary

The system boundary for the MFA is the refurbishment program CPE. Since the program supplies schools all over the country the system is geographically limited to Colombia. Alternative scenarios, e.g. the supply of schools through the OLPC initiative are integrated in the system CPE.

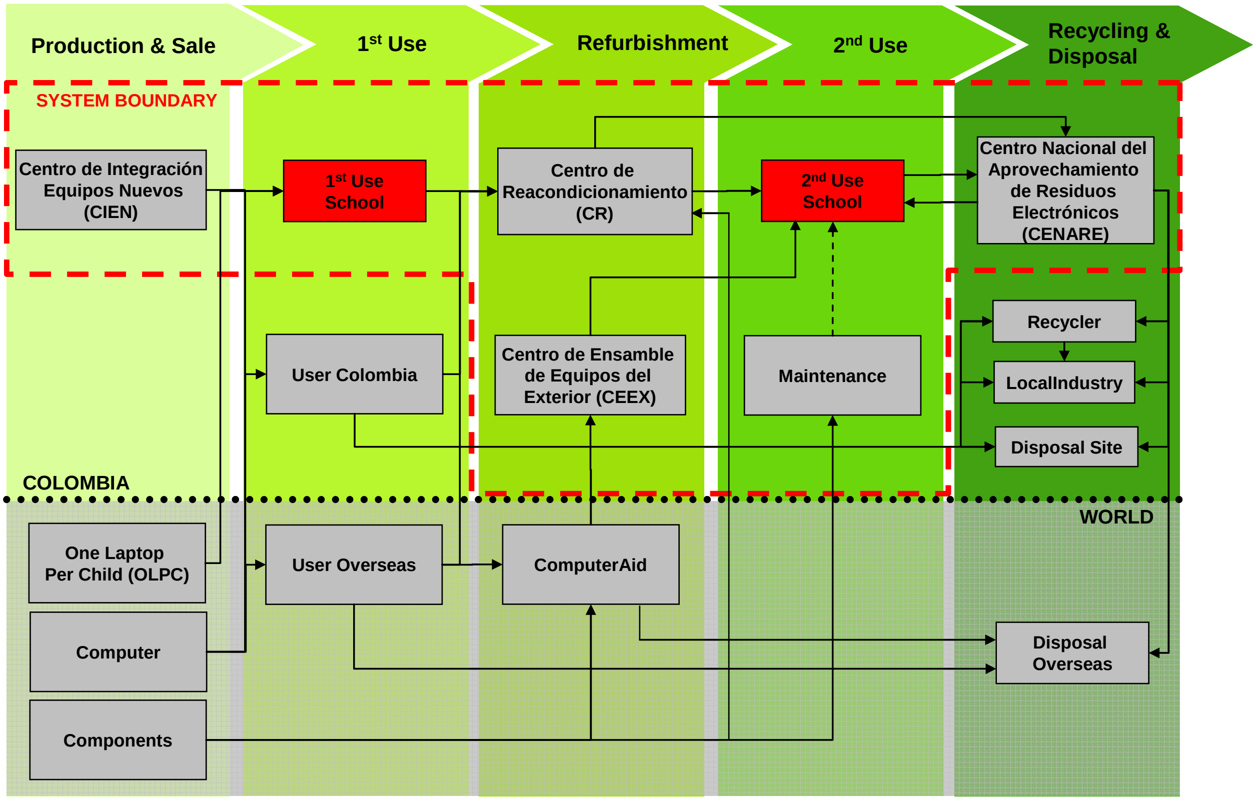

Figure 8: MFA model scheme

2.1.3.2 Material

The material studied in the MFA is a computer with all its parts and components. A differentiation of three levels took place. 'Level one' includes a Central Processing Unit (CPU)[15], a Cathode Ray Tube (CRT) monitor, a keyboard and a mouse. Table 2 gives an overview of the respective weights. The second level includes the specific components of the materials of 'level one' (see also Table 7). The third level refers to chemical elements and raw materials required to produce the material of 'level one' and 'level two'. This level is listed to a certain extend in Table 11 to Table 15. Further data material 'level three' taken into account during the Life Cycle Analysis (LCA) e.g. for the production of a computer, is derived from the Ecoinvent v2.0.

Table 2: Average weight of a CPU, CRT monitor, keyboard and mouse used in this study.

	CPU	CRT Monitor	Keyboard	Mouse
[in kg]	9.74[(1)]	11.12[(2)]	1.18[(3)]	0.12[(4)]

(1) Data source: Gmünder (2007)

(2) Author's own measurments

(3) Data from Ecoinvent2.0 (Atlantic Consulting & IPU (1998))

(4) Data from EMPA laboratory

In alternative scenarios the computer is substituted by a laptop.

15 In the present study the term "Central Processing Unit" is identical to a desktop personal computer without screen and peripheral devices.

2.1.3.3 System data and variables

The principal data and variables to describe the system are as follows:

1) ***Donation and production:*** the inflow or the total amount of computers and its components, respectively.
2) ***Lifespan:*** This variable takes into account the different quality of computers (refurbished or new) and the resulting usage time. It influences the necessary supply for the schools over time of a certain scenario.
3) ***Transfer coefficient (TC):*** Also depending on the quality of a computer. Different qualities of computers result in taking different pathways in the model scheme. In the present study the transfer coefficient refers on one hand to the failure rate during the refurbishment stage and on the other hand to the resulting dismantling during the recycling and disposal stage.

For an illustration of the above defined variables see Figure 9.

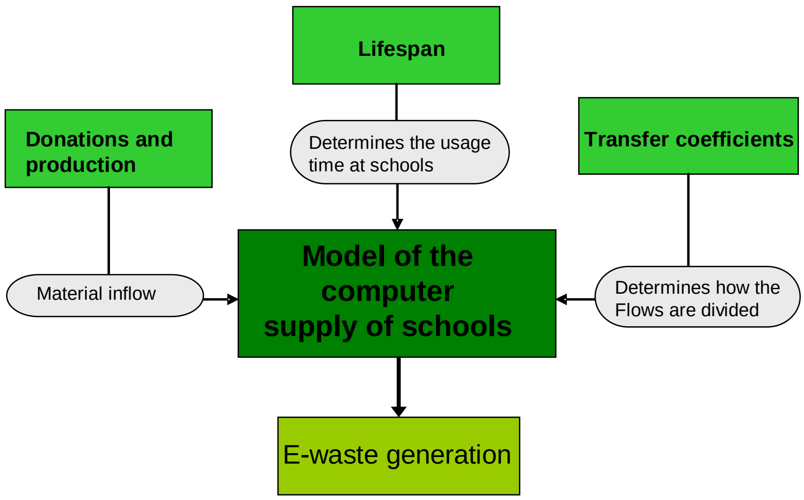

Figure 9: Schematic illustration of the model input data.

2.1.3.4 Processes

The processes used in order to describe the computer supply to schools in Colombia are characterized and subdivided (in life cycle stages) as follows:

Production & sale

A production in form of assembling components takes place at the **Centro de Integración de Equipos Nuevos (CIEN)**. Another production is carried out by the initiative **"One Laptop Per Child" (OLPC)** which produces the 'XO laptop'.

The process **Computer** refers to the ordinary production of a computer made in China.

The process **Parts & Components** refers to the production of components required during the refurbishment stage or the 2nd Use stage (maintenance).

1st Use

A 1st use takes place through the donators. They are either within or outside the boarders of the country characterized by **User Colombia** and **User Overseas**. Another 1st use is possible at the **Schools** supposing that the equipment come directly from the production stage.

Refurbishment

The refurbishment process takes place either in Colombia at one of the **Refurbishment Centres (CRs, Centros de Reacondicionamiento)** or overseas at **ComputerAid** (as representative for all refurbisher overseas). If the refurbishment is being processed outside of Colombia the computers are first sent to the **Centro de Equipos del exterior (CEEX)** in Bogota.

2nd Use

A 2nd use takes place at the **Schools**. This occurs when the provided computers already underwent a 1st use. The 2nd use is prolonged through the process **Maintenance** which refers to a technical maintenance of the computers at the school sites.

Recycling & disposal

Having reached their ‘end-of-life’ the computers are sent to the **Centro Nacional del Aprovechamiento de Residuos Electrónicos (CENARE)** where a manual dismantling process takes place. Some components are then being transported back to the schools for educational purposes (Robotic). Other parts are either directly sold to the **Local Industry** or to other **Recyclers** for further treatment. Due to their composition some parts have to be sent to a **Disposal Site**. The process **Disposal Overseas** refers to the ‘state-of-the-art’ recycling scenario of a computer in Europe.

2.2 Scenario analysis

Out of the MFA model scheme (figure 8) different scenarios have been identified. As mentioned before the **functional unit** is the supply of 46’000 computers for a five year usage at schools.

First, the current situation (2006) was analyzed. Then, under discussion with members of CPE future plans and possibilities (2007 or later) of the program were identified and integrated in different scenarios (Table 3). After that they were assessed with regard to their sustainability, applying the Multi Attribute Utility Theory (MAUT).

Table 3: Description of the model scenarios

Scenario	Description
"100% Colombian refurbishment" (Ia, Ib)	Scenarios Ia, Ib are based on the actual situation in 2006. Computers are exclusively of Colombian origin and refurbished at the CRs. Ia includes maintenance, Ib does not include maintenance.
"Colombian/overseas refurbishment and local assembling" (II)	Scenario II reflects the situation at present (2007). Computers are provided either from the CRs, assembled newly at the CIEN or arrive at the CEEX.
"Overseas refurbishment" (III)[1]	Computers are mainly provided from 'ComputerAid'. For the refurbished computers at the CRs a technical threshold ('Pentium III' or higher) was defined.
"Overseas donations for Colombian refurbishment" (IV)	Computers are guided directly from the users overseas to the CRs. For refurbished computers of Colombian origin a technical threshold ('Pentium III' or higher) was defined.
"XO laptop" (Va) "PC (new)" (Vb)	For refurbished computers of Colombian origin a technical threshold ('Pentium III' or higher) was defined. The remaining computers were replaced by purchasing the 'XO laptop' (scenario Va) or a new computer (scenario Vb).

[1] Please note that 'ComputerAid' serves as a representative for all refurbisher overseas.

2.3 Multi Attribute Utility Theory (MAUT)

The methodology of the Multi Attribute Utility Theory (MAUT) is based on the book 'Embedded Case Study Methods' (Scholz et al., 2002). The MAUT stands as a label for the family of case evaluation methods. They are used for analyzing, evaluating and comparing different alternatives. The objective of a MAUT is *"…to obtain a conjoint measure of the attractiveness (utility) of each outcome of a set of alternatives."* (= scenarios). The outcome (= utility) of each scenario can then be compared among all others.

Within the MAUT the user has to define a set of attributes which tries to reflect the overall attractiveness of each scenario. Attributes are preference-related dimensions of a system and can be system variables but can also measure e.g. quality or aesthetics.

Furthermore, the process of the definition of the attributes should intend to cover all aspects of the evaluation of the scenarios. Previous applications of the MAUT showed that the bigger the set of attributes and therefore the more detailed description of the scenario, the harder the weighting process and less exact the overall utility (Sutter, 2003).

In this study the attributes were defined by the author in discussion with experts from the 'Sustainable Technology Cooperation' (sustec) at the Swiss Federal Laboratories for Materials Testing and Research (EMPA) in St.Gallen and further developed in conjunction with CPE. Zumbühl (2005) applied a similar set of attributes evaluating different scenarios for the disposal of CRT screens in the Republic South Africa. The set represents economic, environmental and social attributes. They are specified in chapter 2.3.2.

The weighting of the attributes is determined by the author based on stakeholder weightings, interviews with employees of CPE and the priorities set by CPE.

Once all alternatives have been rated accordingly to each of the attributes the MAUT composes the ratings and realizes a synthesis resulting in a one-dimensional utility measure.

2.3.1 Mathematical formula of the MAUT

The mathematical description of the MAUT is as followed:

- The set of scenarios $S = (S_1, S_2, S_i, ..., S_m)$
- The set of attributes $a = (a_1, a_2, a_j, ..., a_n)$
- The set of utility functions $U = (u_1, u_2, u_j, ..., u_n), u_j = f(a_j(S_i))$
- The set of importance weights $W = (w_1, w_2, w_j, ..., w_n)$

$$U(S_i) = \sum_{j=1}^{m} w_j u_j \qquad (3)$$

The formula gives the total utility of a scenario whereas 1 represents the highest utility, 0 the lowest.

The scenarios that have been evaluated within this study are described in chapter 3.1.5 and are not further discussed at this point.

2.3.2 Attributes used in the MAUT assessment

The study aims to evaluate the best possible strategy of supplying the schools with computers. This process is defined by the term "sustainability". According to the Brundtland Comission (1987) sustainability refers to a development that *"…meets the needs of the present without compromising the ability of future generations to meet their own need."*. Nowadays it is a common accepted fact that "…*economic development, social development and environmental protection are interdependent and mutually reinforcing components."* underlying the term.

The set therefore aims to cover relevant aspects in the economic and social development and the environmental protection. For each of these categories three attributes were defined. Description of the attributes together with the corresponding scales and units are shown in Table 4.

Table 4: Set of attributes used for the MAUT assessment.

Attributes	Scale / unit	Description
Economy		
Low net costs	\$ / computer	Costs for transport (if additional), new equipment, processing at CPE and labour minus the revenues (material values out of recycling) / computer of scenario S_i.
High technical value[1]	0, 0.25, 0.5, 0.75, 1	Value is based on technical standard (processor) of the computers being supplied.
Involvement/participation of local economy	%	Share of local economy involved into implementation of scenario S_i.
Environment		
Low use of energy	Normalized Eco-Indicator'99 points (= sum of environmental losses and environmental benefits)	Energy needed for the production, transport (if additional), usage phase, refurbishment and recycling/disposal / computer of scenario S_i.
Low use of resources		Resources needed during total lifespan / computer of scenario S_i.
Little toxic emissions		Caused emissions through whole life cycle minus prevented emissions due to savings of raw materials / computer of scenario S_i.
Society		
Creation of jobs low and semi-skilled jobs	Amount of jobs / computer provided for schools	Providing of low and semi-skilled jobs within Colombia.
Creation of highly skilled jobs	Amount of jobs / computer provided for schools	Providing of highly skilled jobs within Colombia.
Capacity building[1]	0, 0.25, 0.5, 0.75, 1	Providing additional capacity building for the local community and quality of computer based education.

[1] Whilst most of the attributes could be calculated, some underlie a qualitative analysis based on the author's own estimations. The qualitative assessments are ranked 0, 0.25, 0.5, 0.75 or 1. Note: 0 stands for very low utility, 0.25 for rather low utility, 0.5 for medium utility, 0.75 for rather high utility and 1 for very high utility.

2.3.3 Economic performance

2.3.3.1 Low net costs

For CPE a detailed cost analysis was realized based on the budgets of the year 2006 and 2007. The costs at the CRs, the CIEN, the CEEX, the CENARE and during the maintenance were all calculated separately. It was distinguished between direct labour costs, indirect labour costs, direct material costs, indirect material costs, indirect costs of fabrication, promotion costs, accompaniment and monitoring and the maintenance (see also **Table 18**). Some corrections, in order to take all cost into account, led to minor differences between the author's calculation and the calculations of CPE.

Due to the lack of information exterior processes could not be analyzed in detail. This is insofar not a problem as the price for the equipment reflects all previous emerged costs. Revenues for selling materials out of the recycling process are considered only for computers entering the program CPE.

The overall costs are then calculated per year per unit computer.

Low net costs implicate high utility.

2.3.3.2 High technical value

This attribute was introduced in order to meet concerns about the different technical levels of the delivered computers. It is reviewed semi-quantitatively and ranked either 0, 0.25, 0.5, 0.75 or 1.

For every scenario the percentage of computers with a processor equivalent to 'Pentium I' or lower, 'Pentium II', 'Pentium III' and 'Pentium IV' and higher, respectively was calculated. The choice of this attribute is based on the author's assumption that a higher technical standard allows a broader application and more adequate education for the users. It therefore creates a higher value for the national economy for future generations.

High technical value implicates high utility.

2.3.3.3 Involvement/participation of local economy

The participation of the local economy was divided in two categories. Category one, called life cycle, takes all processes regarding the production, the refurbishment and the disposal into account. It was assessed by appraising the contribution of CPE to all these processes of a certain scenario. For example if the equipment was purchased no involvement for local economy was allocated. Category two assessed the share of local economy for the transports of a certain scenario. For example, if a computer had to be transferred from a foreign country to Colombia, then from the harbour to the refurbishment site and locally to schools the involvement of the local economy was calculated as one third. To get an approximation of the total involvement/participation of the local economy the category life cycle was counted three times as

high as the category transport (for calculations see appendix A). The involvement/participation is expressed in %.
High involvement/participation of local economy implicates high utility.

2.3.4 Environmental performance

The assessment of the environmental performance plays a major role in this study. As indicated in table 4 the environmental performance is intended to be assessed through the evaluation of the three attributes: 'low use of energy', 'low use of resources', 'little toxic emissions'. However, to determine these three attributes a Life Cycle Analysis (LCA) was conducted. Therefore the environmental impact of the production, the use, the refurbishment process, transport, the recycling and disposal, as well as the environmental benefit of saving raw materials through recycling, was quantified. Figure 10 illustrates the involved processes that have been considered during the different life cycle stages of a computer. Depending on the scenario only some of the life cycle stages had to be taken into account.

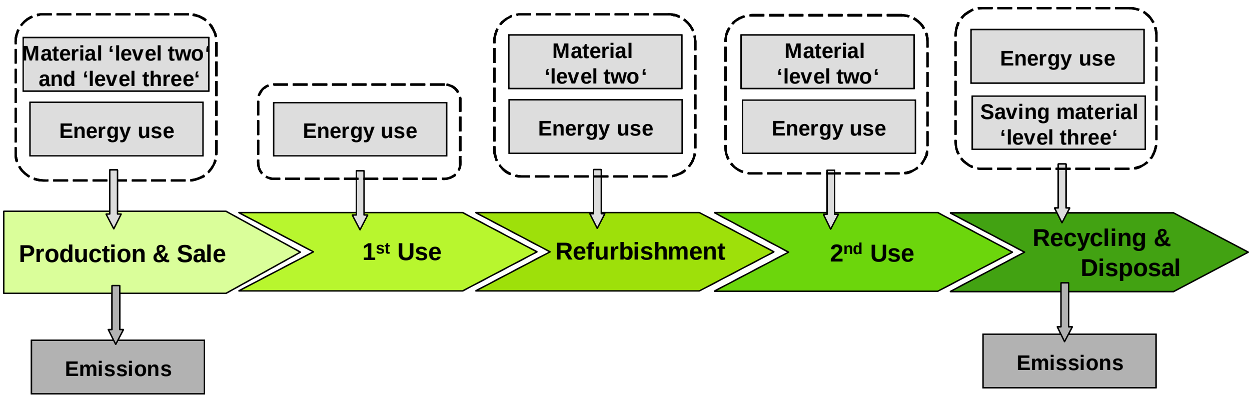

Figure 10: Illustration of the processes being considered during each life cycle stage (for material 'level two' see table 7, for material 'level three' see table 11 to 15).

The collected inventory data through the fieldwork was complemented with data from the database 'Ecoinvent v2.0' and analyzed with the software application 'Simapro'. This allowed an evaluation and assessment of the three attributes by the Eco-indicator'99 (Goedkoop et al., 2000).
The Eco-indicator'99 is a damage-orientated approach and was chosen as a default indicator for the environmental performance due to its consistency and the comprehensive modelling of the positive and negative environmental impacts of a system. Simplified interpretation of the result made it a widely used indicator to support decision-making.

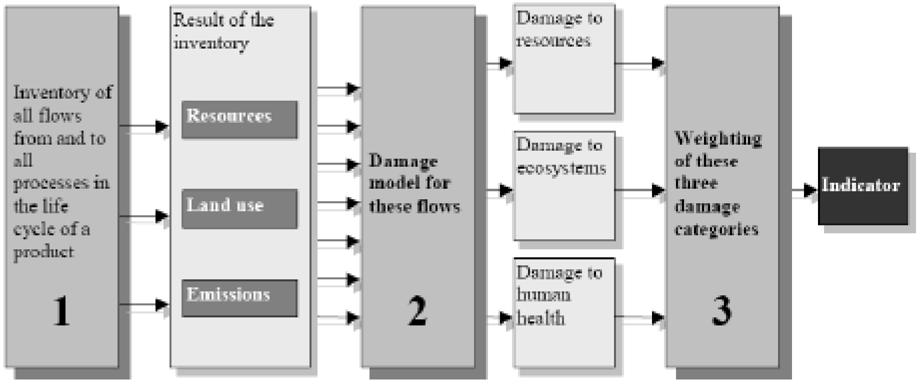

Figure 11: General procedure for the calculation of the Eco-indicator'99. The light coloured boxes refer to the procedures, the dark coloured boxes refer to intermediate results (Source: Goedkoop et al., 2000).

After the inventory of all materials and energy flows (step 1 in Figure 11) the data are linked to the following damage categories (step 2 in Figure 11):

Human Health (HH)

The damage to HH is expressed by the number of years lost or the number of years lived disabled. They are combined to the 'disability adjusted life years' (DALY). To calculate the impact on human health of the recycling system, exposure and effect have to be assessed and linked (Hofstetter, 1998).

Ecosystem Quality (EQ)

The EQ is calculated from the percentage of extinct species in a certain area and time due to environmental exposure. Therefore the ecotoxicology, the acidification/eutrophication and the land usage/land transformation of the processes/flows are calculated and the different 'potentially affected fractions' (PAFs) are determined.

Resource Depletion (RD)

A parameter expressing the remaining quality of the mineral and fossil resources and therefore the surplus energy needed for the extraction (MJ per kg) is used to determine the RD.

During step 3 the damage categories are normalized (dimensionless) and weighted in order to get an aggregated value. This has to be conducted in the most possible transparent way regarding the influence of different environmental perspectives or opinions. In the present study the hierarchist perspective was chosen for the weighting.

Note: The three attributes defined for the MAUT were allocated to the corresponding category of the Ecoindicator'99 ('low use of energy' – *Resource Depletion*, 'low use of resources' – *Ecosystem Quality*, 'little toxic emissions' – *Human Health*). The overall weight for the weighting of the Eco-indicator'99 results was derived from the stakeholder weights given to the corresponding environmental attributes by *adding* those weights.

2.3.5 Social performance

2.3.5.1 Creation of low and semi-skilled jobs

This attributes reflects the amount of low skilled and semi-skilled jobs provided by a scenario. This includes all jobs that do not require a university degree. Only directly provided jobs are considered, e.g. the job for a technician at one of the refurbishment centres (CRs) is included while the creation of a job as driver for a transport company is not included.
A high amount of created jobs implicates high utility.

2.3.5.2 Creation of highly skilled jobs

Only jobs which require a university degree and are directly provided by a scenario are considered for this attribute.
A high amount of created jobs implicates high utility.

2.3.5.3 Capacity building

This attribute was analysed semi-quantitatively. The capacity building on the individual (learning process) and local (education programs) level of each scenario is analysed and evaluated qualitatively.
The utilities were then allocated either 0, 0.25, 0.5, 0.75, 1.
High capacity building implicates high utility.

2.3.6 Normalisation of attributes

The MAUT does have the disadvantage that the utility of one attribute is not comparable with the utility of different attribute due to different units and scales. The attributes therefore have to be normalized in order to make them comparable. This can be achieved by normalizing the values of a single attribute over all the scenarios.
For the attributes for which the values are proportional to their utility (e.g. 'capacity building') the formula is as follows:

$$a_n = \frac{a_i - a_{\min}}{a_{\max} - a_{\min}} \qquad (4)$$

If the values are reciprocally proportional to their utility (e.g. 'low net costs') the formula is as follows:

$$a_n = 1 - \frac{a_i - a_{\min}}{a_{\max} - a_{\min}} \quad (5)$$

a_n = Normalized value of an attribute of a certain scenario S_i

a_i = Value of an attribute of a certain scenario S_i

$a_{\max}$ = Maximal value of an attribute over all scenarios

$a_{\min}$ = Minimal value of an attribute over all scenarios

The resulting range for the values of a_n is between 0 and 1 whereas the normalized lowest attribute value becomes 0 and the highest 1, respectively. This also explains the range of 0, 0.25, 0.5, 0.75 and 1 to qualitatively evaluate an attribute. Other examples of studies that have used the same approach for the linearization of the attributes are Suter (2003) or Zumbühl (2005).

2.3.7 Weighting of the attributes

The weighting of the attributes was realized by a survey in conjunction with employees of CPE and the ‘Ministry of Communication’. All participants hold leading positions in the management or the administration of CPE. Furthermore a representative from ‘ComputerAid’ was consulted. Table 5 illustrates the applied weightings. The stakeholders were given a possibility to allocate an importance to each attribute. 0 implies ‘no importance’, 4 ‘very high importance’.

Table 5: Allocated weights for the sustainability attributes

Possible weights allocated to the attributes	Values used for the priorization
no importance	0
little importance	1
medium importance	2
high importance	3
very high importance	4

2.4 Data collection

Data has been collected by literature and online research, through online questionnaire and expert interviews.

Literature and online research

Data collected through the literature and online research has been used for

- the preparation of the study, i.e. the choice of method
- the introductory chapter on the digital divide and e-waste
- model data, i.e. composition data for the LCA

Survey

A survey, containing a short description of the attributes according to chapter 2.3.3, 2.3.4 and 2.3.5, helped to determine the stakeholder's weightings for the attributes of the MAUT assessment. A total of 12 surveys were distributed whereas five employees at the national directorate at the 'Ministry of Communication', two at the CENARE, one at the CRB, one at the maintenance, one at the 'Universidad Nacional' and one at 'ComputerAid' were asked to fill in the survey. A total of seven inquiries were completed and sent back.

Expert interviews

Personal interviews have been conducted with various experts in order to obtain or complement information. Besides visiting recyclers around Bogota all interview partners were member of CPE (see appendix C for an expert list). They mainly helped to understand the scope and complexity of the program CPE.

3 Results

3.1 System analysis

3.1.1 Computadores Para Educar (CPE)

The program Computadores Para Educar (CPE) was officially launched by the President of Colombia on the 15th of March 2000. Today the program is managed by the ‘Ministry of Communication’ in collaboration and partnership with the ‘Ministry of Education’ and the ‘Servicio Nacional de Aprendizaje’ (SENA). The idea of the initiative is based on a similar program called ‘Computers for Schools’ which has been run since 1993 by the Canadian government. A close cooperation and knowledge transfer between the two countries exists.

The program was founded with the aim to supply public educational institutions (mainly schools) with information technology, through the refurbishment and maintenance of computers and to promote the use and benefits of IT during the education process. A main task of CPE is therefore to provide adequate accompaniment and monitoring before and during the implementation of the computers at the schools. A subsection ‘Robotic’ was established to capacitate students in the diverse applications of IT.

Since the year 2000 CPE supplied more than 9400 public schools all over Colombia. An estimated 2’877’000 student profited from the program.

3.1.1.1 Centros de Reacondicionamiento (CRs)

The refurbishment centres (CRs) are the core of CPE and responsible for the successful outputs (Figure 13). The first centre started operating in July 2000 in Bogotá (CRB). Between May 2001 and January 2002 four other centres located in Barranquilla (CRBQ), Cali (CRC), Cúcuta (CRCU) and Medellín (CRM) joined the production of refurbishing computers. The distribution over these five cities covers approximately 96% of all computers used in Colombia (CPE, 2007).

Figure 12: Refurbishment centre in Bogotá.

Donations and production

The total average amount of donated CPUs to the CRs is 20'135 between 2001 and 2007. No tendencies can be identified, though, since the year 2005 the total amount of donated CPUs was constantly over 20'000. A peak of donations was achieved in 2005 with a total of 23'661 donated CPUs (Figure 13).

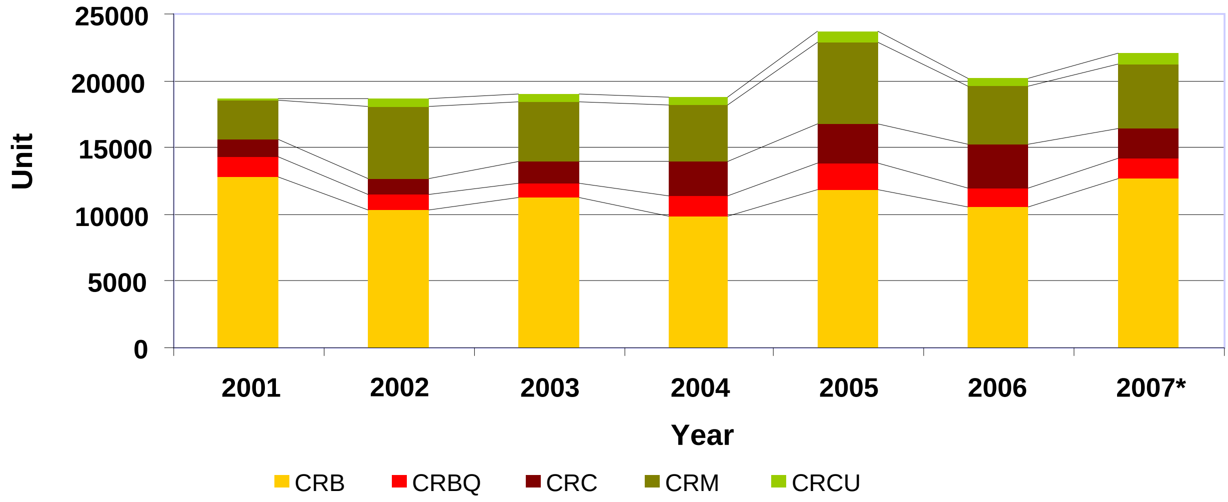

Figure 13: Amount of donated CPUs to each centre of CPE since 2001. *The numbers of 2007 are extrapolated on available data till September 2007 (Source: CPE).

Figure 13 illustrates the importance of the CRB. Approximately 54% of all donations arrive in Bogota. 24% of all donations arrive in Medellin, followed by 11% in Cali, 8% in Baranquilla and only 3% in Cucuta.

A different picture shows the development of the output figures of the five centres (Figure 14). While Bogota increased its production yearly since 2000 (with an exemption of 2003) all other centres achieved their maximum production capacity in 2004.

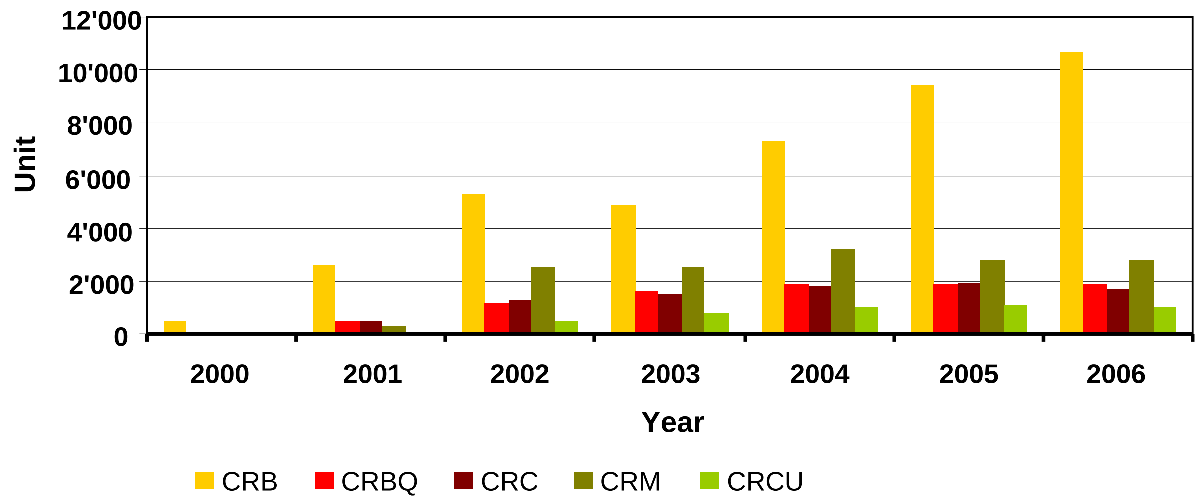

Figure 14: Production of refurbished computers at each of the five centres since 2000 (Source: CPE).

The analysis of the production until September 2007 conducted in this study shows that Bogota reached its capacity, too. Hence, a linear approximation of costs and materials could be made in order to calculate a higher supply of computers than the actual production of totally 18'000 equipment.

The share of each centre of the total production is analogue to the donations (Figure 15). At the start of the program in 2000 Bogota provided a 100% and still 70% in 2001 of the total production. From 2001 until 2003 the other centres could increase their share. This accounts especially for Medellin with a share of approximately 20% from 2002 till 2004. Since the year 2003 Bogota could continuously increase its share again up to 59% in 2006. Cucuta, the smallest centre, has since 2003 a steady share of approximately 8% of the production.

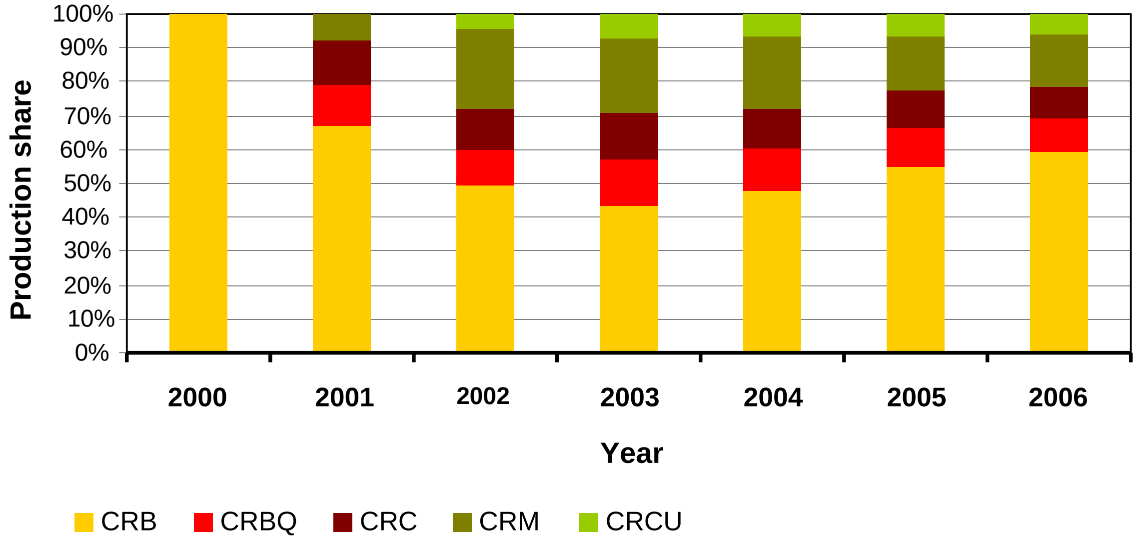

Figure 15: Production share of each centre from 2000 to 2006 (Source: CPE).

Refurbishment process

The different processes a donated computer goes through are in its order the triage (including reception and technical inspection), cleaning and testing, reparation, assembling, final revision and packaging (Figure 16).

All processes are conducted by either a technician rookie, junior or senior (depending on qualification, experience and capacity for teamwork).

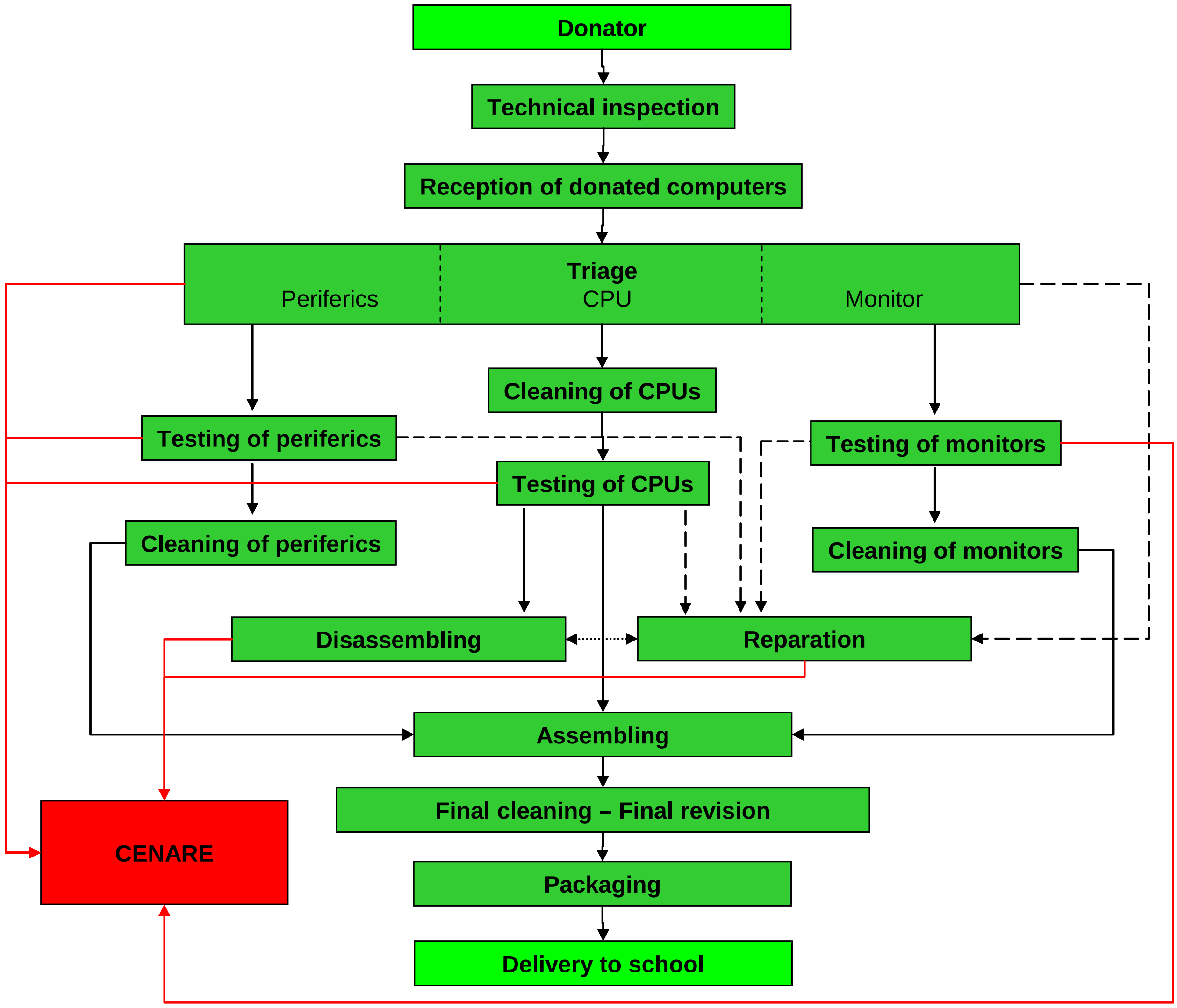

Figure 16: Flow scheme of the processes at the refurbishment centres.

At the triage the donations are received and separated as CPUs, CRT monitors, peripheries, printers or others. If a donation exceeds 50 equipments a technical inspection to determine amount and quality takes place beforehand. Once arrived a technician keeps exact accounts of the date and type of the equipment. CPUs are listed as desktop, tower, minitower, laptop or desktop with integrated monitor. The laptops account only for 4% off all donations while the "normal" desktop accounts for more than 70%. Furthermore brand, processor, memory module, colour and the containment of hard discs, floppy disc drivers or CD-ROM drivers are recorded. CPUs lacking more than two of either the hard disc or the drivers are classified as casings and sent to disassembling. Also for CRT monitors the brand, model, size and the colour are listed. Liquid Crystal Display (LCD) screens are a rarity at arrival and not taken into account in this study.

After the triage the equipment undergoes either a cleaning (CPUs) or are directly tested for functionality (CRT monitors and peripheries). If the equipment works it is further sent to the assembling. Obviously obsolete parts are directed to CENARE for recycling and disposal. CPUs are sent to disassembling in order to restore functioning components for reparation. Also, the

reparation requires a certain amount of new components in order to achieve the output figures. For an exact list of the components required during the refurbishment, see Table 7.
At the assembling the CPUs, CRT monitors and the peripheries are put together again.
Depending on the actual availability of parts, the computers are assembled to a certain technical standard (Table 6). The process also includes a software installation.

Table 6: Different technical standards computers are adjusted to at the CRs. The *M* indicates the addition of a modem (Source: CPE).

Standard[1]	Software	Hardware	Technical specifications
3	Windows 95B Office 97 Internet Explorer 5.0	Internet card	'Pentium I' 133 to 200 Mhz (Chip) 32/64 MB (Memory) 1 GB / 4 GB (Hard disc)
4 or 4M	Windows 98 SE Office 97 Internet Explorer 5.0	Internet card CD-ROM driver Soundcard Loudspeakers	'Pentium II' 266 Mhz to 700 Mhz 64/128 MB 4 GB / 40 GB
5 or 5M	Windows 2000 Office 2000 Internet Explorer 6.0	Internet card CD-ROM driver Soundcard Loudspeakers	'Pentium III' 750 and 'Pentium IV' 2.4 Mhz 128 / 256 MB 10 GB / 80 GB

[1] Since 2006 no computers of standard 1 or 2 are anymore assembled.

From the assembling the now almost-finished computers are sent to final revision. A last check of functionality and durability takes place before the computer are being packaged.
The refurbished computer is ready for delivery.

Mantenimiento (Maintenance)

In 2005 a pilot project was conducted to provide technical support for the schools. One year later the process maintenance was established.
For 2007 the goal is to conduct maintenance for just under 18'000 computers. Until end of October 2007 all computers independent of their origin were maintained whereas a share of 85% of the computers had to be fully functional after maintenance. Most of the defects after two year usage are caused by the battery, followed by the hard disc and the internet card (Figure 17).

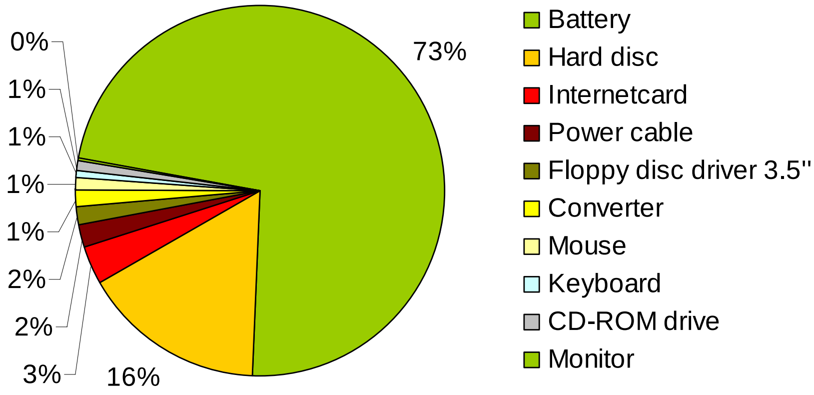

Figure 17: Most likely defect parts after a two year usage at school (Source: CPE).

For a detailed list of parts and components that are required for processing the maintenance please refer to table 7.

At the average the technicians encountered 22 computers at the schools of which 12 computers belonged to CPE. From November 2007, the goal is to leave behind 100% of the computers from CPE fully functioning while for all others only repair recommendations will be made. Furthermore, only the obsolete computers which belong to CPE will be taken back for recycling and disposal.
To build up the local capacity of maintenance CPE, together with the SENA initiated a program which aims to brief local students (aged more than 14 years old) in the maintenance and repairing of computers.

Figure 18: A classroom before and after maintenance.

3.1.1.2 Centro de Integración de Equipos Nuevos (CIEN)

At the Centro de Integración de Equipos Nuevos (CIEN) computers are being assembled newly. Parts and components that are assembled and purchased are CRT monitor, casing, motherboard, hard disc (40 Gigabyte), processor (AMD Athlon 64 3500), CD-ROM RW, memory card (256 RAM), power cable, loudspeakers, microphone, keyboard and mouse. The technical standard is comparable with a 'Pentium IV'.

The different stages during the assembling process are reception, the assembling itself, testing, software installation and packaging. All processes are either conducted by a technician rookie, junior or senior.

The CIEN was founded in 2007 in order to augment the production and fulfil the government's goals. It is aimed to produce 14'000 computers per year.

The delayed start of the operation phase was in September 2007.

3.1.1.3 Centro de Ensamble de Equipos del Exterior (CEEX)

At the Centro de Ensamble de Equipos del Exterior (CEEX) computers arrive, that have been refurbished abroad, for a last check-up before delivery to schools.

Analogue to the CIEN, the CEEX was founded in 2007 in order to increase the output figures. It was calculated to produce 14'000 computers per year. Nevertheless the operating of the CEEX did not take place as planned. This was mainly due to structural changes within the administration of CPE and interminable negotiation to acquire the necessary amount of computers.

The different stages at CEEX include an inspection/testing, cleaning, software installation and packaging. Experiences with 'ComputerAid' show that the computers arrive in working order[16].

The operating of the CEEX has been included in the model hypothetically.

3.1.1.4 Centro Nacional del Aprovechamiento de Residuos Electrónicos (CENARE)

The Centro Nacional del Aprovechamiento de Residuos Electrónicos (CENARE) was initiated due to the constantly growing amount of 'e-waste' that has been accumulating at the CRs. So far each centre stored the non-usable computers and components.

In 2007 the CENARE started to operate. It is still in the process of building and developing its own techniques for the most efficient ways to dismantle a computer. A pilot project to gain information about the dismantling process and the outputs of a CPU took place in 2006. At present the same is being processed for the dismantling of CRT monitors.

A characteristic of the CENARE is that some of the components are being stored and reused for 'Robotic' kits.

[16] According to Uca Silva, e-waste coordinator Latin America

Recycling

The recycling includes the dismantling of a CPU, a CRT monitor, a keyboard and a mouse. All processes are carried out manually. Exemptions are the stripping of the motherboard and the printed wiring boards (PWBs) as well as the separation of the CRT monitor glass (Figure 19).

Figure 19: Improvised hot wiring technique for separating CRT glass at the CENARE.

For separating the funnel and panel glass of a CRT monitor the hot wiring technique is applied. The installation to do so is still very basic. At present six rookie technicians are able to dismantle a hundred CRT monitors per day.

In order to loosen the parts from a Printed Wiring Board (PWB) the soldered spots are being heated up with a solder stick. Due to the developing of this process no exact time measurements could be taken. The responsible technician estimates a complete detachment of eight PWBs per day.

Robotic platform

To sensitize students of possible applications of information technology and to spark their interest for technology in general, CPE initiated the subprogram ‘Robotic’. Out of components of a computer CPE designs kits to teach the students various applications.

So far four different kits have been designed. Namely, these are an electronic door, a fotomobile, a weather vane and a tetrapod (Figure 20). More kits are in planning stage.

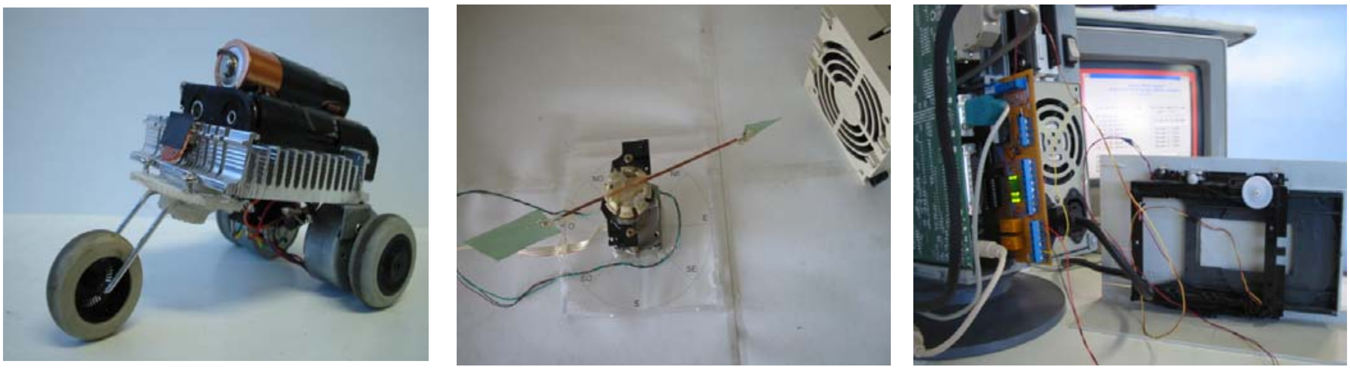

Figure 20: Photos of a fotomobile, a weather vane and an electronic door.

Components from the PWBs which are not used for 'Robotic' kits are being stocked. At a later stage they will be handed out for electronic courses at high schools and universities.

3.1.2 ComputerAid

'ComputerAid' is a refurbisher of computers based in England. It collects obsolete computers either from the public or private sector and prepares them for shipment. The technical standard of the computers are mostly 'Pentium III' and 'Pentium IV'. Computer with lower technical specifications are not accepted for donations.

The program has provided computers to organisations in more than 100 different countries during the last nine years. Having shipped over 100'000 computers 'ComputerAid' represents the biggest non-profit supplier of computers to developing countries.

In this study 'ComputerAid' serves as representative for overseas refurbisher. Similar programs that have not been investigated are e.g. 'World Computer Exchange' or 'Close the Gap'.

3.1.3 One Laptop Per Child (OLPC)

"It's an educational program, not a laptop program", stated Nicholas Negroponte, co-founder of the One Laptop Per Child (OLPC) initiative, when he introduced the vision of the US $100 laptop. The aim of the initiative is to provide a low cost laptop, the so-called 'XO laptop', to developing countries by producing huge amounts. The idea of providing a computer exclusively designed for children goes back more than four decades to the early days of computing.

Being delivered to children living in poor regions and some of the most remote environments the design and configuration of the 'XO laptop' faces several challenges.

In order to achieve a durability of five years under extreme circumstances the 'XO laptop' has no hard drive to crash and only two internal cables (hard disc and internal connectors are the laptop components most likely to fail). The machine's plastic walls are 2mm thick, as opposed to the standard of 1.3mm.

To discourage gray-market traffic the machine has a very distinctive appearance (Figure 21). The approximate dimensions are 242mm x 228mm x 32mm.

The LCD screen is 7.5 inches and available in two display modes. A transmissive, full color mode and a reflective, black and white mode that is sunlight readable.

Figure 21: The child-friendly and distinctive design of the XO laptop.

The machine is fully compliant with the European Union's RoHS Directive and contains no hazardous materials.
Integrated peripherals are a keyboard, gamepad, touchpad, audio, wireless networker, status indicator and a video camera.

Regarding the handling of the machine OLPC follows the motto ‘learning learning’. The ‘XO laptop’ is built from free and open-source software allowing children to use and modify their laptops on their own turns. Therefore a new interface software called ‘Sugar’ was designed exclusively for the ‘XO laptop’.

Both, the hard- and software are extensively tested in field studies and underlie a constant development.
Since the initiative is a non-profit program OLPC makes all developments transparent. Everyone is invited to actively participate and a discussion forum on wiki enables people to address concerns and open questions regarding the program.

The price of the ‘XO laptop’ depends to a certain extend on the demand of the market and underlies fluctuations. At present the price is set at US $188.
So far, Uruguay is the only country that submitted to the project and placed an order of 100’000 laptops. The production is done by Quanta Computer Inc. situated in Taiwan.

3.2 Mass flow analysis

3.2.1 Model input

3.2.1.1 Parts and components for refurbishment and maintenance

For the refurbishment processes CRs and 'ComputerAid' as well as for the process maintenance the purchase of new parts and components is necessary. Table 7 gives an overview of all required materials for the output of 1000 computers. For the process CR with computers of Colombia origin the data is based on the average consumption of the years 2005/06/07 at the CRs. Data for 'ComputerAid' is based solely on the year 2006. For the process maintenance data was taken from the projection and goals for the year 2007 made by CPE.

The data is used to determine the production costs as well as the environmental impacts of a process. Due to lack of data in 'Ecoinvent v2.0' some of the components had to be replaced through the author's own estimation (see also appendix B). Due to the level of detail the inputs are not illustrated graphically in chapter 3.2.2.

Table 7: Specification of the required parts and components during the process CR, Maintenance and ComputerAid. All numbers are adjusted to the production of 1000 computers (Source: CPE, Inventory 2005/06/07)

Parts (per 1000 unit)	CRs (User Colombia)	ComputerAid	Maintenance
CRT Monitor	311	-	-
Keyboard	92	200	4
Mice	293	65	4
Components			
Hard disc	375	-	71
CD-ROM driver	238	-	3
Floppy disc driver[a]	70	-	7
Transformer	28	-	-
Transistor	7	-	-
Converter (Keyboard)	34	-	7
Lithium - Battery	280	-	235
Alcaly - Battery	19	-	-
NiMH - Battery	8	-	-
Cable (modem, audio)	20	-	-
Microphones	517	-	-
Loudspeakers	477	-	-
Sound card	223	-	-
Fax modem card	4	-	-
Internet card	123	-	14
Video card	4	-	-
Memory modules[b]	62	-	-
Power cable	894	50	9
Monitor cable	3	-	-

[a] Due to lack of data at the floppy disc driver 3.5'' was replaced with a CD-ROM drive.

[b] Added up were memory modules of 30 and 72 pines, dual in-line memory modules (DIMM) PC-100 and PC 133 and rambus inline memory modules (RIMM).

3.2.1.2 Lifespan

The lifespan of a computer has an essential influence on the achievement of the functional unit. Since computers of different origins, different technical standards and variable usage time during the first use are processed and being sent to the schools, estimations of the possible usage time at schools have been made.

For computers of Colombian origin, treated at one of the CRs an average usage time of two years at the schools based on experience at CPE is assumed. The age of a computer at entrance into the program CPE is estimated to be around five years. Both estimations are based on expert interviews with members of CPE.

Further, the author assumes that computers achieving the technical ‘standard 5’ at the CRs have a prolonged lifetime at schools of one year. Table 8 shows that this assumption applies to around 22% of refurbished computers. The data is based on the production output at the CRB from January 2007 to August 2007.

Table 8: The apportionments of the standards in unit and % during the production at the CRB from January 2007 to August 2007 (Source: CPE)

Standard[1]									
3		**4**		**4M**		**5**		**5M**	
Unit	%	Unit	%	Unit	%	Unit	%	Unit	%
3678	54	1477	22	75	1	1315	19	235	3

[1] see Table 7 for description of the technical standards.

The average usage time of four years before entering the refurbishment process overseas is based on declarations made by ‘ComputerAid’. This number is confirmed by companies in Switzerland that state their first use at an average of four years (Marthaler, 2007). The author assumes that the usage time at school for these computers equals three years. The same lifespan is applied for computers donated overseas directly to the CRs.

The duration of five years of the ‘XO laptop’ at schools is based on assumptions made by OLPC. The author assumes the same lifespan for new assembled computers at CIEN as well as purchased computers. The ‘XO laptop’ is exclusively built for a long endurance under hard circumstances. The fact that the exposure of the ‘XO laptop’ is higher, due to its mobility, justifies the above assumption.

For all computers being delivered for a second use at schools the maintenance prolongs their lifetime for two years. This assumption is based on experiences made at CPE.

Table 9 summarizes the assumptions made and illustrates the necessary adjustment factors of a certain scenario in order to comply with the functional unit. Mathematical formula of the adjustment factors are given below Table 9.

Table 9: Illustration of the assumed lifespan of a computer in a certain scenario together with the corresponding adjustment factors (P = Production of a computer at any site, Rc = Refurbishment at a CR, R_o = Refurbishment at ComputerAid, P_c = Production at CIEN, P_L = Production of the XO laptop, D = Disposal).

Scenario[1]		1^{st} or 2^{nd} use at school (functional unit)		Adjustment factor[3]
Ia	P, 5 years, R_c	2 years, 2 years, D		1.19
	P, 5 years, R_c		2 years, 2 years, D	
Ib	P, 5 years, R_c	2 years, D		2.27
	P, 5 years, R_c	2 years, D		
	P, 5 years, R_c		2 years, D	
all[2]	P, 5 years, R_c	3 years, 2 years	D	1
II, III	P, 4 years, R_o	3 years, 2 years	D	1
II	P_c	5 years	2 years, 2 years, D	0.56
IV	P, 4 years, R_c	3 years, 2 years	D	1
Va	P_L	5 years	D	1
Vb	P	5 years	D	1
OFF[4]				
User Colombia	P, 5 years, D			1
User Overseas	P, 4 years, D			1.25

[1] For an illustration and description of the scenarios please refer to chapter 3.2.2

[2] Lifespan projection of computers complying 'standard 5' at the CRs.

[3] Mathematical formula are given below. The adjustment factor takes into account that 22% of the computers at the CRs comply with 'standard 5' (see also Table 8).

[4] Illustration of the average duration of the first use of a computer in Colombia and overseas. 'OFF' refers to the fact that computers not refurbished or reused are sent directly to the process stage recycling and disposal.

Adjustment factor

The adjustment factors are being introduced in order to comply with the functional unit of 46'000 computers during their five year usage at schools. This results in a slightly increased production for computers that do not last five years during their usage at schools. New computers are assumed to last five years. All others require a maintenance which prolongs the lifetime for about two years. The adjustment factors are applied for all further calculations made.

Mathematical formula for the adjustment factor if maintenance takes place is:

$$A_1 = (1+p) - \left(\frac{(2L_1 - f)}{L_1} pq + \frac{(2L_2 - f)}{L_2} p^2 \right) \qquad (6)$$

Mathematical formula for the adjustment factor if maintenance does not take place is:

$$A_2 = (1+p+q+p^2) - \left(\frac{(2L_1 - f)}{L_1} q^2 + \frac{(3L_2 - f)}{L_2} p^3 + \frac{2}{3} L_1 p^2 q \right) \qquad (7)$$

A_1 = Adjustment factor scenario Ia

A_2 = Adjustment factor scenario Ib

p = percentage of computer below ‘standard 5’

q = percentage of computer ‘standard 5’

L_1 = lifespan of computer below ‘standard 5’ (in years)

L_2 = lifespan of computer ‘standard 5’ (in years)

f = functional unit (in years)

Mathematical formula for computers originating CIEN is:

$$A_3 = \frac{f}{f + r(L_3 - f)} \qquad (8)$$

A_3 = Adjustment factor computer originating CIEN

L_3 = lifespan of computer originating CIEN (in years, incl. refurbishment)

r = failure rate at refurbishment

f = functional unit (in years)

The adjustment factor for scenario Ia is 1.19. If the maintenance does not take place as in scenario Ib the factor increases up to 2.27.

Computers assembled at the CIEN will be refurbished and delivered for a second use. Including a failure rate of 15% after the first use (see Table 10), this results in an adjustment factor of 0.56. For all other computers actively participating the adjustment factor is 1.

The ‘OFF’ illustrates the duration of the first use in Colombia and overseas. These computers are sent directly to recycling and disposal (the ‘OFF’) after their first use. An adjustment factor 1.25 is applied for computers originating overseas where the 'OFF' flow overseas had to be taken into account (scenario II, III, IV).

3.2.1.3 Transfer coefficient

Refurbishment stage

Depending on the origin of the computers the failure rate during the refurbishment stage differs. The failure rate for donations from Colombia was calculated on available data for the years 2000 to 2006 at the CRs. For donators overseas to ComputerAid the partition is based on expert declarations of the program. This then led to the transfer coefficient used for computers originating from overseas donations and refurbished at the CRs (Figure 22).

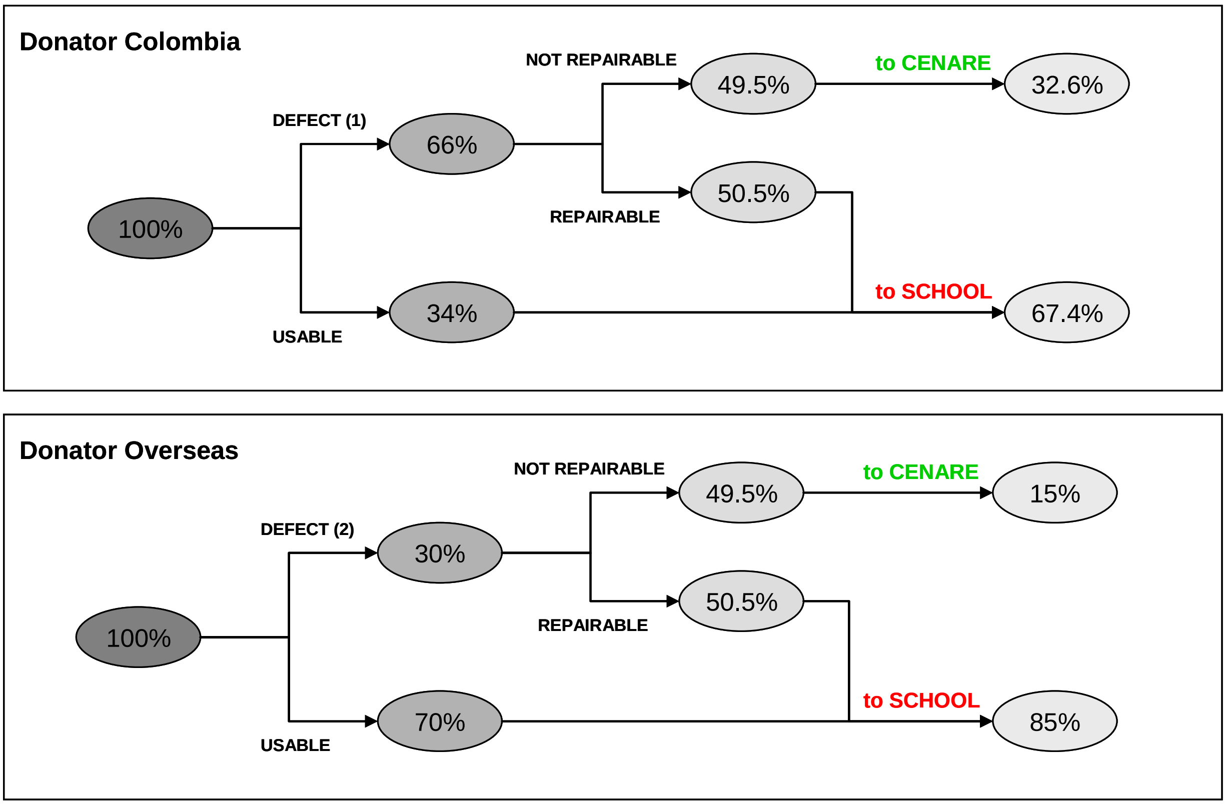

Figure 22: Schematic derivation of the failure rate for computers treated at the CRs originating from users overseas. (1) Data base on percentage of CPUs lacking either the processor, the hard disc, the floppy disc or the CD-ROM drive arriving at the triage in the CRB. Repair rate for CRT monitors, keyboards or mice unknown. (2) Data base on assumptions made by 'ComputerAid'. The calculations result in a diminished process at the CRs of the factor 2.2 for computer donated overseas (this factor is taken into account for the prices, the production and the transport of required parts and components for the refurbishment process).

Table 10 summarizes the used transfer coefficients. For the refurbishment process at the CRs the flows are calculated separately for CPUs (A), CRT monitors (B), keyboards (C) and mice (C). This accounts only for donations from Colombia.

Table 10: Overview of used transfer coefficients.

ORIGIN	From	To	Computer	CPU	CRT monitor	Keyboard	Mouse
User Colombia	CRs	School	-	67.4%	53.1%	63.4%	50.5%
		CENARE		32.6%	46.9%	36.6%	49.5%
User Overseas[1]	CRs	School	85%	-	-	-	-
		CENARE	15%				
User Overseas	ComputerAid	CEEX	70%	-	-	-	-
		Recycling	30%				
ComputerAid	CEEX	School	100%	-	-	-	-
		CENARE	0%				
CIEN	CIEN	School	100%	-	-	-	-
		CENARE	0%				
OLPC	OLPC	School	100%	-	-	-	-
		CENARE	0%				
CENARE	CENARE	Robotic	See below				
		Recycling					

[1] For computers being assembled at the CIEN and refurbished for a second use the same failure rate is being applied.

Recycling and disposal stage

At the CENARE the computers are being dismantled manually. The gained materials are of 'level two' or 'level three' and then either reused for 'Robotic', sold to the local industry (no further treatment is included), to a recycler (further treatment included) or sent to disposal.

The transfer coefficients for this stage are given in % of the total weight per unit. The data are of importance in calculating the environment performance as well as the cost revenues. Due to level of detail they are not illustrated graphically in chapter 3.2.2.

The share of material that can be reused for 'Robotic' is derived from the PWBs. Note: The total weight of a PWB adds to 30% from the board and 70% from the parts fixed to it. All parts are being detached through heating up the solder points. It is assumed that 70% of these parts can be reused for 'Robotic'. Hence, a total of 50% of the PWBs of a CPU and a CRT monitor is used for 'Robotic' (due to their low convenience no parts from the PWBs of a keyboard or a mouse are taken into account). The total weight applied for 'Robotic' adds up to 9.6% of a CPU and 4.3% of a CRT monitor (Table 11,Table 14). The rest of the PWBs together with the funnel glass are assumed to be exported to Europe for a 'state-of-the-art' treatment[17].

[17] A 'state-of-the-art' processing of PWBs and funel glass would also be possible to take place in the United States. But the environmental policies of Colombia prohibit the export of hazardous waste to countries that did not ratify the Basel Convention.

Steel, copper and aluminium – whose weight adds up together to a total of 69.7% of a CPU, 10.5% of a CRT monitor, 23.7% of a keyboard and 9.9% of a mouse – are sold directly on the Colombian market (Table 11 to Table 15).

Cables which have a weight share of 2.4% for a CPU, 3.5% for a CRT monitor, 5.9% for a keyboard and 36% for a mouse are sold to local recyclers. There they are stripped and an estimated share of 65% Copper and 35% Polyvinylchlorid (PVC) can be regained. Plastics which account for 8.1% of a CPU, 22.2% of a monitor, 65.3% of a keyboard and 42.3% of the weight of a mouse are sold to local recyclers. They are washed, melted and cut into small pieces and further sold on the market where they are eventually reused e.g. for shoe soles or light switches.

Table 11: Transfer coefficients of 'level two' and 'level three' materials and their further destination after the dismantling of a CRT monitor. The total amount being reused for 'Robotic' or sent to disposal overseas is illustrated separately.

CRT Monitor			
Components	**TC (in %)**	**g/unit**	**Destination**
Steel	7.1	790	Local industry (Substitution)
Copper	2.7	300	Local industry (Substitution)
Aluminium	0.7	80	Local industry (Substitution)
Plastic	22.2	2470	Recycler
Cables	3.5	394	Recycler
Ferrite	0.8	90	Local industry (Substitution)
Panel glass	29.5	3282	Local industry (Substitution)
Funnel glass	19.1	2122	Export (state-of-the-art treatment)
Waste	0.1	16	Municipial solid waste
PWB	14.2	1578	50% Robotic, 50% Export
TOTAL	**100.0**	**11122**	
PWB to 'Robotic'	4.3	789	
PWB to disposal	9.9	789	

Table 12: Transfer coefficients of 'level two' and 'level three' materials and their further destination after the dismantling of a keyboard.

Keyboard			
Components	**TC (in %)**	**g/unit**	**Destination**
Steel	23.7	280	Local industry (Substitution)
Plastic	65.3	770	Recycler
Cables	5.9	70	Recycler
PWB	5.1	60	Export (state-of-the-art treatment)
TOTAL	**100.0**	**1180**	

Table 13: Transfer coefficients of 'level two' and 'level three' materials and their further destination after the dismantling of a mouse.

Mouse			
Components	**TC (in %)**	**g/unit**	**Destination**
Steel	9.9	11	Local industry (Substitution)
Plastic	42.3	47	Recycler
Cables	36.0	40	Recycler
PWB	11.7	13	Export (state-of-the-art treatment)
TOTAL	**100.0**	**111**	

Data for the CRT monitor is based on the author's own measurements with a sampling size of a hundred dismantled CRT monitors at the CENARE.
Data for keyboard and mouse is derived from the 'Ecoinvent v2.0'.

The data for the CPU is based on a manual dismantling process in China (Gmünder, 2007). So far CPE conducted only a pilot project to gain some first hand information of the dismantling of CPUs. No exact data could be obtained. Though, the level of dismantling corresponded to the dismantling level observed in China. Results are illustrated in Table 14.

Table 14: Transfer coefficients of 'level two' and 'level three' materials and their further destination after the dismantling process of a CPU. (Source: Gmünder, 2007). The total amount being reused for 'Robotic' or sent to disposal overseas is illustrated separately.

	Power supply[1]		Hard disc drive		CD-ROM drive		Floppy disc drive		Rest of a computer		TOTAL		
	TC in %	g / unit	TC in %	g / unit	TC in %	g / unit	TC in %	g / unit	TC in %	g / unit	TC in %	g / unit	Destination
Steel	5.62	548.63	1.22	119.32	5.71	557.02	2.47	240.55	50.05	4883.70	65.07	6349.23	Local industry (Substituition)
Copper	0.59	57.29	0.02	1.75			0.10	9.92	0.04	4.35	0.75	73.31	Local industry (Substituition)
Aluminium	0.86	84.25	2.39	232.87	0.03	2.66	0.55	53.77			3.83	373.55	Local industry (Substituition)
Plastics[2]	0.39	38.31			1.87	182.83	0.09	8.59	5.76	561.74	8.11	791.47	Recycler
Cables/wires[3]	0.97	95.10			0.01	0.87			1.45	141.34	2.43	237.31	Recycler
PWB (incl. Motherboard)	1.08	105.53	0.78	76.48	1.25	121.81	0.56	54.91	9.28	905.65	12.96	1264.38	
PWB to Robotic			0.39	38.24	0.62	60.91	0.28	27.46	4.64	452.83	5.94	579.43	50% to Robotic (Substitution), 50% to export, state-of-the-art treatment
PWB to disposal	1.08	105.53	0.39	38.24	0.62	60.91	0.28	27.46	4.64	452.83	7.02	684.95	
Ferrite	0.07	6.71	0.22	21.21							0.29	27.92	Local industry (Substitution)
Ceramics	0.56	54.76									0.56	54.76	Inert waste
Battery									0.33	32.00	0.33	32.00	State-of-the-art treatment
Waste	0.34	33.19	0.05	4.94	0.04	4.15			0.01	1.09	0.44	43.36	Municipial solid waste
Subtotal	10.49	1023.77	4.68	456.56	8.91	869.34	3.77	367.75	66.92	6529.87	94.76	9247.29	Subtotal without parts being stripped from PWBs after basic dismantling
Switches									0.01	1.13	0.01	1.13	
Connector	0.56	54.83	0.03	3.38					0.74	72.14	1.34	130.35	
Transformer	1.64	159.65									1.64	159.65	70% Robotic (Substitution), 30% Export (state-of-the-art treatment). Note: Parts are already stripped off after basic dismantling and ready for reuse robotic.
Transistor	0.21	20.69									0.21	20.69	
Ventilator	0.20	19.50									0.20	19.50	
Capacitor	0.68	66.57									0.68	66.57	
Motors			0.36	35.11	0.65	63.68	0.15	14.19			1.16	112.99	
TOTAL	**13.78**	**1345.00**	**5.07**	**495.05**	**9.56**	**933.03**	**3.91**	**381.94**	**67.56**	**6603.14**	**100.00**	**9758.16**	
TOTAL to Robotic[4]											**9.6**	**937**	
TOTAL to disposal (PWB)											**8.59**	**838.2**	

[1] The PWB of the power supply is already stripped. Therefore no costs for further treatment of the PWB were included.

[2] Further treated plastics are assumed to substitute the relative amount of 65% Acrylnitril-Butadien-Styrol (ABS), 20% Polycarbonat (PC) and 15% Polyvinylchlorid (PVC) of the total weight. A correction factor of 0.9 was applied (according to Préconsultant, SIMAPRO). Economical revenues are higher if sorted (this is the case at the CENARE).

[3] Further treated cables are assumed to substitute a relative amount of 65% Copper and 35% Polyvinylchlorid of the total weight. A correction factor of 0.9 was applied for plastic.

[4] In order to determine the environmental substitution value of the parts used for robotic, a robotic mixture out of the relative weights of switches, connectors, transformers, transistors, capacitors, resistors, LEDs was defined in SIMAPRO (see also appendix B)

In order to complete the list of dismantled computers at the CENARE the 'XO laptop' had to be included. An approximation of the composition of an 'XO laptop' has been conducted based on the RoHS[18] data of the 'XO laptop' provided by Quanta Computer Inc. and in conjunction with an LCA expert at the EMPA. The total weight is calculated to add up to 1578.9 g. According to the methods described above the total share that can be reused for robotic is 7.6%. For the LCD module and the rest of the PWB, an export to a 'state-of-the-art' treatment is assumed. Table 15 summarizes the transfer coefficients of an 'XO laptop' for the recycling and disposal stage and states the further destinations of the parts.

Table 15: Transfer coefficients of materials 'level two' and 'level three' and their further destination after the dismantling of a XO laptop. The total amount being reused for 'Robotic' or sent to disposal overseas is illustrated separately.

XO laptop			
Components	**TC (in %)**	**g/unit**	**Destination**
Steel	4.1	64	Local industry (Substitution)
Aluminium	1.0	16	Local industry (Substitution)
Plastics	45.9	725.2	Recycler
Battery (Lithium)	12.6	198.82	State-of-the-art treatment
LCD module	10.9	172	Export (state-of-the-art treatment)
PWB	15.2	240.58	50% Robotic, 50% Export
Power adapter			
Cables	2.7	42.1	Recycler
Plastics	2.3	36.7	Recycler
Copper	1.2	19.3	Local industry (Substitution)
Steel	4.1	64.2	Local industry (Substitution)
TOTAL	**100.0**	**1578.9**	
Total PWB to Robotic	7.6	120.29	
Total PWB to disposal	7.6	120.29	

18 RoHS is a common used expression for the **Directive on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment** 2002/95/EC adopted in February 2003 by the European Union. The directive is closely linked to the Waste Electrical and Electronic Equipment Directive 2002/96/EC. The RoHS directive took effect on 1st July 2006 and is required to be enforced and become law in each member state of the European Union. The directive sets restrictions for the use of cadmium, lead, mercury, hexavalent chromium, polybrominated byphenils and polybrominated dyphenil ether in EEE and became nowadays a worldwide accepted standard for the production of new EEE.

3.2.2 Model scenarios

Possible scenarios that incorporate different strategies in order to guarantee a sufficient supply of computers for the schools were defined. The flows are all adjusted to the functional unit of providing 46'000 computers for a five year usage time at schools. Adjusted means that the supply is calculated for the required production (new or refurbished) during one year, including the amount that is directed to the recycling and disposal stage from the production and the five year usage at schools. Table 16 gives an overview of all flows taking place during each scenario.

Table 16: Material flows 'level one' for each scenario.

Scenario	From	To	Amount			
			PC / CPU[1]	Monitor	Keyboard	Mouse
II	CIEN	School (1st Use)	8'330			
Va	OLPC	School (1st Use)	42'040			
Vb	PC (new)	School (1st Use)	42'040			
II	School (1st Use)	CRs	8'330			
Va, Vb	School (1st Use)	CENARE	42'040			
Ia	User Colombia	CRs	82'176	75'147	79'099	83'647
Ib	User Colombia	CRs	156'875	143'457	151'002	159'683
II	User Colombia	CRs	32'156	29'405	30'952	32'731
III, IV, Va, Vb	User Colombia	CRs	5'960	5'450	5'737	6'066
II	User Overseas	ComputerAid	20'000			
III	User Overseas	ComputerAid	60'057			
IV	User Overseas	ComputerAid	49'459			
Ia	CRs	School (2nd Use)	54'602			
Ib	CRs	School (2nd Use)	104'236			
II	CRs	School (2nd Use)	28'447			
III, Va, Vb	CRs	School (2nd Use)	3'960			
IV	CRs	School (2nd Use)	46'000			
Ia	CRs	CENARE	26'752	35'233	28'982	41'409
Ib	CRs	CENARE	51'070	67'260	55'327	79'051
II	CRs	CENARE	11'718	15'036	12'590	17'453
III, Va, Vb	CRs	CENARE	1'940	2'555	2'102	3'003
IV	CRs	CENARE	9'359	9'974	9'521	10'422
II	ComputerAid (via CEEX)	School (2nd Use)	14'000			
III	ComputerAid (via CEEX)	School (2nd Use)	42'040			
Ia	School (2nd Use)	CENARE	54'602			
Ib	School (2nd Use)	CENARE	104'236			
II	School (2nd Use)	CENARE	42'447			
III, IV	School (2nd Use)	CENARE	46'000			
Va, Vb	School (2nd Use)	CENARE	3'960			

[1] All calculations are based on the number of PCs and CPUs respectively (where flows of monitors, keyboards and mice are included the number refers to CPUs).

Because CPE does have different failure rates for CPUs (A), CRT monitors (B), keyboards (C) and mice (D) their flows were all assessed, where necessary, separately. This is the case for the amount of donations of Colombian origin and for the parts being then transferred directly to the CENARE. However, the flows of monitors, keyboards and mice are not illustrated graphically.
All further calculations are based on the amount of CPUs.

The material flows ‘level two’ are not included graphically in the figures but marked with an arrow. This concerns the flows for parts and components used during the refurbishment processes at the CRs and ‘ComputerAid’ as well as the necessary amount used during the maintenance. Furthermore the flows for ‘Robotic’ (marked with an arrow from the CENARE back to the schools) and the flows from the CENARE to the local industry, further recycling treatment or disposal site.

The dismantling process at the CENARE results in materials ‘level three’ that can either be sold directly to the local industry, must be disposed off (within or outside of Colombia) or undergo a further treatment through a recycler. This relates on one hand to cables which are further stripped in order to regain plastic and copper. On the other hand to plastics which are being washed and melted. The arrow drawn from recycler to local industry reflects the fact that these materials are eventually sold to the local industry.

Flows marked yellow are responsible for the supply to schools (including flows to recycling and disposal). Flows marked orange signify the ‘OFF’ flows. ‘OFF’ flows are given by the maximum number of computers that could enter the supply chain. A differentiation between computers of Colombian origin and overseas origin takes place. In this case the maximum amount of computers of Colombian origin is given by scenario I “100% Colombian refurbishment” and for computers originating from overseas by scenario III “Overseas refurbishment”. The flows (yellow) and the ‘OFF’ flows (orange) have to add up equally for each scenario.
This results in the total amount of 142’233 computers calculated for each of the scenarios whereas 82’176 stem from Colombia and 60’057 stem from overseas.

Boxes marked light grey are playing an active part in the supply chain (inclusive recycling and disposal). Boxes marked dark grey are not taking part in the corresponding scenario.

The stock refers to the amount of CPUs, CRT monitors, keyboards and mice still in process at the end of the year or used for employees of CPE. This accounts approximately for 1% of the total amount entering the refurbishment process. The stock was extrapolated or adjusted where necessary (scenario I, III, IV, Va, Vb).

3.2.2.1 Scenario I: “100% Colombian refurbishment”

The scenario “100% Colombian refurbishment” is based on the situation CPE faced in 2006. The computer supply to the schools is exclusively provided by the five refurbishment centres (CRs). The production in 2006 was around 18’000 refurbished computers, the required demand of the functional unit is 46’000 computers. The failure rate at the CRs was assumed to be constant. Hence, a linear extrapolation of all other flows was possible.

All the computers are obtained from donators within Colombia and transferred to one of the five refurbishment centres. There the computers are refurbished and further delivered to schools. Based on experiences of CPE a usage time of two years can be assumed in schools.

In order to gain information about the environmental advantages of the process ‘maintenance’, a scenario Ia and a sub-scenario Ib were defined.

The maintenance prolongs the lifespan of a computer for another two years. While for the scenario Ia maintenance is applied, the computers of scenario Ib are being sent directly to the CENARE after their use at schools. This means a higher amount of computers have to enter the program CPE in order to fulfil the functional unit. No ‘OFF’ flow is allocated within Colombia. The increased production required for Ib equals the ‘OFF’ flow of Ia.

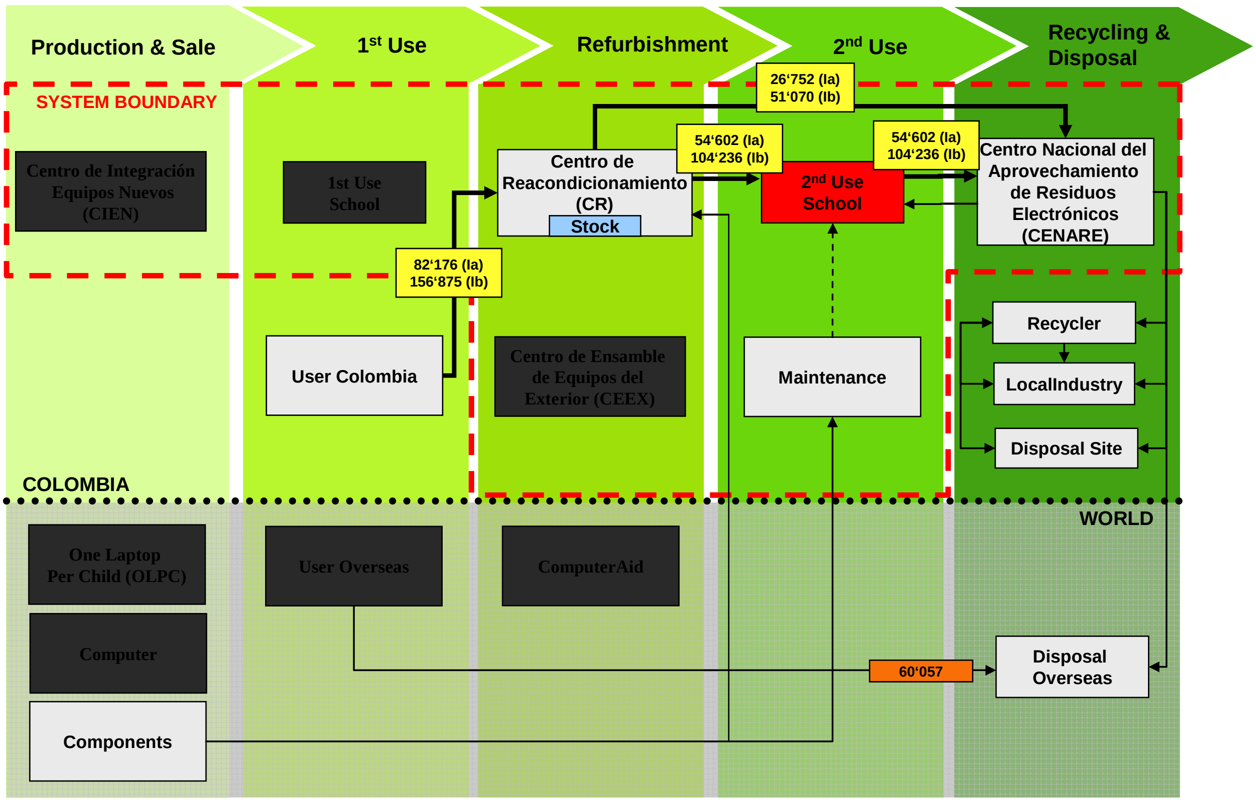

Figure 23: Model scheme of the material flows of the scenarios “100% Colombian refurbishment” Ia and Ib. Computers are provided exclusively by Colombian users.

The mass flows are adjusted according to their lifespan and therefore higher than the actual 46’000 computers (see Table 9). For scenario Ia the adjusted amount is 54’602 computers, for Ib 104’236 computers.

The according 'OFF flow' overseas of 60'057 computers is the same for both scenarios.

Note: Further comparisons of the scenarios always relate to the mass flows of scenario Ia!

3.2.2.2 Scenario II: "Colombian/overseas refurbishment and local assembling"

Scenario II "Colombian/overseas refurbishment and local assembling" is defined according to the actual situation in 2007. It combines the supply from the CRs with assembling at the CIEN and a refurbishment process realized overseas by 'ComputerAid'. The computers delivered by 'ComputerAid' further undergo a treatment at the CEEX.

Adjustment factors were applied for computers provided by the CIEN and the CRs. The maintenance only takes place for computers entering the stage '2nd use' in schools.

The CIEN provides an amount of 8'330 computers that is being reused after the '1st use' at schools. The CEEX provides 14'000 computer and the CRs 28'447 whereas the amount of 7'080 computers stem from the CIEN.

The 'OFF' flow of 50'020 computers from 'Users Colombia' is directed to the recycling and disposal stage without entering the system.

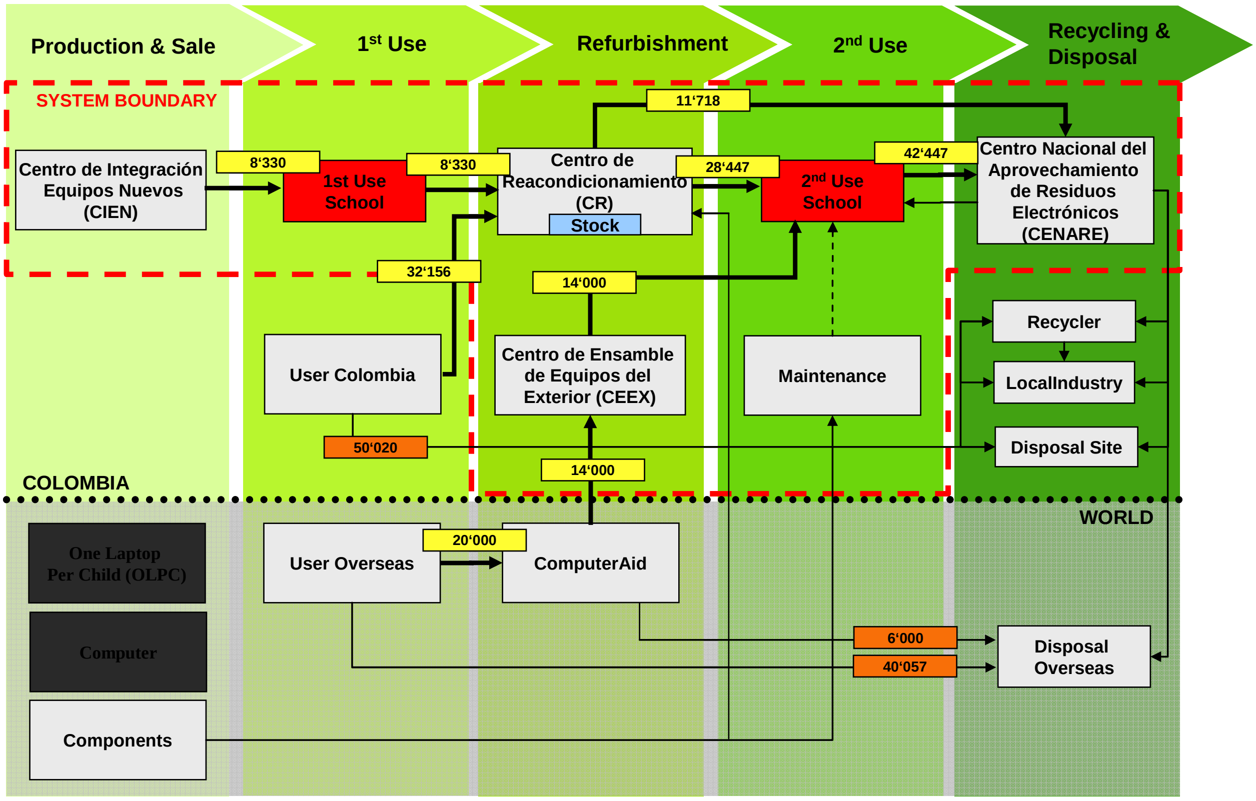

Figure 24: Model scheme of the mass flows of scenario "Colombian/overseas refurbishment and local assembling". Computers are provided either by the CIEN, the CEEX (ComputerAid) or the CRs.

3.2.2.3 Scenario III: "Overseas refurbishment"

The scenario "Overseas refurbishment" is derived from the actual situation in 2007 and sets a technical threshold 'standard 5' for the refurbished computers at the CRs. Only 3'960 computers accomplishing 'standard 5' are provided through the CRs. This accounts to 22% of the actual production of 18'000 computers. The remaining amount of 42'040 computers have to be granted by

'ComputerAid'. Due to a failure rate of 30% a total amount of 60'057 computers have to be provided by overseas donations. An amount of 18'017 computers is directed from 'ComputerAid' to disposal overseas.

The maintenance takes place for all computers being delivered to schools. A five year usage time for all computers is assumed. Hence, no adjustment factors were necessary.

The amount of 'OFF' flows within Colombia adds up to 76'216 computers and is directed to disposal without entering the system.

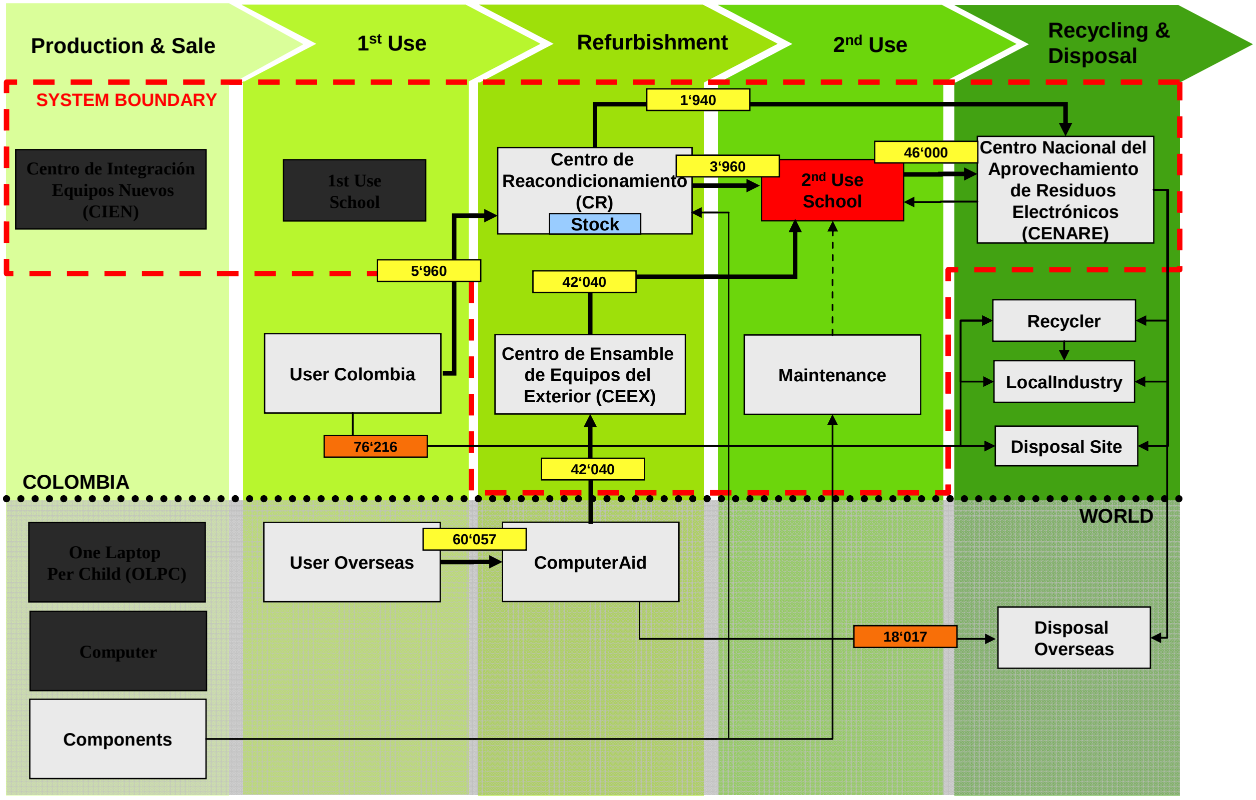

Figure 25: Model scheme of the mass flows of scenario "Overseas refurbishment". Computers are mainly provided by 'ComputerAid'. For computers provided through the CRs a technical threshold is implemented.

3.2.2.4 Scenario IV: "Overseas donations for Colombian refurbishment"

Scenario "Overseas donations for Colombian refurbishment" is based on interviews with members of CPE, wherein the possibility exists that donations could be imported, as soon as a proper recycling and disposal scenario for the computer waste was being implemented.

As with scenario III "Overseas refurbishment" the scenario "Overseas donations for Colombian refurbishment" sets a technical threshold 'standard 5' for computers refurbished at the CRs. This results again in the supply of 3'960 computers of Colombian origin through the CRs. The rest of the computers are supplied directly from overseas to one of the five CRs. For these computers a failure rate of 15% is calculated. Therefore a total amount of 49'459 computers have to be imported. The process maintenance takes place for all computers at schools.

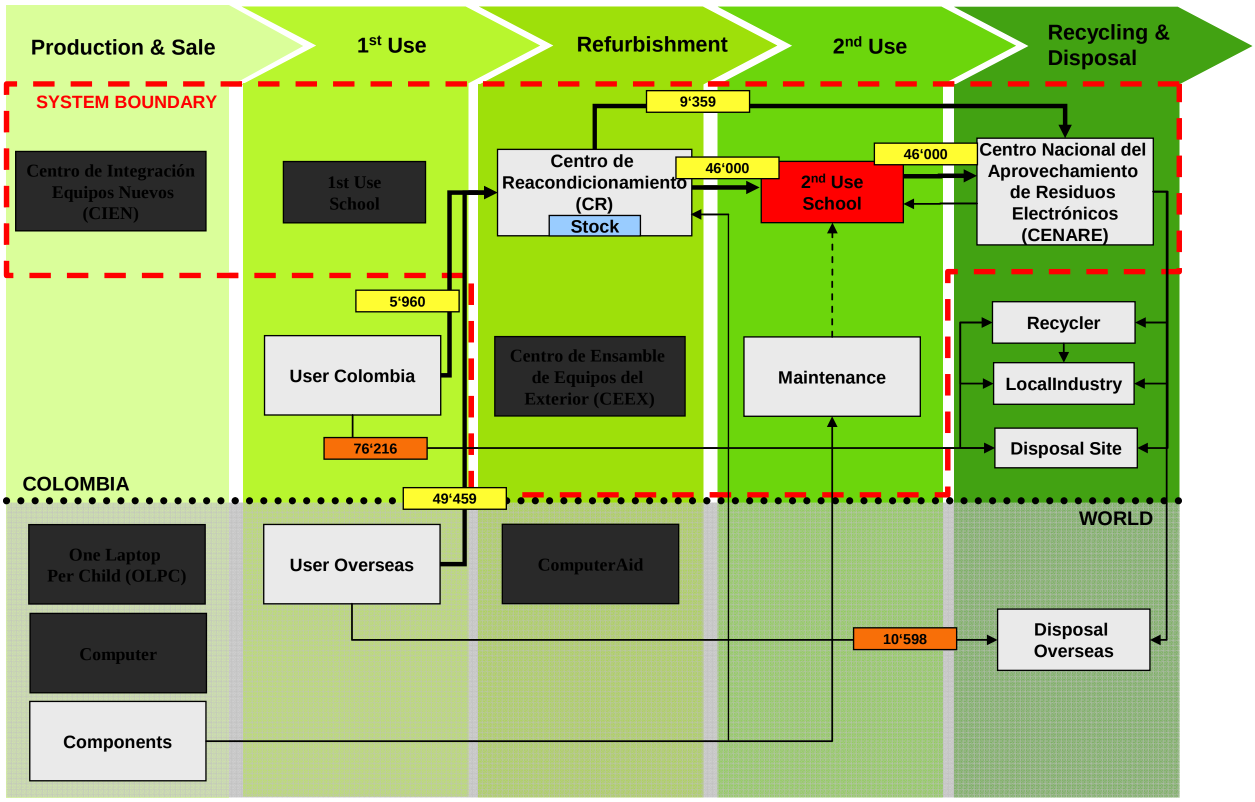

Figure 26: Model scheme of the mass flows of scenario “Overseas donations for Colombian refurbishment”. Computers are directly provided to the CRs either from ‘User Colombia’ or ‘User Overseas’.

3.2.2.5 Scenario Va, Vb: “XO laptop”, “Purchase PC (new)”

As with the scenarios “Overseas refurbishment” and “Overseas donations for Colombian refurbishment”, a technical threshold ‘standard 5’ is set for the partial supply through the CRs. This supply of 3’960 computers can be provided entirely by donations from Colombia.

In scenario Va “XO laptop” the remaining amount of 42’040 computers is replaced by the purchase of the ‘XO laptop’ from the OLPC initiative. After the usage time of five years – the lifetime of an ‘XO laptop’ as assumed by OLPC – the laptops are directed straight to the CENARE.

Scenario Vb “PC (new)” replaces the remaining amount of computers through the purchase of computers available on the Colombian market.

Both scenarios result in the maximum ‘OFF’ flows in Colombia and overseas.

For the refurbished computers the process maintenance is included.

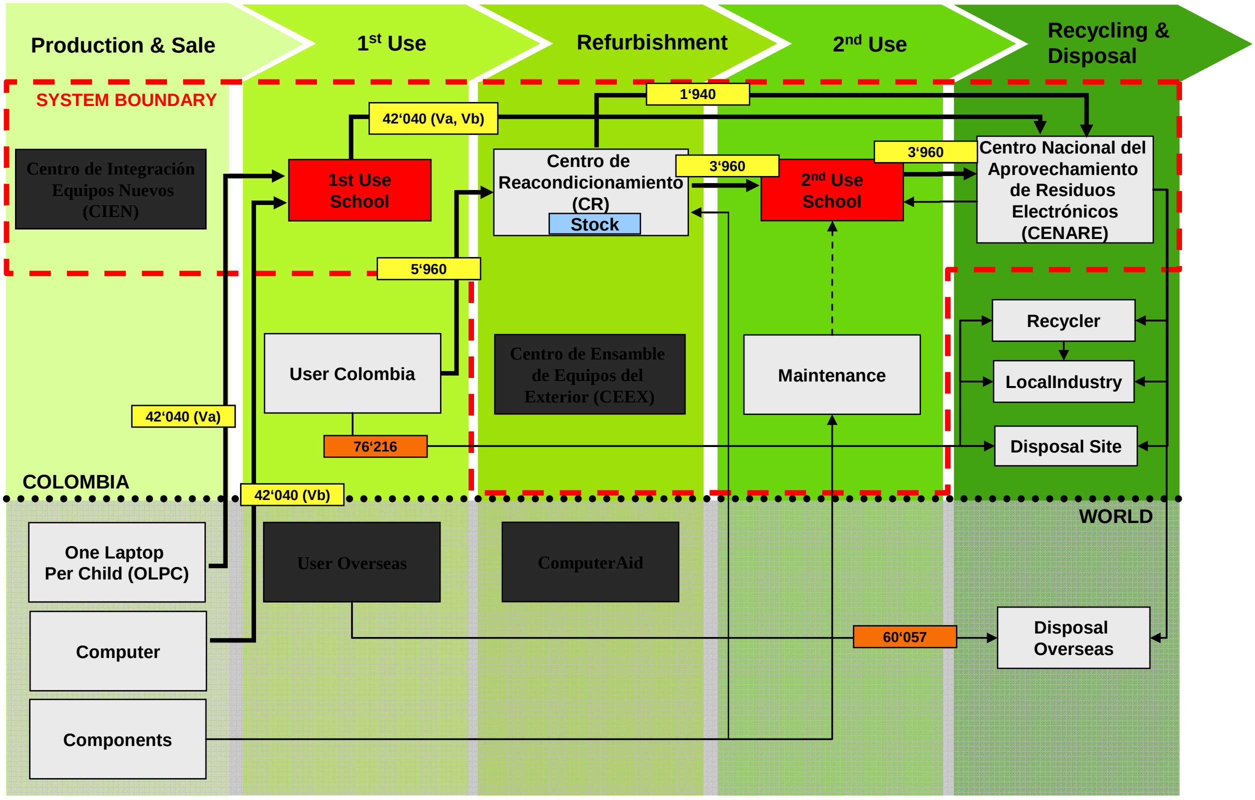

Figure 27: Model scheme of the mass flows of the scenarios Va "XO laptop" and Vb "PC (new)". Scenario Va assumes the purchase of the 'XO laptop'. In Vb the computers stem from the Colombian market.

3.3 Application of the MAUT

In this chapter the application of the MAUT is illustrated. First, the results of the weighting process are presented. Second, each attribute is explained and calculated separately for each of the scenarios.

3.3.1 Weighting of the attributes

The weighting of the attributes applied during the MAUT was mainly conducted with members of the program CPE, on one hand from the national directorate at the 'Ministry of Communication' and on the other hand with management staff of the CENARE, the CRB and the maintenance. Furthermore one weighting was collected at 'ComputerAid'. The results of the weighting process are listed in Table 17.

Table 17: Result of the weighting process of the attributes and the weightings applied in the MAUT. Please note that for the overall environmental performance the weightings were added (marked grey).

Attributes defined for weighting	Stakeholders weight	Applied in the MAUT
	0 to 4	0 to 4
Economy		
Low net costs	3.33	3.33
High technical value	2.83	2.83
Involvement/participation of local economy	3.33	3.33
Environment		
Low use of energy	2.67	7.67
Low use of resources	3	
Little toxic emissions	2	
Society		
Creation of low and semi-skilled jobs	2.5	2.5
Creation of highly skilled jobs	3.33	3.33
Capacity building	3.5	3.5

The weightings through the stakeholders show that the highest ranking was given to the attribute 'capacity building' followed by the attributes 'low net costs', 'involvement/participation of local economy' and the 'creation of highly skilled jobs'. The overall environmental performance is judged to be of the lowest importance.

3.3.2 Economical performance

The economical performance was subdivided into the three attributes 'low net costs', 'high technical value' and 'involvement/participation of local economy'.

3.3.2.1 Low net costs

The low net costs for computers provided through the CRs, the CIEN or the CEEX include; direct/indirect labour costs, direct/indirect material costs and indirect fabrication costs. All costs are based on the 2007 budget of CPE. For the computers provided through the CEEX an average price of a computer at 'ComputerAid' was assumed[19]. The prices for the 'XO laptop' or a newly purchased computer are based on their corresponding market price.

Furthermore general costs of the program CPE were evaluated and included for each of the scenarios. This includes costs for promotion, the accompaniment, the monitoring and the maintenance, as well as transportation for distribution from schools to disposal.

Distribution costs from the centres to the schools are based on declarations of CPE. Note: the transport costs for recollecting the computers, as well as the costs for translation transports between centres are already included in the indirect costs for fabrication. Hence, the transport costs from the CRs to the CENARE can be neglected. It is assumed that the price for the 'XO laptop' includes transportation to the country of destination.

So far no official take-back program has been implemented by CPE and therefore no costs raised for the transport of obsolete computers from schools to the CENARE. Since the model includes this flow, the costs were included. It suggests that these costs equal the distribution costs.

For the transport for computers arriving to Colombia – either from 'ComputerAid' at the CEEX or directly at the CRs from a user overseas – costs relate to the oceanic transport, custom duties and transport to Bogota (listed separately). Please note that a computer sent directly from 'ComputerAid' (representing a finished consumer good) might have a different custom duty level than computers directed to the refurbishment process (being intermediate and capital good not produced in Colombia).

All the above mentioned costs could be calculated per unit computer. Therefore a linear extrapolation to determine the total costs of each scenario could be made. **Table 18** summarizes and describes the costs further detailed. It also describes corrections made by the author.

[19] Price based on declarations of 'ComputerAid' on their homepage (June 2007) and take into account a 20%/80% mix of PIV/PIII. PIII is assumed to be half medium- and half high-end quality.

Table 18: Description of the costs taken into account and corrections made to determine the attribute 'low net costs'.

Type of costs	Description	Notes/corrections by the author
Production costs CR, CIEN or CEEX		
Direct labour costs	Includes technicians (rookie, junior, senior), workers at the depot	The actual amount of workers at the CIEN and CEEX differs from budget 2007.
Indirect labour costs	Includes directors of centers, supervisors, staff administration at the centers	Effective amount of supervisors at CIEN differs from budget 2007
Direct material costs	Includes purchase of parts (hard disc, memory module, etc.) and software for the refurbishment process	Adopted directly from budget 2007. For refurbished computers of overseas origin as well as from the CIEN a diminished price of the factor 2.2 was applied.
Indirect material costs	Includes material for packaging (paperboard box, plastic bags, etc.) and material for the workers (cleaning materials, tools, etc.)	Stocks of previous years were not taken into account. Effective material use of CIEN is based on expert interviews (Supervisors) and adapted for the CEEX. The budget of CPE in contrary extrapolated the material use of the CRs for the amount of 46'000 computers.
Indirect costs for fabrication	Includes all expenditures, not being taken into account above, necessary for the production (e.g. rent for the centers, transport for recollection of donated computers, transport for translations between centers, insurance, public services, cleaning service, furniture, machines)	Until recently the CRC, CRBQ, CRM and the CRCU had some discount on rental costs (they are included in this study). Costs for insurance were calculated separately for the CRs, the CEEX and the CIEN. For the machinery a lifespan of 25 years was assumed.
Further costs of CPE		
Promotion	Includes staff, promotion of CPE in general (TV and radio spots, advertisement, etc.), events for donators	Staff, as well as the expenditures related to donators e.g. events, are entirely allocated to the CRs. General promotion of the program is divided among the CRs, the CIEN and the CEEX according to their share of production.
Accompaniment & Monitoring	Includes staff and material costs during the initial phase, the support phase, the monitoring and evaluation	The costs for the support phase are not taken into account for scenario Va "XO laptop". This is justified by the aim of the XO laptop to provide highly sophisticated software enabling children to have an autonomous learning process.
Maintenance	Includes labour work, tools, purchased parts, travel costs, rent and general expenditures (e.g. paper, public services)	The administration of the maintenance is located in the CRB. The general expenditures and the rent were therefore estimated to account for 5% of the expenditures at the CRB. The costs for maintenance are only aggregated for computers at the second use stage in schools.

Table 19 gives an overview of the production costs (in US $) depending on the origin of each of the computers. Table 20 illustrates further costs of the program CPE.

Since the program CPE is a public organisation externalised processes are subject to bidding processes. Therefore a discount of the production costs of 12.5% for computers originating from the CRs, a 42.5% discount for computers originating from the CIEN and a 3% discount for computers provided through the CEEX is applied (based on the 2007 budget of CPE).

Table 19: Overview of the production costs (in US $) per unit computer depending on its origin (Source: CPE, Budget 2007).

	CRs (origin Colombia)	CRs (origin overseas)[1]	CIEN	CEEX	OLPC[2]	PC (new)[3]
Transport to Colombia	-	32[4]		32[4]	included	included
Costs material (direct)	86	39	632	118[5]		
Costs material (indirect)	14	14	10	1		
Labour work (direct)	40	40	14	5		
Labour work (indirect)	29	29	6	4		
Costs of fabrication (indirect)	58	58	39	22		
TOTAL I	228	181	700	149		
Discount[6]	12.57%	12.57%	42.56%	2.67%		
TOTAL II	**199**	**158**	**402**	**145**	**188**	**582**

[1] Applying the same repair rate to computers donated from overseas results in a diminished requirement of the factor 2.2 for the direct material costs. This accounts also for computer '2nd use' originating from CIEN (no transport to Colombia included).
[2] Source: www.pcworld.com (September, 2007). The price fluctuate depending on demand. It is assumed that the price includes transport to Colombia.
[3] The price estimation is based on the average of three different computer models with similar specifications available on the Colombian market (Qbex, Hewlett Packard, Lenovo), Source: CPE. A recent market assessment confirms this price level (Ott, 2008).
[4] Price is subdivided into an estimated oceanic transport of US $12 based on the transport of a 40 feet container (Zumbühl, 2006) and the custom duty and transport to the CEEX of US $20 (Source: CPE, Budget 2007).
[5] Price based on declarations of 'ComputerAid' on their homepage (June 2007) and taking into account a 20%/80% mix of PIV/PIII. PIII is assumed to be half medium- and half high-end quality.
[6] Discount due to public bidding.

Table 20: Overview of further costs (in US $) per unit computer (Source: CPE, Budget 2007).

Further costs	Costs (in US$)	Notes
Promotion	46	If the computer is not donated the costs add up to US $4.6. This accounts for purchased computers (OLPC, Colombian market) or computers originating from the CIEN and the CEEX.
Accompaniment & Monitoring	147	In the case of the 'XO laptop' the costs of US $52 during the support phase are not being included.
Maintenance	61	Accounts only for computers of the 2nd use at schools
Distribution to Schools	20	The same amount is accounted for computers transferred from the harbour to the schools
Transport Schools to CENARE	20	

To determine the costs of the recycling and disposal stage for the CENARE further calculations were required. So far the CENARE employs only six technician rookies who have the capacity of dismantling an estimated 100 CRT monitors per day to the level described in Table 11. To calculate the time for dismantling a CPU, measurements stated by CPE were combined with time specifications for the complete dismantling to the level described in Table 14 from China (Gmünder, 2007). The dismantling times for keyboards and mice were estimated by the author. All costs were then calculated based on the annual salary of a technician rookie at CPE and the revenues derived from selling some of the materials on the Colombian market. The prices for these materials were obtained from local recyclers[20]. Table 21 summarizes the costs of the dismantling a CPU, a CRT monitor, a keyboard, a mouse and an 'XO laptop'. Please note that the costs are calculated for the dismantling level CENARE aims to achieve in the future which includes 'Robotic'. It therefore does not necessarily correspond with the most cost efficient level for dismantling.

Table 21: Revenues and costs for the dismantling processes at the CENARE (in US $).

Parts	Number of dismantled pieces per day per technician[1]	Dismantling costs[2] (in US$)	Revenue[3] (in US$)	TOTAL costs (in US$)
CPU	3.31	6.14	4.17	1.97
CRT Monitor	5.71	3.56	5.15	-1.59
Keyboard	100.00	0.20	0.57	-0.36
Mouse	200.00	0.10	0.13	-0.03
XO laptop	16.00	1.27	0.72	0.55

[1] The numbers include the detachment of 'Robotic' parts

[2] Costs are based on the salary of a technician rookie at CPE (US $379 per month)

[3] Revenues are based on Colombian market prices of the sold materials (see also Appendix B)

Table 22 gives an overview of the costs in US$ related to each of the scenarios. The costs are listed separately for production, promotion, accompaniment & monitoring, maintenance, transport and recycling and disposal through the CENARE. The corresponding utility is calculated and added to the table.

Table 22: Overview of the overall costs (in US$) of each scenario including the normalized utility value.

Scenario	I	II	III	IV	Va	Vb
Production costs	10'892'590	11'056'587	6'887'755	7'446'015	8'693'503	25'257'263
Promotion	2'500'483	1'405'733	375'282	2'106'556	375'282	375'282
Accompaniment & Monitoring	8'022'390	7'460'402	6'758'542	6'758'542	4'569'644	6'758'542
Maintenance	3'303'421	2'568'044	2'783'000	2'783'000	239'580	239'580
Transport (includes distribution and take back to CENARE)	2’184’080	2’031’080	1’840’000	1’840’000	1’840’000	1’840’000
Costs CENARE	-15’541	-6'308	-1'547	-1'622	22’029	-1'547
TOTAL	24'718'884	22'484'458	16'803'033	19'092'492	13'878'010	32'629'121
TOTAL per unit	**537**	**489**	**365**	**415**	**302**	**709**
Utility, normalized (unweighted)	**0.422**	**0.541**	**0.844**	**0.722**	**1**	**0**

[20] The prices for steel, aluminium, copper, plastic and glass stem from different local recyclers in Bogota. The prices for cables and printed wiring boards stem from ASEI Ltda. in Medellin.

The results in Table 22 show that significant differences exist between the scenarios. It is obvious that the scenario “XO laptop” is far more economic than the others. This is mainly due to reduced maintenance, accompaniment & monitoring and promotional costs. Even if the maintenance and promotion costs for the scenario “PC (new)” are the same the production costs lead to a significantly higher total cost compared to all the others. While the overall cost for scenario “XO laptop” is US $302 the overall cost of purchasing a new computer is US $709, more than double.

The higher the required amount of computers to fulfil the functional unit the higher the overall cost for one unit (exception scenario Vb). This leads to the relatively high cost of US $537 per unit for scenario I “100% Colombian refurbishment”.

Looking only at the production costs, the lowest amount is observed when a large share of computers is provided through the refurbishment program ‘ComputerAid’ from overseas (e.g. scenario III “Overseas refurbishment”). This is explained by the fact that the actual refurbishing process is far less sophisticated than in Colombia and therefore less costly.

Scenario “Overseas refurbishment” has the second lowest overall cost of US $365. As mentioned this is partly due to the low production costs. Another reason is the low costs for promoting and attracting donators. It can be assumed that first users overseas look at ‘obsolete’ computers as garbage, therefore are happy for it to be used for a good course. In contrast ‘obsolete’ computers in developing countries are often looked at as of value. Therefore more money needs to be invested to promote a refurbishment program among first users. In scenario “Overseas donations for Colombian refurbishment” the costs of promotion was allocated to all computers arriving at the CRs.

If the costs of promotion would only be allocated for computers of Colombian origin the overall costs of US $415 for this scenario would be reduced by US $38. However the cost was added to take into account that CPE would have to promote its program to a certain degree in a foreign country in order to attract possible donators.

For accompaniment & monitoring, reduced costs are mainly due to lower amounts of computers necessary in a certain scenario. For the ‘XO laptop’ the costs of the support phase can be saved.

For the costs of maintenance a similar structure appears. Costs depend mainly on the amount of computers required. Since the scenarios “Colombian/overseas refurbishment and local assembling”, “XO laptop” and “PC (new)” provide a certain amount of computers for first use in schools, no costs for maintenance appear for them.

The cost of assembling a new computer at the CIEN is similar to purchasing a new computer. Therefore the overall cost of the scenario “Colombian/overseas refurbishment and local assembling” is the third highest, US $489 per unit.

Analysing the transport costs it can be concluded that the differences are of minor influence on the overall costs. However, the fact that the computers provided by the CIEN are transferred to the centres after their first use and again distributed for a second use to the schools, results for scenario “Colombian/overseas refurbishment and local assembling” in high transport costs. Only scenario “100% Colombian refurbishment” has higher transport costs due to the high amount of computers involved.

The revenues through the CENARE are of minor importance for the total costs in all scenarios. However in the case of the ‘XO laptop’, due to the small material regain, the dismantling process at the CENARE is not financed autonomously.

Further remarks

Administrative costs of the national directorate at the ‘Ministry of Communication’ are not included (the author assumes similar operating expenses for all scenarios).

Up until the end of 2006 the production of printers equalled around 20% of the total production of computers at the CRs. No exact data could be obtained to determine their influence on the overall cost per unit computer.

On a nation wide level the tax reductions for donators would have to be taken into account. The reductions take place due to the fact that valuable donated goods (e.g. not yet amortized computers) can be subtracted from one’s tax return.

Possible cost revenues such as replacement of parts out of the ‘Robotic’ stock for universities or high schools are not taken into account.

3.3.2.2 High technical standard

The technical standard was an often discussed issue for the provided computers by CPE. Even if it is commonly accepted that school children do not require necessarily a high end computer the program aims to deliver the highest standard possible. Each delivery to the school comprehends a minimum of ‘standard 5’ computers. For the year 2007 the aim was to provide a maximum of 30% ‘standard 3’, 40% ‘standard 4’ and ‘standard 5’ and 30% with the highest standard originating mainly from the CIEN.

Data to determine the percentages of the standards are derived from the production 2006. Since ‘standard 5’ includes both, ‘Pentium III’ and ‘Pentium IV’, the data of the triage for the years 2006 and 2007 at the CRB was analysed. This led to the assumption that 88% of ‘standard 5’ computers equal the quality of a ‘Pentium III’ and 12% of a ‘Pentium IV’. Together ‘Pentium III’ and ‘Pentium IV’ add up to the low total of 9.6% of all computers arriving at the CRB.

The technical standards for computer originating from ‘ComputerAid’ are based on their declarations. At present ‘ComputerAid’ guarantees a share of 20% ‘Pentium IV’ and 80% ‘Pentium III’ for their deliveries.

The computers that are assembled at the CIEN contain an AMD Athlon 65 3500+ processor. This is considered to equal the quality of a ‘Pentium IV’. This quality is applied for the ‘2nd use’ at schools of the computers as well.

The technical standards for computer originating from overseas and directed to the CRs were estimated by the author.

For scenario “XO laptop” and scenario “PC (new)” the highest possible quality is assumed.

Table 23 summarizes the retrieved data and illustrates the allocated utility.

Table 23: Percentages of the technical standard of each scenario and their allocated utility.

Scenario	Origin	Units	Pentium I or lower	Pentium II	Pentium III	Pentium IV or higher	Utility
I	CR	54'602	39.70%	50.20%	8.50%	1.20%	0
		54'602	39.70%	50.20%	8.50%	1.20%	
II	CR	21'366	39.70%	50.20%	8.50%	1.20%	0.50
	CEEX	14000			80.00%	20.00%	
	CIEN	15410				100.00%	
		50776	16.71%	21.12%	25.63%	36.37%	
III	CR (Standard 5)	3960			88.00%	12.00%	0.75
	CEEX	42040			80.00%	20.00%	
		46000			80.69%	19.31%	
IV	CR (Standard 5)	3960			88.00%	12.00%	0.50
	User Overseas	42040		20.00%	65.00%	15.00%	
		46000		18.28%	66.98%	14.74%	
Va	CR (Standard 5)	3960			88.00%	12.00%	1
	XO laptop	42040				100.00%	
		46000			7.58%	92.42%	
Vb	CR (Standard 5)	3960			88.00%	12.00%	1
	PC (new)	42040				100.00%	
		46000			7.58%	92.42%	

The results show that the highest technical standard is achieved by purchasing new computers. This accounts for the scenario "XO laptop" and "PC (new)". To scenario "Overseas refurbishment" an utility of 0.75 is allocated. To scenario "Colombian/overseas refurbishment and local assembling" and "Overseas donations for Colombian refurbishment" the same utility of 0.5 is allocated. Although scenario "Colombian/overseas refurbishment and local assembling" delivers more 'Pentium II' and even some 'Pentium I' computers to the schools, the high share of 'Pentium IV' computers compensates the difference compared to scenario "Overseas donations for Colombian refurbishment". The lowest technical standard is achieved by scenario "100% Colombian refurbishment".

3.3.2.3 Involvement/participation of local industry

The involvement/participation of the local economy was assessed in two categories. First the participation of CPE during the processes for supplying and disposing the computers was assessed.

This category is called life cycle and relates to the production, the refurbishment, the recycling and disposal stages.
For the assembling production at the CIEN a 100% involvement was allocated. For the production of a new computer the share of 50% participation was assumed. This stays in contrast to the production of the 'XO laptop' where 0% involvement was assumed. All computers being provided by the CRs record a 100% involvement. For the involvement during the process at the CENARE the weight share of the materials that do require a further treatment outside Colombia (all PWBs for disposal) were taken as basis for calculations. This led to a 83% participation of the CENARE during the recycling and disposal stage. The cables and plastics which account for 21.7% of the total weight and are sold and further treated within Colombia are allocated as a 100% involvement of the local industry.
The 'OFF' flows in Colombia were taken into account for calculations. No parts for 'Robotic' are being reused at the recycling and disposal stage outside the CENARE. An export of the complete PWBs was therefore assumed. Based again on the weight share of the materials this led to a total involvement of the local economy of 75%.
For the life cycle involvement for computers provided by the CEEX a total share of 30% participation of the local economy is estimated.

In a second category the involvement during transport was calculated. The transport was calculated in two steps. First, the transport from the origin of a computer to the schools was assessed. Second, the transport from the schools to final disposal was calculated.
For computers of Colombian origin a 100% share of the transport to the schools was allocated. This accounts for computers provided by the CIEN and the CRs if originated from Colombia. For purchased computers (Vb) a total share of 100% is conducted through the local economy. For computers provided by 'ComputerAid' or donators overseas two thirds of the transport were allocated to the local economy. This due to the fact that a transport takes place from overseas to Colombia, from the harbour to further treatment either at the CEEX or the CRs and eventually to the schools.
For the purchase of an 'XO laptop' it is estimated to have a 50% participation of local economy (transport takes place directly from harbour to schools).
For the transport from schools to final disposal one third was allocated (based on the weight share) to the total amount being exported (school – CENARE – harbour – overseas). The same accounts for computers entering the 'OFF' flow (user – recycler – harbour – overseas).

To get an approximation of the total involvement/participation of the local economy the category life cycle was weighted three times as high as the category transport.
The resulting utilities are listed in Table 24. For calculations please refer to appendix A.

Table 24: Involvement/participation of the local economy for each scenario (in %) and the corresponding utilities.

Scenario	I	II	III	IV	Va	Vb
Total involvement/participation of the local economy (in %)	92%	83%	72%	85%	65%	77%
Utility, normalized (unweighted)	**1**	**0.6762**	**0.25**	**0.753**	**0**	**0.467**

The results in Table 24 show that the highest involvement of the local economy is achieved in scenario "100% Colombian refurbishment" with 91.5%. The second highest participation (85%) results from scenario "Overseas donations for Colombian refurbishment". This is closely followed by scenario "Colombian/overseas refurbishment and local assembling" with 83% local share. Both these scenarios process their computers within Colombia. Scenario "PC (new)" which does only have a diminished process at the CRs follows next with 77.4%. Scenario "Overseas refurbishment" (71.7%) and scenario "XO laptop" (65.1%) where processes outside of Colombia take place result in the lowest overall involvement of local economy.

3.3.3 Environmental performance

The assessment of the overall environmental performance was given the main focus in the present study. The three attributes 'low use of energy', 'low use of resources' and 'little toxic emission' were defined to embrace the environmental impacts of each scenario. Nevertheless a more holistic approach by conducting a LCA was performed. The results were then elaborated with the software 'Simapro' and made comparable by applying the Eco-indicator'99 to them. Since this approach includes all of the three defined attributes their weightings were added in order to consider stakeholder preferences.

In this chapter all considerations and made assumptions regarding the assessment are presented. Furthermore processes taken into account in order to perform the LCA with the software 'Simapro' are described. The results are then summarized and expressed as utilities in Table 30. Out of the gained results further interpretations could be drawn. They are presented in chapter 3.4.

To calculate the comprehensive environmental performance of a certain scenario the production, transport, electricity use and the disposal of all included materials were assessed. As fundament for the calculations serve the results of the MFA illustrated in chapter 3.2.

Production

For the production stage data are mainly derived from 'Ecoinvent v2.0'. This refers to the production of the CPU, CRT monitor, keyboard and mouse as well as to the majority of their components.

Exemptions are the loudspeakers and microphones[21] for which an approximation of the manufacturing was inserted in 'Simapro'. As described in chapter 3.2.1.3 also the manufacturing of the 'XO laptop' had to be approximated. Furthermore calculation modules for a lithium button cell and an alkaline battery were adapted. The rest of the production data was all derived from the 'Ecoinvent v2.0' database.
Note: In order to have comparable data, correction factors for the production of a CPU and a CRT monitor were applied. This is due to differences of the weight derived from the author's own measurements and the weights assumed in the 'Ecoinvent v2.0'. (Please refer to appendix B for all the above mentioned corrections).

Electricity use

The electricity use was calculated on one hand for processing the computers at the CIEN, the CEEX, the CRs and the CENARE and on the other for the usage of five years at the schools. Assumptions made regarding the electricity use at the schools do not distinguish between 1st and 2nd use but rather between the different qualities of provided computers.

The data obtained to determine the required amount of electricity at the CIEN and the CEEX are based on electricity bills of the months November/December 2007 from the CIEN. No further information could be obtained since the production at the CIEN started late September 2007 (at the start of the operating phase a significant lower amount of electricity was required. The author therefore decided to not take into account the month October). For the electricity use at the CEEX (operation has not yet started) the data were taken one to one from the CIEN since both conduct similar processes and require the same space for storage.

For the CRs data regarding the electricity use were available for the CRB and the CRM. Both together are responsible for 70% of the total production. An extrapolation therefore is justified.

For the CENARE data were available only for the month October 2007. They were extrapolated to one year. Main share of the required electricity is allocated to the depot since the dismantling processes take place manually (exception is the hot wiring technique for separating the monitors). No regular detachment process of PWBs for the robotic takes place at present. Therefore the depot consumption of the CIEN which is of similar size is subtracted from the total of the year. The same electricity consumption as the hot wire technique is assumed for the detachment process. Furthermore the required storage space was relatively allocated to a CPU, a CRT monitor, a keyboard and a mouse. Hence, the overall electricity use for dismantling one unit CPU (incl. PWB), CRT monitor (incl. PWB), keyboard or mouse could be calculated.

[21] Source: CPM (2006). Download from http://database.imi.chalmers.se/nukes/index.html

Due to lack of data no electricity use could be accounted for the refurbishment process at ‘ComputerAid’.
Table 25 gives an overview of the results of the above mentioned processes.

Table 25: Electricity use at the CIEN, CEEX, CRs and CENARE per unit (in kWh).

Part	CIEN/CEEX	CRs	CENARE
Computer	1.66 kWh	9.35 kWh	-
CPU	-	-	0.38 kWh
CRT Monitor	-	-	0.66 kWh
Keyboard	-	-	0.012 kWh
Mouse	-	-	0.005 kWh
XO laptop	-	-	0.066 kWh

Data about the electricity use for the further treatment of plastics stem from recyclers around Bogota and is stated to be an approximate 35 kWh per ton.
For all other materials (e.g. cables, funnel glass, PWB, etc) that are further treated the electricity use is included in ‘Ecoinvent v2.0’.

To determine the electricity use at school the usage time of a computer per day had to be investigated. The day is divided into an active, a standby and an off mode. Depending on the availability of electricity the division differs. It is distinguished between electricity originating from a generator (diesel) and electricity drawn from the grid. Due to lack of data in ‘Ecoinvent v2.0’ the electricity from the generator was replaced by electricity derived from a European oil power plant. For the power derived from the grid an approximation of the Colombian power mix was implemented (for further specification see appendix D). Table 26 gives an overview of the usage time at school for each of the three modes.

Table 26: Usage times at school depending on the derivation of the electricity (Source: CPE).

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

According to the three usage modes active, standby and off, the electricity use varies. Table 27 summarizes the corresponding data found in the literature. The data for the ‘XO laptop’ is based on assumptions by OLPC. Where possible a minimum and maximum were identified. The table distinguishes between the electricity use of a computer without screen, a CRT monitor and the ‘XO laptop'. All values are given in Watt (W). The average value refers to the values applied in 'Ecoinvent v2.0'.

Table 27: Minima and maxima of electricity use of a computer without screen, a CRT monitor and the 'XO laptop'.

Mode	Computer		Ecoinvent v2.0	CRT monitor		Ecoinvent v2.0	XO laptop		OLPC
	Min.	Max.	Ø value	Min.	Max.	Ø value	Min.	Max.	Ø value
Active	50 W	78 W	60 W	67 W	120 W	90 W	2 W	6 W	2.5 W
Standby	9 W	65 W	25 W	12 W	45 W	20 W	0.3 W	0.3 W	0.3 W
Off	1.5 W	4 W	2 W	1 W	8 W	3 W	0.3 W	0.3 W	0.3 W

The following assumptions regarding the electricity use were made: The consumption of computers from the CIEN correlates with the minimum. Computers originating from users overseas and computers fulfilling 'standard 5' at the CRs are assumed to consume the average value derived from the 'Ecoinvent v2.0'. The rest of refurbished computers at the CRs are assumed to consume the maximum. For the 'XO laptop' declarations from OLPC were applied.

In order to determine the share of schools that need electricity from a generator (diesel) visited schools from members of the accompaniment and monitoring program were assessed regarding their electricity power supply (Table 28).

Table 28: Derivation of the electricity of selected schools all over Colombia. (Source: CPE)

Department	Generator		Grid	
	Amount of schools	%	Amount of schools	%
Amazonas	4	57.1%	3	42,9%
Caquetá	24	53.3%	21	46,7%
Cundinamarca		0%	10	100,0%
Guainía	1	100%		
Guaviare	9	75%	3	25,0%
Nariño	14	11.9%	104	88,1%
Putumayo	11	34.4%	21	65,6%
Vichada	5	100%		
TOTAL	**68**	**29.6%**	**162**	**70,4%**

Table 28 shows that around 30% of schools need a generator (diesel) while a little more than 70% draw their electricity power from the grid.

Transport

Most of the transports take place within Colombia and are mainly conducted by a truck.

An exemption is the transport to the schools which requires for some destination a boat or even an airplane in order to get there. For the transport from the CIEN and the CEEX to the schools the same data were applied. Since more than half of all transports from the CRs to the schools stem from Bogota this is justified. The data for this transport were mainly provided by Rodarcarga SA who is responsible for the distribution of the computers to the nearest municipality of the schools. According to them 95% of the municipalities are reached by truck, 4% require transport by boat[22] and 1% can only be reached by plane. In the year 2006 91.1% of the computers required a further transport to their final destination. This last bit is done to 80% by a truck, to 15% by boats and to 5% by horses or mules. The total distance to a school accounts to 70% from the providing centre to the municipality and to 30% from the municipality to the school (estimations made by staff of the accompaniment and monitoring at the National University in Bogota). Based on this an average total distance of 172.3 km per school was calculated of which 162.7 km are conducted by truck.

Due to the fact that around 5% of the computer fall under warranty during the first year an additional transport was calculated (is assumed to account only for equipment below 'standard 5').

For the process maintenance the same distances have been taken but were calculated for a passenger. Due to lack of data in 'Ecoinvent v2.0' no passenger data were available for the transport by boat. The distance was therefore allocated to the transport by car.

For new purchased computers, the 'XO laptop', parts & components for the refurbishment and maintenance and for the assembling parts at the CIEN an oceanic transport from China to Colombia was calculated. Where necessary a second transport from the harbour to the centres was included. For the 'XO laptop' and a newly purchased computer a transport directly to the schools was calculated. It was assumed that this equals the transport from the CRs to the schools.

Computers provided either by 'ComputerAid' to the CEEX or users overseas to the CRs an oceanic transport from England to Colombia was taken into account. The transport from the harbour to the centre was added.

The transport of parts & components to England during the refurbishment of 'ComputerAid' was neglected due to the marginal amount of required parts.

The transport of the 'OFF' flows within Colombia and further to disposal overseas was also taken into account. Please note that the transports 'User Colombia' – CRs, 'User Colombia' – Recycling and CRs – CENARE are all calculated on the amount of CPUs (weight of the other parts were included).

[22] According to Rodarcarga SA, 95% of the total distance of transports that do require a boat are conducted by a truck beforehand.

Transport for the ‘Robotic’ kits is assumed to take place within the delivery of computers to schools and is therefore neglected. The same accounts for additional transports that occur when a donation exceeds the amount of 50 equipments. If that happens a pretest is conducted by a technician. Due to the low percentage of occurrence it was ignored.

Table 29 summarizes the above mentioned transports and allocates them to each of the scenarios applied.

Table 29: Overview of transports taken into account for calculating the environmental performance.

From	To	Notes	Used in scenario
User Colombia	CRs	Calculations are based on data from the transport company Surenvios.	All
CRs	School	Calculations are based on data from the transport company Rodarcarga SA. This transport accounts also for the CEEX and the CIEN.	All
School	CRs	5% of the refurbished computers at the CRs have to be sent back within the first year (under warranty) due to damages during transport or usage. The warranty is assumed to take place for computers below ‘standard 5’. This transport takes also place for the computers provided by the CIEN after their ’1st use’.	Ia, II
CRs	CENARE	Only the transports from the CRBQ, CRC, CRM and CRCU to the CENARE are taken into account. The distance from the CRB is negligible (they are suited next to each other).	All
School	CENARE	After reaching their end-of-life the computers are transported back for final disposal. The distances were calculated by adding the transports School – CRs to CRs – CENARE.	All
CENARE	Disposal overseas	Refers to the transport of PWBs, the funnel glass and the LCD module (‘XO laptop’) for a state-of-the-art treatment overseas. Material resulting from CPUs, CRT monitors, keyboards, mice and the ‘XO laptop’ were distinguished	All
ComputerAid /User overseas	CEEX/CRs	Transport from UK to Colombia based on data from www.imadxb.com	II, III, IV
Production	CRs/ Maintenance	Refers to the transport of parts and components required for the refurbishment at the CRs and the maintenance.	All
Production	CIEN	Since the production is additional the transport for the assembling parts is calculated from China to Colombia. Data from www.imadxb.com	II
User Colombia	Recycling & Disposal	Accounts to the ‘OFF’ flow within Colombia.	II, III, IV, Va, Vb
OLPC	School	Transport from China to Colombia. The transport CRs – School is added in order to consider the transport from the harbour to the schools.	Va
Maintenance	School	Transport is calculated for persons (no material included). Due to lack of data in Ecoinvent v2.0 the ship transport of a passenger was added to the car transport.	All

Recycling & Disposal

In order to embrace the complete life cycle of a computer the final disposal has to be included. In the present study this was conducted by modelling the dismantling processes at the CENARE as well as the further destinations of the materials.

Table 11 to Table 15 give an overview of the material flows that are leaving the CENARE and therefore had to be modelled.

Because some of them substitute the primary production of raw materials (e.g. steel, cooper, aluminium, etc.) they were calculated in 'Simapro' as avoided products. Note: The lower quality of regained materials was taken into account (see appendix B for further specifications). The parts reused for 'Robotic' were also assumed to substitute raw materials. This is insofar justified that some of them serve as stock for technical education at universities or high schools and the ones delivered to schools experience a significant life extension.

Cables are calculated to substitute copper to 65% and polyvynilchlorid (PVC) to 35% of their weight (based on data from Gmünder, 2007). Since it was not possible to gather information about the exact stripping process in Colombia, a 'state-of-the-art' recycling according to Switzerland was assumed. Note: This accounts only for the stripping process but not for the final disposal.

For further treatment of plastics the commonly applied recycling process in Colombia was investigated and modelled in 'Simapro'. It is assumed that plastic substitutes to 65% of its weight acrylonitrile-butadiene-styrene copolymer (ABS), to 20% polycarbonate and to 15% polyvinylchloride. These percentages base on observations made at the CENARE. Again, for plastics a significant life extension can be assumed and therefore a substitution is justified.

As described in chapter 3.2.1.3 the funnel glass and the PWBs of a PC as well as the LCD module of the 'XO laptop' are assumed to be exported since no adequate treatment in Colombia is established at present. The data therefore could be obtained from 'Ecoinvent v2.0'.

For batteries a 'state-of-the-art' treatment according to Switzerland takes place in Colombia. The same accounts for panel glass. Data stem from 'Ecoinvent v2.0'. To map the final destination of ceramics the disposal of glass to inert material landfill served as approximation. For waste that could not be identified (accounts only for 0.44% of the weight of a CPU and 0.1% of a CRT monitor) a disposal of municipal solid waste to sanitary landfill was applied.

Results

To make the scenarios comparable no environmental impacts caused by the production for donated computers were taken into account. If the computers are new the production was included. The environmental benefits out of the recycling were allocated to 100% if an entering computer is guided directly to the CENARE. If used at schools only 50% of the recycling benefits are allocated.

The overall environmental impacts were aggregated with the Eco-indicator'99 to one value and normalized to the utility value. The results of the environmental performance are shown in Table 30.

Note: Low values implicate low negative environmental impacts. For further evaluations of the environmental performance of the scenarios please refer to chapter 3.4.

Table 30: Environmental performance of each scenario illustrated as Eco-indicator'99 points and their related utilities.

Scenario	I	II	III	IV	Va	Vb
Eco-indicator'99 value	6.79	13.54	8.49	19.74	8.33	34.33
Utility, normalized (unweighted)	**1**	**0.76**	**0.94**	**0.53**	**0.94**	**0**

The results in Table 30 show that the best environmental performance is achieved in the case where all computers stem from Colombia (scenario I "100% Colombian refurbishment"). Since the production of donated computers entering the system were not taken into account due to comparability of the scenarios, the benefits of the recycling and disposal stage outplays the negative impacts of the system.

Best solutions (after scenario I "100% Colombian refurbishment") regarding the environmental performance are scenario Va "XO laptop" and scenario III "Overseas refurbishment". Both are based on a high share of computers arriving from overseas. Scenario II "Colombian/overseas refurbishment and local assembling" which accounts for the actual situation of CPE follows forth in the ranking. The lower environmental performance is mainly due to the required production of new assembling parts at the CIEN. Ranked fifth is scenario IV "Overseas donations for Colombian refurbishment". Although the intercontinental transport is irrelevant regarding the environmental performance the negative impacts of an more extensive refurbishment process compared to scenario II and the lesser benefits of the recycling and disposal process compared to scenario I lead to a relatively low environmental performance.

The worst environmental performance is achieved when new PCs are entering the system. This accounts for scenario Vb "PC (new)" but not for scenario Va "XO laptop" since the production of an 'XO laptop' has significant lower impact than the production of a new PC.

For an illustration of the individual impacts of the production, electricity use, transport and disposal please refer to chapter 3.4.

3.3.4 Social performance

The assessment of the social performance was subdivided into the three attribute ‘creation of low and semi-skilled jobs’, ‘creation of highly skilled jobs’ and ‘capacity building’.

3.3.4.1 Creation of low and semi-skilled jobs

In the present study low and semi-skilled jobs include all employments that do not require necessarily a university degree.

Considered for calculations were only jobs directly process related. This accounts for jobs at the CIEN, the CEEX, the CRs, the maintenance and the CENARE. Jobs for e.g. transportation or the recycling of the ‘OFF’ flows were not taken into account. Also jobs created outside Colombia were not considered since they are not included in the system boundary.

Table 31 gives an overview of all jobs considered for this attribute.

Table 31: Overview of low and semi-skilled jobs being considered.

Centre	Type of job
CRs[1]	Supervisor (informatics) Technician senior, junior and rookie Technician (informatics) Operator depot Assistant technical support and depot Secretary Digitador
CIEN	Technician senior, junior and rookie Operator depot
CEEX	Technician junior Operator depot
Maintenance	Technician junior, rookie Operator depot
CENARE	Technician rookie

[1] The employment of a supervisor (informatics), technician (informatics), assistant technical support and depot, secretary and digitador account only for the CRB

The amount of jobs was linearly extrapolated for the corresponding production of each scenario. This took place for calculations of the CRs, the CIEN, the CEEX and the maintenance. As a baseline scenario served the production of the year 2007 and its according amount of jobs.

Note: Exemptions are scenario III, Va and Vb. For these scenarios the total amount of provided computers by the CRs corresponds only to 22% of the total production. It was assumed that this could take place only at the CRB. Therefore the amount of jobs at the CRs for the scenario III, Va and Vb were calculated accordingly to the production at the CRB in 2007.

For the CENARE a different approach was chosen due to the fact that a complete regular dismantling process does not take place yet. Therefore the time for dismantling a CPU, a CRT monitor, a keyboard, a mouse and the 'XO laptop' was calculated separately. The calculations for the amount of jobs are then based on the assumption that a year has 220 working days à 8 hours. Table 32 summarizes the amount of jobs calculated for each scenario and illustrates the related, normalized utility.

Table 32: Created low and semi-skilled jobs per scenario and the corresponding utility.

Scenario	I	II	III	IV	Va	Vb
Total amount of low and semi-skilled jobs	766	507	330	610	67	149
Utility, normalized (unweighted)	**1**	**0.630**	**0.377**	**0.777**	**0**	**0.117**

The results in Table 32 show that the highest amount of low and semi-skilled jobs are created by scenario "100% Colombian refurbishment", 766 jobs and scenario "Overseas donations for Colombian refurbishment", 610 jobs. The two are followed by scenario "Colombian/overseas refurbishment and local assembling" which creates 507 jobs. Scenario "Overseas refurbishment" where a high share of computers are pre-treated overseas only 330 jobs are created, less than half of scenario "100% Colombian refurbishment". These are still a lot more jobs than are provided if new computers are purchased. For the purchase of a 'XO laptop' 67 created jobs were calculated and for scenario "PC (new)", 149 jobs. The difference between scenario Va and Vb is mainly due to the higher amount of workers required to dismantle the obsolete computers at the CENARE.

3.3.4.2 Creation of highly skilled jobs

For calculating the amount of highly skilled jobs, employments requiring a university degree were considered.

Identically to the calculations for low and semi-skilled jobs only directly process related jobs were taken into account.
Again the production of the year 2007 and the corresponding amount of jobs served as a baseline for extrapolations. Table 33 gives an overview of all jobs considered for this attribute.

Table 33: Overview of highly skilled jobs being considered.

Centre	Type of job
CRs[1]	Director of plant Director of centre Supervisor Administration assistant
CIEN, CEEX	Director of centre Supervisor
Maintenance	Coordinator Maintenance Administration assistant
CENARE	Coordinator CENARE Director of centre Supervisor Assistant (developing robotic)

[1] The employment of the director of plant and the administration assistant account only for the CRB.

Since the amount of centres stays the same for all scenarios the amount of jobs regarding the director of plant, the directors of the centres, the coordinator maintenance and the coordinator CENARE were assumed to be identical for all scenarios. Note: Again, exemptions build the scenario III, Va and Vb. Their total amount of highly skilled jobs was calculated accordingly to the production at the CRB in 2007.

For the CENARE the amount of supervisors was calculated by applying the same ratio of 10.8 technicians per supervisor accordingly to the CRs. For the 'Robotic' it was assumed that the production (detachment of parts) is conducted by technician rookies. Therefore the amount of assistants required for developing 'Robotic' is calculated accordingly to the production ratio. As baseline serves the year 2007.

Table 34 summarizes the amount of jobs calculated for each scenario and illustrates the related, normalized utility. For calculations please refer to appendix A.

Table 34: Created highly skilled jobs per scenario with the corresponding utility.

Scenario	**I**	**II**	**III**	**IV**	**Va**	**Vb**
Total amount of high skilled jobs	69	49	27	56	13	21
Utility, normalized (unweighted)	**1**	**0.648**	**0.252**	**0.78**	**0**	**0.137**

The results in Table 34 show a similar structure like the results in Table 33. The most highly skilled jobs, 69 are created by scenario "100% Colombian refurbishment" followed by scenario "Overseas donations for Colombian refurbishment", 56 jobs. Scenario "Colombian/overseas refurbishment and local assembling" provides a total of 49 highly skilled jobs. This is almost double than scenario "Overseas refurbishment", with 27 jobs. At last position are again scenario "XO laptop", 13 jobs and scenario "PC (new)", 21 created jobs. Again, the difference scenario Va and Vb is due to the higher amount of workers required during the dismantling process at the CENARE.

3.3.4.3 Capacity building

Since computers stemming either from the CRs, the CEEX , the CIEN or from purchase are all integrated into the program CPE, no differences can be identified regarding the capacity building. For all scenarios the maximum utility of 1 is appointed. An exemption is the purchase of the 'XO laptop'. For its project, OLPC designed a complete new user interface called 'Sugar'. The didactical concept of the software aims to encourage children to autonomous learning. Furthermore it enables them to conduct some first programming steps and design their own operating surface. Even though this leads to lower costs after implementing the project (see also 'low net costs'), the design specifically made for children has the disadvantage that e.g. no capacity building can be offered for adult members of the community. This is the case in all other scenarios. Furthermore the shortly initiated program of CPE in conjunction with the SENA to develop local knowledge for maintaining and repairing computers can only take place in an alleviated extent.

To assess the quality and effectiveness of either an autonomous learning process as it takes place with the 'XO laptop' or the more collaborative process during all other scenarios, the cognitive style has to be taken into account. It guides the manner in which people acquire, conceptualize and process knowledge (Hayes & Allison, 1998). When cognitive style and learning environment are congruent, people perceive greater learning effectiveness and are judged to have higher performance levels (Hayes & Allinson, 1998; Sternberg, 1997). Workman (2003) investigates in his study the influence of different cognitive styles for the learning performance and effectiveness of a computer based education (in this case the 'XO laptop') and a computer aided education (in this case all other scenarios). For the evaluation he applies the three different aspects of an individual's cognitive style, global level, liberal leaning and internal scope according to the taxonomy of Sternberg's (1997) theory of mental self-government, called thinking styles. Depending on their cognitive styles people performed either better in computer based education or in computer aided education. No utility difference is therefore identified and allocated for the capacity building for the different educational approaches.
The allocated total utilities are illustrated in Table 35.

Table 35: Qualitatively assessed utilities of the attribute capacity building.

Scenario	I	II	III	IV	Va	Vb
Utility, normalized (unweighted)	**1**	**1**	**1**	**1**	**0.75**	**1**

3.4 Summary of the results

In the following chapter the aggregated utilities (weighted and unweighted) of the MAUT are summarized. Additionally, some consolidated findings regarding the benefits of maintenance for the scenarios defined in chapter 3.2.2 are illustrated. Finally, a comparison of the environmental performance of an 'XO laptop', a directly recycled PC and a refurbished PC is presented.

3.4.1 Comparison of weighted and unweighted utilities

The results of the MAUT show that scenario "100% Colombian refurbishment" is the most sustainable solution for supplying computers to schools in Colombia (Figure 28). This applies to both cases, the weighted and unweighted. Taking into account that most of the work is done within Colombia, the result is not surprising. Furthermore, the scenario incorporates the highest amount of computers whose lifespan is prolonged.

In the unweighted case the scenario "Overseas donations for Colombian refurbishment" is the 2nd most sustainable solution, followed by the actual situation taking place in Colombia, scenario "Colombian/overseas refurbishment and local assembling". Scenario "Overseas refurbishment" is ranked as 4th best solution. Then follow scenario "XO laptop" and scenario "PC (new)". Both implement a new infrastructure rather than using existing synergies and resources.

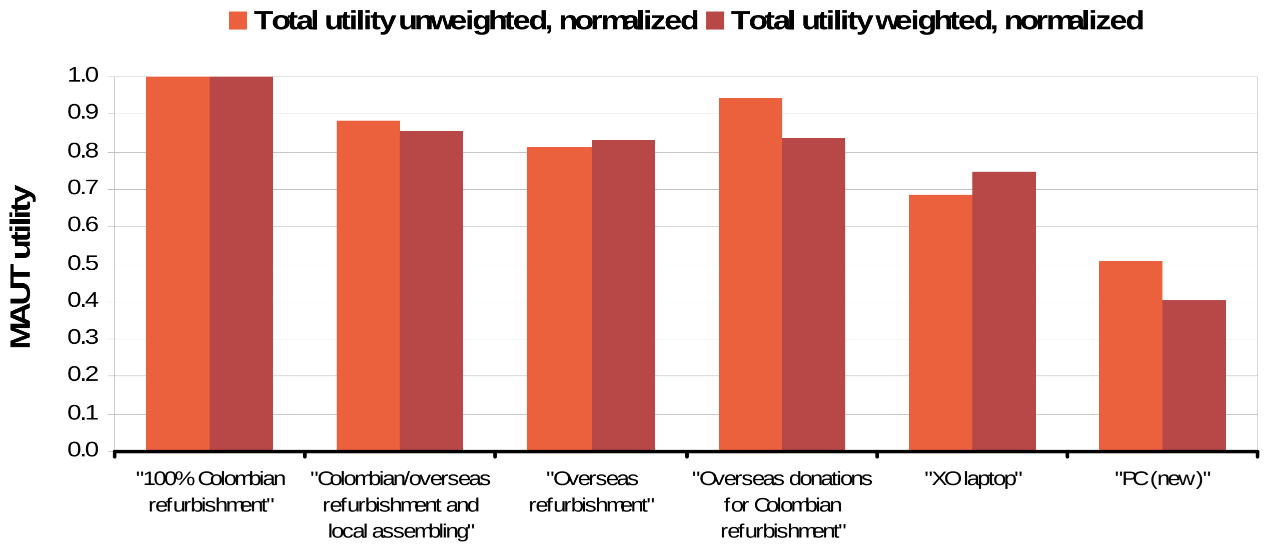

Figure 28: Weighted and unweighted MAUT results of the different scenarios.

Figure 28 illustrates the influence of the stakeholder's weightings regarding the ranking. Scenario II, IV and Vb experience a relative decrease in the utility compared to scenario "100% Colombian refurbishment" and their own, unweighted counterparts. Scenario III and Va experience a relative increase in the utility. This leads to a convergence between the overall utility of scenario II, III and IV.

Comparing the attributes individually one recognizes that the environmental utility contributes much less to the total, in the unweighted than the weighted case. This is due to the fact that the Eco-indicator'99 weight consists of the sum of all weights from the attributes 'low use of energy', 'low use of resources' and 'little toxic emissions'. Furthermore one observes that the utilities of scenario "XO laptop" and "PC (new)" are mainly based on four respectively three attributes. For the scenario "XO laptop" these are namely the attributes 'low net costs', 'high technical standard', 'eco-indicator'99' and 'capacity building'. For scenario "PC (new)" these are 'technical standard', 'involvement/participation of local economy' and 'capacity building'. All other scenarios show a rather heterogeneous picture (Figure 29).

Note: The two graphs in Figure 29 have different scales. The maximum possible utility in the unweighted case is 7, in the weighted case 1.

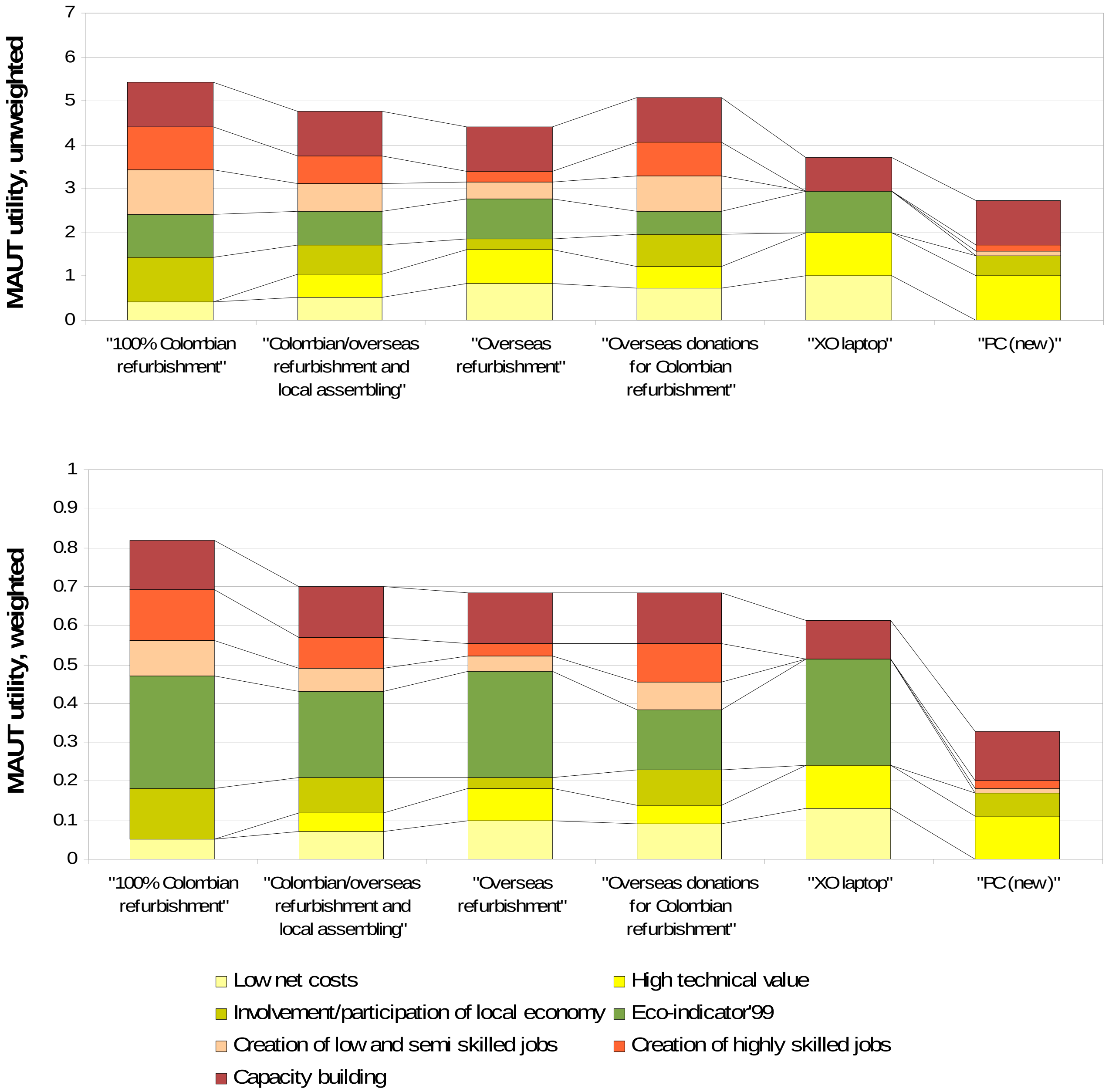

Figure 29: Comparison of the weighted and unweighted utilities.

3.4.2 The benefits of maintenance

The maintenance process was recently introduced by CPE. In 2006 a pilot project phase took place in order to gain information about feasibility, costs and possible obstacles to overcome. Since 2007, the maintenance is an inherent element of CPE and is planned to occur on a regular basis.

To assess the environmental benefits of the maintenance process a scenario Ib was defined and compared to scenario Ia (see Figure 23 in chapter 3.2.2.2).

Since both fulfil the functional unit of providing 46'000 computers during five years, the production was taken into account for comparability (remember: the recycling and disposal stage results in environmental benefits). Also, transportation from production site to Colombia was integrated. All other processes were calculated according to the information given in chapter 3.3.3.

The correction factors of 0.893 for a CPU and 0.559 for a CRT monitor were applied.

The environmental impacts of the process production (new parts), production of parts required during the refurbishment, electricity use, transport, water use and disposal were then aggregated to one value. For scenario Ia the impact of the maintenance was included separately.

The maintenance is responsible of an impact of 1.1% of the total environmental performance (Figure 30). The production of a new computer accounts for 105.3% positive impact followed by the electricity use with 22.6% (of which approximately 60% are caused by the generator and 40% by the grid) and the production of parts required for the refurbishment with 12.7%. Transport accounts responsible for 4.3% positive impact. Water use is negligible.

Note: Positive values mean negative environmental impacts and vice versa.

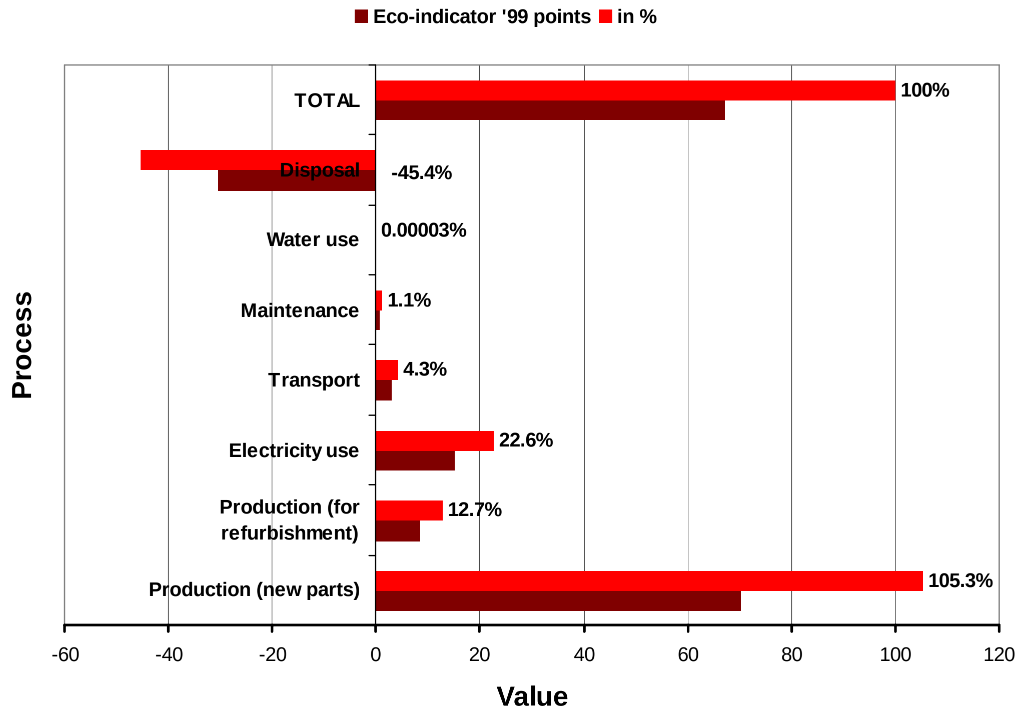

Figure 30: Environmental performances of the corresponding processes during scenario Ia.

The values in Figure 30 are according to the Eco-indicator’99 and further pointed out in percentages. Although disposal accounts for a negative impact of 45.4% it is still less than half of the positive impact caused by the production stage.

Compared with scenario Ib one observes that a prolonging of the lifespan, as takes place due to the maintenance process in scenario Ia is of great environmental benefit (Figure 31).

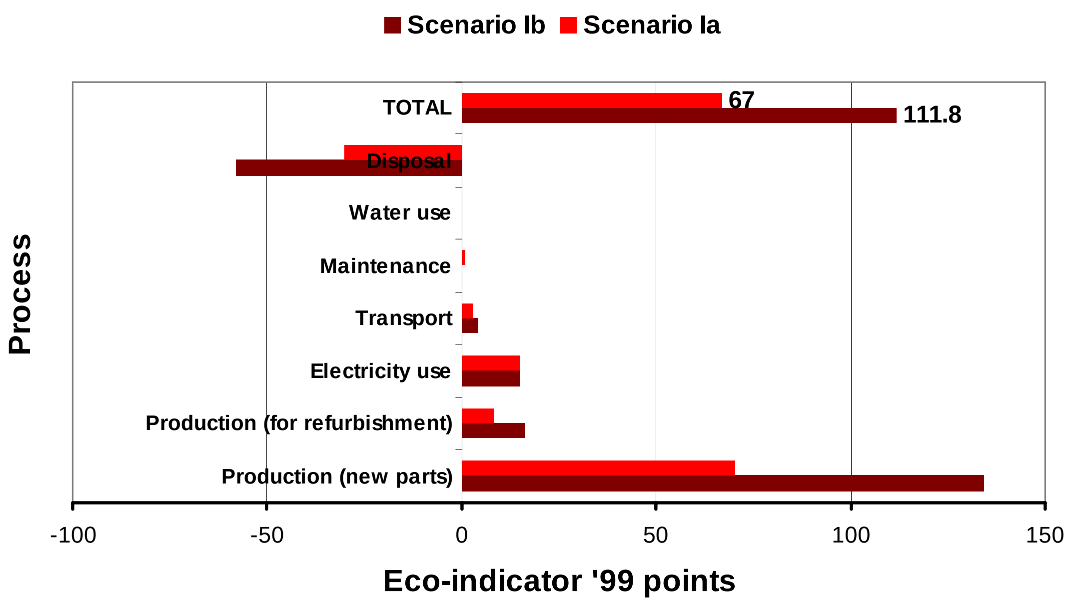

Figure 31: Comparison of the environmental performance of scenario Ia and Ib.

Figure 31 illustrates the environmental impacts of scenario Ia and Ib according to the above mentioned processes. If maintenance is performed the scenario scores a total of 67 Eco-indicator’99 points. This is a great discrepancy with the score of 111.8 Eco-indicator’99 points if maintenance does not take place. Taking the Eco-indicator’99 as a reference, one concludes that the maintenance is responsible for a 60% environmental benefit of the system.

3.4.3 The benefits of refurbishment

The collected data at CPE allows assessing the particular environmental benefits of the refurbishment of a computer independent of the defined scenarios. The collected data was accounted to the life cycle of a single PC. The projection is made for a computer used at a school in Colombia. The total usage time is calculated for ten years.

Production data are derived from the ‘Ecoinvent v2.0’. The electricity use, transport and the refurbishment process data is according to the situation in Colombia.

A total lifespan of five years was assumed for computers being recycled directly. Seven years were accounted to a computer being refurbished and nine years for computers where maintenance occurs additionally.

The calculations show the importance of the electricity consumption and use stage for a refurbished computer (Figure 32). The environmental performance of the use stage during the first five years scores only an approximated 8% less than the production stage. Added up, the use stage is responsible for 55.6% of the negative environmental impacts compared to the 37.8% of the production for a computer refurbished and maintained. For a computer only refurbished the use stage accounts for a total of 49.6% compared to the 43.4% of the production.

Note: Positive performance values implicate negative environmental impacts.

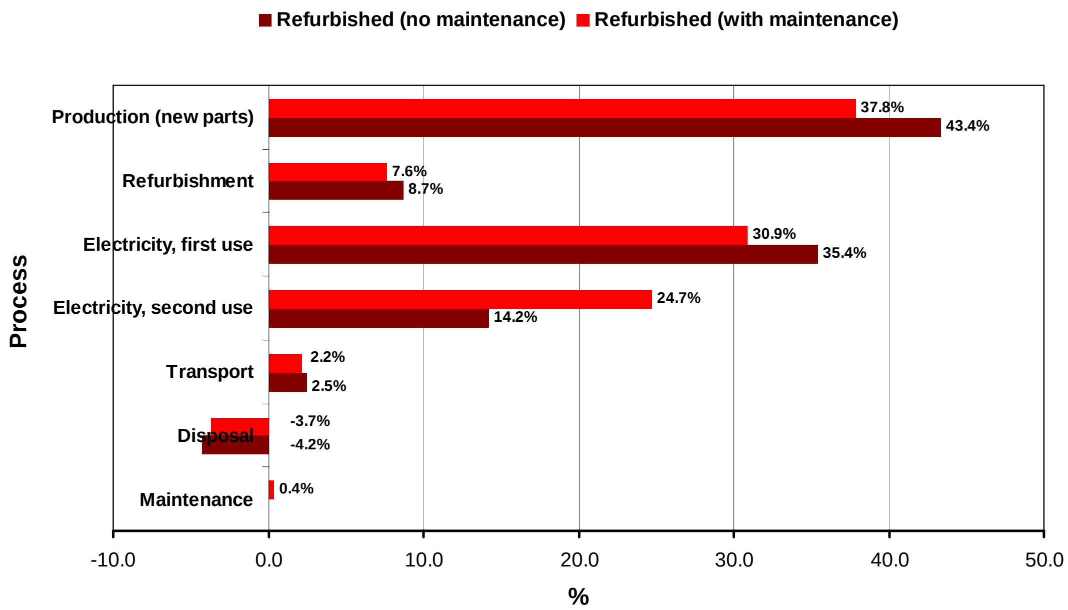

Figure 32: Process distribution of the environmental performance of a refurbished computer during a life cycle. A differentiation between refurbished computers and computers maintained additionally is illustrated.

Figure 32 illustrates that in both cases the refurbishment process only has an influence of 7.6% and 8.7%, respectively. The transport is of minor importance and made up by the regain of the recycling and disposal stage. The maintenance accounts for only 0.4% of the total performance.

The life cycle performance of an 'XO laptop' and a recycled computer shows a different picture (Figure 33). For both, the production stage plays a critical role regarding the environmental impacts. For the 'XO laptop' this accounts to a total negative impact of 101%. The use stage with 12.1% and the transport with 1.3% are of minor importance. Remarkable is the high share of positive impact of 14.3% during the recycling and disposal stage. This implicates a high reuse and substitution potential of the parts used for manufacturing the 'XO laptop'.

For the recycled computer the production stage accounts for 59.2% of the environmental performance followed by the use stage with a responsibility of 41.8%. The transport is compensated for the recycling and disposal stage.

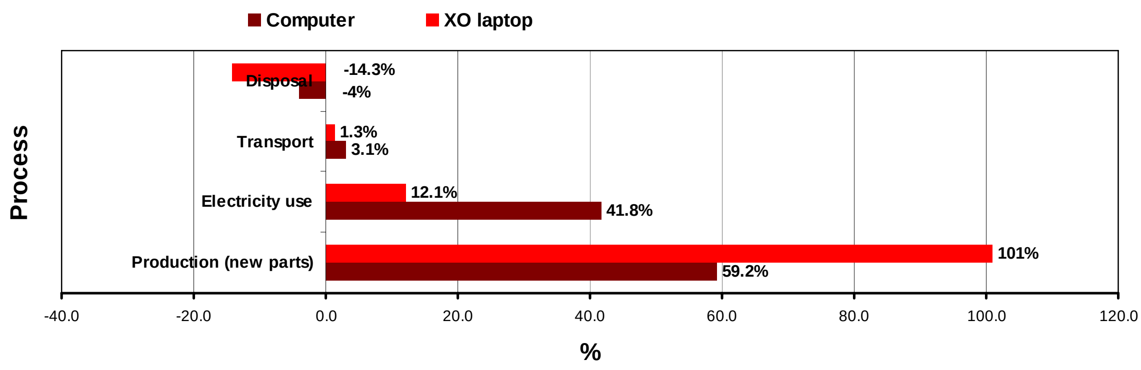

Figure 33: Process distribution of the environmental performance of a recycled computer and a XO laptop during a life cycle.

In order to calculate the relative impacts for all scenarios over ten years, an adjustment factor of 2 for a recycled computer and the 'XO laptop' was applied. For the refurbished computer an adjustment factor of 1.42857, and for the refurbished and maintained computer a factor of 1.1111 were included for calculations.

For the usage time at school an average of 6 hours active mode, 2.5 hours standby mode and 15.5 hours off mode during 220 days per year was considered. Again, it was taken into account that 30% of the schools derive their power from a generator and 70% from the grid.

During the first five years the electricity use of all computers was based on the average values applied by 'Ecoinvent v2.0'. This continues regarding the 2nd use for refurbished computers. For the recycled computers the minimum use shown in Table 27 was applied to the second five years. This accounts also for the replaced refurbished computers. For the 'XO laptop' the declaration by OLPC were applied for calculations.

Transports from production site to Colombia were included.

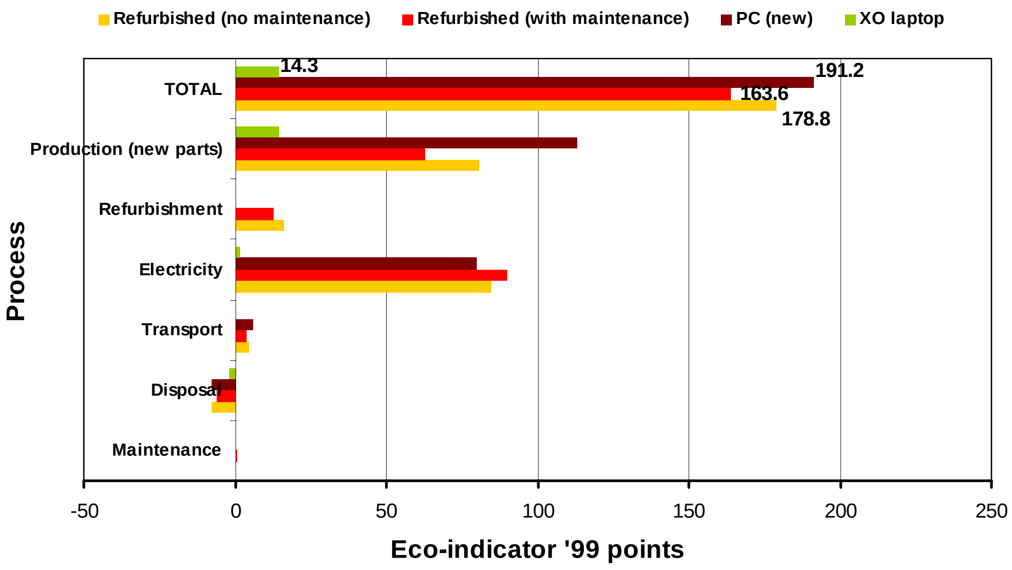

Figure 34: Comparison of the total environmental performance (in Eco-indicator'99 points) of a refurbished computer (with/without maintenance), a recycled computer and a recycled 'XO laptop'.

Taking the Eco-indicator'99 points as a reference the impacts of the 'XO laptop' are more than 90% lower compared to all others. This is on one hand due to the low impacts during the production stage. Manufacturing an 'XO laptop' has seven to eight times lower negative impact than the manufacturing of a computer. On the other hand it is due to an immensely lower need of electricity during the use stage.

The comparison of a refurbished computer with a directly recycled computer leads, in both cases (with or without maintenance), to a preference of the refurbishment. The non-existence of the refurbishment and the slightly smaller electricity consumption during the use stage do not compensate for the high impacts of the production. Also, for transport where the shipment from the production site to Colombia accounts for the highest negative impacts, the recycled computer performs the highest.

Taking the Eco-indicator'99 points as reference one concludes that if a PC is being refurbished and maintained it results in a 16.8% better environmental performance than if the PC is directly recycled. The same computer not being maintained has still a 6.9% better environmental performance compared as when recycled directly.

4 Discussion

4.1 Consolidation and discussion of research

Overall, the aim of the study was achieved. A statement could be made regarding the economic, environmental and social impacts of the strategies identified to supply computers to schools in Colombia. Furthermore, the study delivers new findings regarding the benefits of refurbishing computers and relates them to recent developments in the supply market.

In the following pages the methods and results are reviewed and discussed in the context of the research questions.

A What are the exact material flows of the refurbishment program CPE?

To analyze the exact material flows of the refurbishment program CPE the MFA was chosen as a default method. It allowed a realistic analysis to be made despite the inevitable shortcomings discussed in the following section. It was appropriate to understand the system, helped to elaborate a profound foundation and worked as a precursor for later calculations required applying the MAUT.

Model input

This section discusses the results of chapter 3.2.1.

Reliability and comprehensiveness of model input data are crucial elements of authenticity.

Data regarding the refurbishment process at the CRs could be obtained first hand. This accounts for: parts and components required during the refurbishment process, the average lifespan of a computer before entering the system, the average usage time in schools; the separate failure rate of a CPU, CRT monitor, keyboard or mouse.

For the maintenance model input data could be obtained in situ as well.

No detailed data was available regarding the material flows of the processes at the CIEN and the CEEX which were incorporated into the program CPE. Due to the recent start of the 'operation phase' at the CIEN, and the fact that the CEEX has not yet begun to function, many real time output figures had to be assumed.

A similar situation took place at the CENARE. The centre is not yet running at its capacity and dismantling processes are still in development. Nevertheless, the transfer coefficients could either be

determined in situ (CRT monitor)[23], obtained from a comparable Chinese dismantling plant (CPU)[24] or derived from the 'Ecoinvent v2.0' (keyboard, mouse).
Two critical elements regarding the MFA at the CENARE are the 'Robotic' and the further destination for final disposal of the materials. The 'Robotic' is still in development and more kits are planned. An approximation of the composition of these components had to be made (see also appendix B). Furthermore, the present study excludes the environmental responsibility of CPE for delivered kits. This is only justified assuming that the kits will not be dumped in the near future.
Once established, investigations regarding the material flows of robotic kits have to be made continuously. Likewise, the benefit of stockpiling separated components, for future use at universities or high schools, would first have to be proven.

For the final disposal of 'e-waste', real life solutions for Colombia were identified. Currently, the MAVDT is evaluating existing and possible future e-waste treatments within Colombia. However, based on the present situation, this study assumes an export of PWBs (without parts used for 'Robotic'), funnel glass and LCD modules ('XO laptop').

As a crucial model input, the lifespan of the computers could be identified. In this study the lifespan indicated in table 9 were applied. Further research in the field should include a sensitivity analysis regarding the lifespan of computers of different origins.

B What are possible alternative scenarios to provide a sufficient supply of computers to schools in Colombia?

Having begun the study with the possibility of certain alternative supply strategies ('ComputerAid', 'XO laptop'), the iterative process of conducting a MFA at CPE revealed further possible scenarios. Interviews with members of CPE, helped to reveal new strategies and identify their requirements. This resulted in incorporating the CIEN or the CEEX as possible scenarios into the program CPE.
Five scenarios were identified that could potentially provide a sufficient supply of computers, two of them with sub scenarios (see chapter 3.2.2).

Model scenarios

The functional unit proved to be well chosen. The amount of 46'000 computers corresponds with the set targets of the Colombian government. An assumed five year usage at schools allowed a realistic projection of supply strategies.

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[23] Sampling size were a hundred CRT monitors dismantled at the CENARE.
[24] CPE conducted a pilot project of dismantling CPUs in 2005. The basic dismantling depth is comparable to the results in China (Gmünder, 2007). However, due to the requirements of the 'Robotic' further dismantling times of the HDD, FDD and CDD were derived from experiences made in China.

The modelling of the scenarios is exclusively based on the functional unit. As a result adaptations were required of some scenarios.
For the scenarios Ia and Ib “100% Colombian refrubishment” an extrapolation from the present production of 18’000 to the model of 46’000 computers had to be made. Regarding the input this is justified since sale figures of computers in Colombia outnumber the required amount of CPE.
Scenario II “Colombian/overseas refurbishment and local assembling” fulfils this requirement without having to be adapted.
For scenario III “Overseas refurbishment” it must be taken into account that the required amount of 42’040 computers is a huge number even for ComputerAid, the largest and most experienced overseas computer refurbisher. Furthermore it can not be assumed that ComputerAid would give so many computers to one organisation. This problem does not exist regarding scenario IV “Overseas donations for Colombian refurbishment”, though the required amount of over 49’000 computers is rather at the high end of a possible supply.[25] This is in contrast to the supply by OLPC who aims to sell at least 100’000 ‘XO laptops’ at once. However, ordering 42’040 computers over several years would be possible[26].

In summary, a sufficient supply is guaranteed in the case of new purchases (scenario Va, Vb) or in the combination of different strategies (scenario II). In all other cases additional efforts would have to be made to achieve the set targets. In scenario “100% Colombian refurbishment” sufficient input figures could possibly be achieved by investing in the promoting of CPE. The same accounts for scenario “Overseas donations for Colombian refrubishment”. However, in Colombia the program has an established reputation while in a foreign country the reputation would have to be built. Scenario III “Overseas refurbishment” does not function within the control of CPE and is therefore of questionable possibility.

C What are the involved costs of each of these scenarios?

The cost analysis was, in the form of the attribute ‘low net costs’, part of the MAUT assessment.
The production costs, as well as further costs incurred by the program CPE (see table 14) were both taken into account.

The results in chapter 3.3.2.1 show that the purchase of the ‘XO laptop’ is by far the most cost efficient solution. This is mainly because no support during accompaniment is assumed to be required, due to the concept of the ‘XO laptop’ to encourage autonomous learning. Low maintenance requirements (calculated to be US $61) per computer are another reason.

[25] Angel Camacho (Coordinator CENARE) estimates the total amount of computers that could directly be acquired through donations from overseas between 30’000 and 40’000 computers.
[26] According to Mary Lou Jepsen, former chief technology officer of OLPC.

Though they have lower production costs than the ‘XO laptop’, computers provided by ‘ComputerAid’ and refurbished computers at the CRs originating from overseas (both requiring maintenance) result in higher overall cost.

This is also the case for refurbished computers at the CRs donated within Colombia. High maintenance requirements and, in this case high costs for promotion directed to donators (US $46 per computer) result in approximately 75% higher overall costs than the ‘XO laptop’.

New computers (assembled at the CIEN or purchased) are due to high production costs no improvement of the present situation.

CPE calculates in its budget the production costs for a refurbished computer to be US $164 while this study estimates costs to be US $199. The discrepancy arises from the ‘direct material’ as well as the ‘indirect costs of fabrication’. The calculations of the ‘direct material’ costs within this study did not include stocks from the previous year. For the ‘indirect costs of fabrication’, rentals and public services of the CRC, CRM, CRBQ and the CRCU which are, at present partly paid by the government, were included.

For a computer provided by a refurbishing program from abroad CPE calculated a price of US $221, the present study of US $145. The discrepancy arises from different assumptions regarding the ‘direct material’ costs. The present study calculated ‘direct material’ costs according to declarations of ‘ComputerAid’[27].

For computers assembled at the CIEN CPE budgeted a price of US $390, the present study of US $402. The discrepancy arises from the different amount of workers effectively required in the ‘operating phase’.

An estimation of the financial value of the ‘Robotic’ parts was not taken into account.

Overall the costs could be estimated satisfyingly. However, they remain subject to fluctuations and must be assessed continuously.

D What are the critical stages during the life cycle of a refurbished or recycled computer regarding the environmental impacts?

In order to identify the critical stages during the life cycle of a computer, a Life Cycle Analysis (LCA) with the software tool ‘Simapro’ was performed. Taken into account were: the production stage, the use stage (measured by the electricity consumption), the refurbishment, the transport, the maintenance, the recycling and disposal stage.

[27] Listed on www.computeraid.org are: Mid-range P III PCs at £49, high-end P III PCs at £59 and 256Mb RAM P IV PCs at £ 89 (all excl. shipping).

Overall the critical stages could be identified by applying the LCA. Most of the data could be derived from the ‘Ecoinvent v2.0’ database. However, some had to be adjusted e.g. correction factors were applied for the production of the CPU (0.893) and the CRT monitor (0.559) in order to balance the weights of the author’s own measurements with the applied weights in ‘Ecoinvent v2.0’ or even be created new e.g. the production of a loudspeaker or microphone (for further specifications please refer to appendix B).
Data from the ‘Ecoinvent v2.0’ is based mainly on European or Swiss conditions. Nevertheless it does allow an approximation.

To enable a decision making process the results had to be weighted and compared in some way. In this study the widely accepted Eco-indicator’99 was applied. Possible deficiencies of such simplified interpretation of results are not further discussed at this point.
In the following results from chapter 3.3.3, 3.4.2 and 3.4.3 are discussed.

For refurbished computers (see also Figure 32) the production stage accounted for 37.8% (maintained) or 43.4% (not maintained) of negative environmental impacts for the duration of its life cycle. The use phase (1st and 2nd use) was responsible for 55.6% (maintained) and 49.6% (not maintained). The data is similar in the case of a recycled computer (see also Figure 33). While the production stage accounts for 59.2% of the negative impacts of the electricity use sums up to 41.8%. Although the production of a CPU and a CRT monitor is adjusted (see above) this shows the crucial role of the electricity consumption during the life cycle of a computer. In this study the assumption was made that the electricity consumption will decrease for newer computers. This is correct in the case of a CRT monitor. For the CPU different opinions are represented in relevant literature.
In a review of the literature Bray (2006) concludes that the energy consumption of a CPU increased over the last decade. However, Hofer and Aehlen (2002) assume that in the near future energy consumption of IT devices will decrease due to technical advances e.g. more sophisticated power management which allow a faster shifting between active and standby mode. In any case, the assumption made in this study is very optimistic. Further calculations taking variable electricity consumptions into account are required.

The consumption of the generator is responsible for approximately 60% of the negative impacts and was replaced in ‘Simapro’ by an average European power plant. Further investigations are required to see if this approach is correct.
Only little influence shows the electricity use in the case of the ‘XO laptop’.

The impacts of the refurbishment process turned out to be of minor importance. 7.6% for a maintained computer and 8.7% for a computer only refurbished. In both cases the production of the parts required to refurbish the computer was responsible for over 95% of the negative impact of refurbishment (taking into account the electricity used at the CRs and all related transports).

Transport accounts between 1.3% (for the 'XO laptop') and 3.1% (for the directly recycled computer) of the negative impact. The influence of transport from the production site to the user stands out. For refurbished computers this accounts for approximately 70% of all transports, for a directly recycled computer this increases to 80% and for the XO laptop it is still responsible for just over 50% of all negative impacts.
However, possible improvements regarding the transport within Colombia are listed as follows:

At present CPE takes back computers under warrantee, repairs them at a centre and delivers the same again back to the school. The author suggests to directly deliver a 'newly refurbished' computer during the pick up. The collected computer can be sent to another school following renovation.

The dismantling process could be decentralized. Regained materials could be sold within local markets. Transport of 'e-waste' from the CRM, CRC, CRBQ and CRCU to Bogota would be avoided.

Although the maintenance has a little overall impact of 0.4% during the life cycle of a computer it showed a huge benefit of more than 50% for the environmental performance by comparing the two scenarios Ia and Ib (see also Figure 31). The maintenance is therefore of indisputable benefit regarding the supply of computers to schools. The value of the recent initiative to build local capacity for maintaining and repairing computers is priceless.

E Which of the scenarios has the best performance regarding its economic, environmental and social impacts?

In order to determine the overall sustainability of a scenario and make them comparable the method MAUT was chosen.
The following section will first discuss the applied method and then the results.

A MAUT allows the assessment and comparison of different scenarios while incorporating subjective preferences. A set of attributes is defined and weighted with relation to affected stakeholders. In this study only people somehow involved with CPE and one person from 'ComputerAid' were asked to provide their preferences. Further stakeholders e.g. members of the OLPC initiative would have to be involved in expansion of the study.
The defined attributes aim to cover all important aspects of the scenarios. For all three impact categories (economy, environmental, society) three attributes were defined. In the following the attributes are discussed individually (for a discussion of the attribute ***low net costs*** please see above).

High technical value

This attribute was the easiest to assess. It was incorporated due to frequently mentioned concerns about the importance of the technical standard of the computers. The allocation to the category economy is due to the greater offer of applications, closer education regarding requests and challenges of modern economic and working environment and therefore creation of an added value for future generations. However, there are also arguments for its allocation to the category environment (longer usefulness and less likely to be dumped after a short time) or even society (concern regarding the ‘shifting off’ of old technology to impoverished regions).

Involvement/participation of the local economy

This is undoubtedly an important attribute regarding the completeness of the category economy.
The fact that different strategies were partly incorporated into CPE made it hard to evaluate in a correct manner. Only processes directly integrated were included for the subcategory ‘life cycle’. For the subcategory ‘transport’ a simplification of relative efforts took place (transport from the school to the harbour is weighted the same as a transport from the harbour to final disposal).
Counting the ‘life cycle’ three times higher than the ‘transport’ is subject to discussion.

Overall a satisfying coverage of the category economy could be achieved with the three above mentioned attributes. The highest utility in this category resulted for scenario Va “XO laptop” (see also appendix A).

For the category environment the three attributes ***low use of energy, low use of resources*** and ***little toxic emission*** were defined. However, with the LCA assessment combined with ‘Simapro’ and an interpretation of the results with the Eco-indicator’99 a far more holistic approach took place in this study (see also above). Regardless, the stakeholder weighting was conducted according to the three attributes. This is only partly a correct approach but can be justified to a certain extend. The Eco-indicator’99 involves among others the three above mentioned attributes. The weightings were summed up and added at the end. For all categories (economy, environment, society) three attributes were defined. A balanced weighting of the three categories therefore is the result. Additionally the three attributes can be allocate to the three damage categories of the Eco-indicator’99 (‘low use of energy’ – *Resource Depletion*, ‘low use of resources’ – *Ecosystem Quality*, ‘little toxic emissions’ – *Human Health*).

The best environmental performance was achieved by scenario I “100% Colombian refurbishment” (see also appendix A).

Creation of low and semi-skilled jobs

Two thirds of the category 'society' were assessed by the amount of created jobs (see also below). For the low and semi-skilled jobs all employments of CPE that do not require a university degree were taken into account. Jobs in the administration at the ministry or jobs not directly process related (e.g. drivers for transport) were not taken into account.

CPE aims to employ highly educated staff. As a result many positions originally not requiring a university degree are staffed with high skilled employees. Furthermore, many of the technicians are in schooling at university. This is not counted in the data.

Calculations based on the output figures and the corresponding extrapolation of the amount of employees at all CRs. For the diminished amount of computers provided through the CRs in scenario III, Va and Vb it was assumed that the process could only take place in the CRB. Hence, the calculations for these three scenarios were based on the output figures and amount of employees at the CRB.

Creation of highly skilled jobs

Only jobs at CPE requiring a university degree were taken into account. The same assumptions as for low and semi-skilled jobs (see also above) were applied for this attribute. It is assumed that no additional centres are built up by an expansion of the program. Hence, no extrapolation for the director of plant, directors of the centres and the coordinators took place.

Capacity building

This attribute was ranked of highest importance by the stakeholder. At the same time it was the most difficult to assess due to its non-quantifiable nature. Two aspects of capacity building were taken into account and assessed qualitatively.

Aspect one looked at the capacity building on the level of the local community. Since all the different scenarios are incorporated into the communities by CPE no differences on the level of local community capacity building could be identified. Scenario Va "XO laptop" is an exception. The design of the 'XO laptop' (exclusively for children) does not allow computer training of adults. Also, capacitating locals in its maintenance and repair would have to take place on a very specific level due to the unique nature of its construction.

Aspect two looked at the capacity building on the level of the individual.

Little data exists regarding the newly created user interface 'Sugar' for the 'XO laptop'. However, Workman (2004) shows that between computer based education (allocated to the 'XO laptop') and computer aided education (allocated to all other scenarios) one is not intrinsically advantageous over the other but rather depends on the individual's cognitive style.

The highest utility in the category society was achieved by scenario I "100% Colombian refurbishment" (see also appendix A).

Eventually a statement regarding the economic, environmental and social impacts of each scenario can be made. The discussion relates heavily to figure 27, 28 and appendix A:

Scenario I: “100% Colombian refrubsihment”

Scenario “100% Colombian refurbishment” is the most sustainable strategy within the defined system boarder and given circumstances. The use of the existing infrastructure and resources of Colombia leads to the best environmental performance and the most positive social impacts. Economically it is the second most costly scenario, though expenses stay exclusively within the borders of Colombia.

The scenario is built upon a hypothetical amount of donations. It has yet to be proven possible to acquire this amount of computers.

Scenario II: “Colombian/overseas refurbishment and local assembling”

This scenario reflects the current situation and turned out to be the second most sustainable overall (together with scenario III and IV). It is relatively costly but compensates with a high involvement in the local economy. As with scenario I it uses the infrastructure and resources of Colombia and has high positive social impacts. However, the production of new computers at the CIEN leads to a relatively low environmental performance.

It is the only scenario, next to Va and Vb, that has been proven able to achieve a sufficient supply of computers. Nevertheless, investigations of a combination of “CRs and CEEX” rather than “CIEN and CEEX” should be conducted in order to improve the environmental performance.

Scenario III: “Overseas refurbishment”

The scenario “Overseas refurbishment” is ranked second for overall sustainability (together with scenario II and IV). Although resulting in relatively high positive economic and environmental performance, the strategy to refurbish computers abroad before shipping them to a developing nation does not utilize local human resources. The positive social impacts of this strategy are relatively low.

At present no refurbishing program exists that would have the capacity to deliver the required amount by Colombia. As mentioned above, this strategy might be an option in combination with scenario I.

Scenario IV: “Overseas donations for Colombian refurbishment”

Scenario “Overseas donations for Colombian refurbishment” was ranked second for overall sustainability (together with scenario II and IV), due to the use of the existing infrastructure and human resources of Colombia similar to scenario I.

Due to the low negative environmental impact of intercontinental transport, one could conclude that the origin of a computer is of no relevance. However, situations where developing countries serve as a dumping ground for ‘e-waste’ have to be avoided (Puckett et al., 2005). It is therefore essential that donations sent directly by the user pass through established systems like CPE, which can take care of the computers in an appropriate way. Well functioning recycling systems have to be in place. In Colombia the CENARE is still in development. Therefore, at present, “Overseas donations for Colombian refurbishment” is not a strategy that should be considered. Furthermore, the scenario has still to prove itself able to supply a sufficient amount of computers.

Scenario Va: “XO laptop”

This scenario represents one of the recent developments regarding strategies to supply schools with computers.

Although having by far the lowest overall costs (by more than US $110) than all other scenarios and resulting in the highest positive economic impacts, the overall sustainability of the scenario “XO laptop” is relatively low. It is ranked fifth for overall sustainability. The scenario does not use local human resources but rather implements a solution from outside. This results in a low social performance. However, OLPC envisages outsourcing the assembling process to the corresponding countries of destination. This would significantly improve the social performance and make the ‘XO laptop’ a viable solution.

Next to scenario II it is the only strategy that guarantees a sufficient supply of computers.

Scenario Vb: “PC (new)”

This scenario was investigated in order to have a comparison of computers being recycled directly and computers being refurbished first. The results are presented and discussed in chapter 3.4.3.

However, the overall sustainability of this scenario is assessed to be the lowest. The scenario “PC (new)” gets the lowest utilities for the categories economy and environment. Regarding the positive social impacts it does score better than the ‘XO laptop’ due to a slightly higher use of existing human resources.

Although offering the possibility of a sufficient supply of computers, this strategy is not an appropriate alternative to the above described scenarios.

4.2 Limitations of the study

As is with any study the modelling of the reality is only possible to certain extent. In this study three main aspects were identified as having limited the certitude of the results.

The first aspect is the required extrapolations or adjustments in some of the scenarios. The costs and environmental impacts were calculated per computer and extrapolated based on the existing infrastructure and regarding to the output figures. The expansion in reality of the program CPE e.g. in scenario I to a total production of 46’000 computers might have some benefiting/unfavourable economic or environmental impacts that were not considered in the scope of this study. Also, scenario III, Va and Vb do involve a partial supply from the CRs that equals only 22% of the actual production. For the case of the attributes ‘creation of low and semi-skilled jobs’ as well as ‘creation of high skilled jobs’, the calculations are based upon the assumption that the total production could be achieved solely in Bogota. However, for all attributes especially in regard to costs and environmental performance this could not be assumed.

The second aspect of limitation is the fact that some processes of CPE which are of essential nature to this study were still in development. This concerns the CIEN, the CEEX and the CENARE. Regarding the CIEN two months of ‘operating phase’ could be evaluated. This allowed an appropriate approximation. For the CEEX the estimations base exclusively on future plans and expert interviews. In regard to the CENARE the dismantling of CRT monitors could be observed at first hand. For dismantling the CPU data evaluated under similar conditions was obtained from Gmünder (2007). Other processes e.g. the detaching of parts of the PWBs data was based on expert estimations and would have to be further investigated once the process is established.

Continuous evaluation of the actual situation is therefore a crucial.

The third aspect of limitation concerns the used ‘Ecoinvent v2.0’ data. The reflection of specific processes in the ‘Ecoinvent v2.0’ allows only an approximation if applied under different circumstances.

5 Conclusion and Outlook

This study investigated a previously unexplored field that is of great importance to the decision-making process regarding the relative viability of strategies for supplying schools in developing countries with computers. It proves that, in the case of Colombia, use of the existing infrastructure and resources is integral to the success and sustainability of a scenario.

For Colombia, with its well established program CPE, the refurbishment of computers proved to be the most sustainable solution. However the supply is inadequate and further investigation, regarding the best methods to procure larger quantities of donations would have to be carried out.

A solution that guarantees a sufficient supply is the combination of the existing refurbishment centres, the acquiring of computers from refurbishers abroad and the assembling of new computers.
However, the inclusion of the production of new computers within a scenario has a negative impact on its overall sustainability. Analyzing the refurbishment process at CPE this study concludes that an extension of a computer's lifespan is desirable in any case. The critical stages were identified as the production for a recycled computer and the 'XO laptop'; and as the use phase for a refurbished computer.
The relative unimportance of transport regarding the environmental impacts during the life cycle of a computer revealed that there is little discrepancy, on the level of sustainability, between obtaining computers domestically or from abroad.
The success of establishing a direct import channel of used computers from overseas might be possible in the case of Colombia. With the further development of the CENARE and the existing infrastructure CPE could soon be able to take care of computers from abroad in an appropriate way. In other countries where the standard of a CENARE has not yet been reached the risk exists that such a strategy could turn into the dumping of 'e-waste'. For these nations it is still assumed that a pre processing through 'ComputerAid' offers a valuable solution. Further research would have to be conducted to investigate the best synergy between obtaining computers domestically and acquisition from abroad.

At present an established refurbishment program of the magnitude of CPE is not matched by the potential of the 'XO laptop', the latest developments on the supply market. The 'XO laptop' does not use the existing infrastructure or resources but rather implements a solution from outside. In the case of Colombia this study concludes that the 'XO laptop' shows shortcomings in the social performance. However, within the scope of this study it was not investigated in relation to a refurbishment program run on a smaller scale or the total inexistence of it. In Latin America several programs exist (e.g. TodoChilenter in Chile) that refurbish computers on a smaller scale. Investigations would have to be made into whether a small scale refurbishment program combined with recent developments, like the ‘XO laptop’, offer a sustainable way to supply schools with computers. Furthermore the consequences of outsourcing the assembling process should be investigated regarding the improvement of the social performance.

6 Literature

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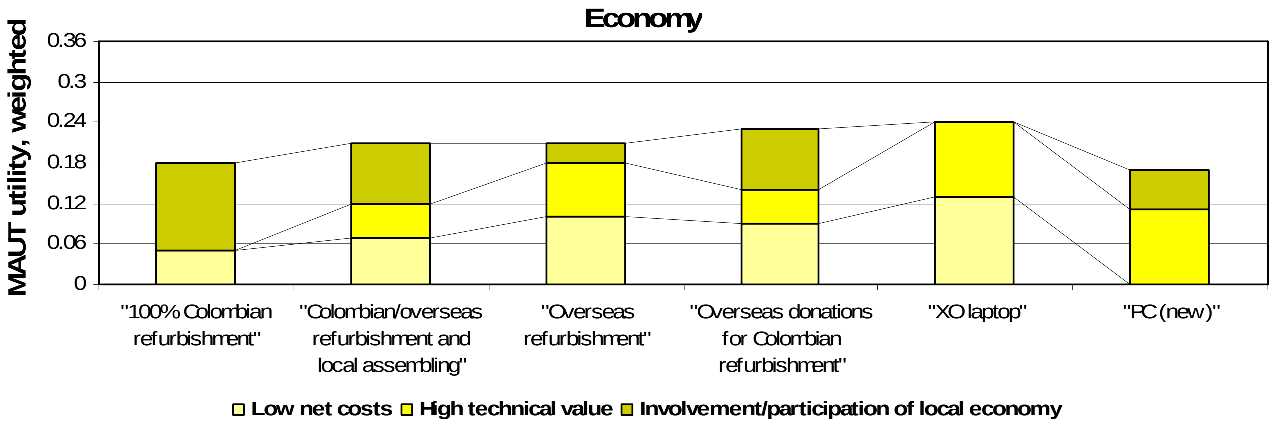
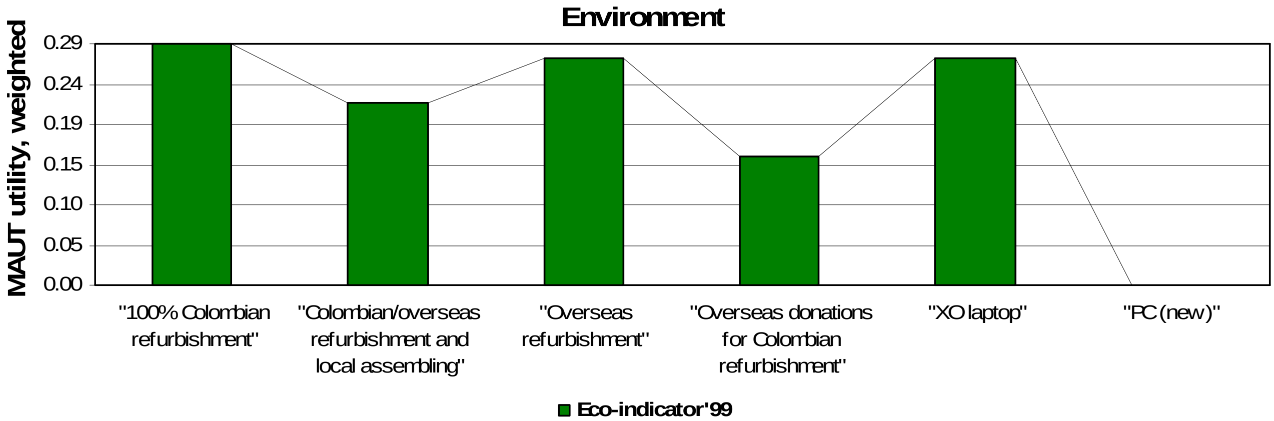
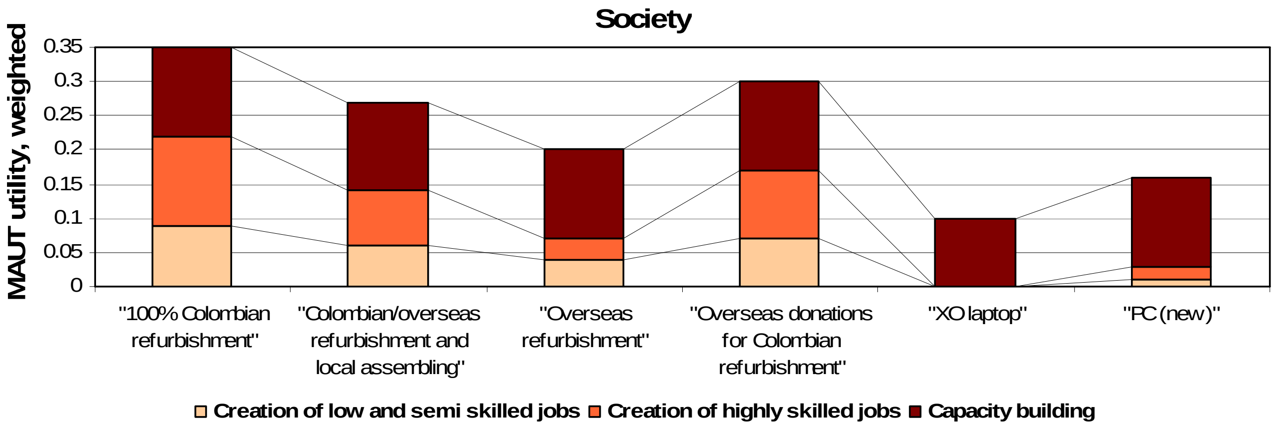
7 Appendix

Appendix A: Further results and calculations

Appendix A1: MAUT results according to the categories economy, environment and society.







Appendix A2: MAUT attribute vs. scenario matrix. The weights, the scales, the values of the attributes and the normalized and weighted utilities.

	Weighting			Scenario I			Scenario II			Scenario III			Scenario IV			Scenario Va			Scenario Vb		
Criteria	Stakeholder weights	weight normalized	Scale / unit	value	utility normalized	Utility weighted	value	utility normalized	Utility weighted	value	utility normalized	Utility weighted	value	utility normalized	Utility weighted	value	utility normalized	Utility weighted	value	utility normalized	Utility weighted
Low net costs	3.33	0.13	$ / computer	537	0.422	0.05	489	0.541	0.07	365	0.844	0.1	415	0.722	0.09	302	1	0.13	709	0	0
High technical value	2.83	0.11	0, 0.25, 0.5, 0.75, 1	0	0	0	0.5	0.5	0.05	0.75	0.75	0.08	0.5	0.5	0.05	1	1	0.11	1	1	0.11
Involvement/participation of local economy	3.33	0.13	%	0.92	1	0.13	0.83	0.68	0.09	0.72	0.25	0.03	0.85	0.75	0.09	0.65	0	0	0.77	0.47	0.06
Economy	9.49	0.36			1.422	0.18		1.721	0.21		1.844	0.21		1.972	0.23		2	0.24		1.47	0.17
Low use of energy	2.67	0.1																			
Low use of resources	3	0.11	Eco-indicator'99	6.793	1	0.29	13.5	0.755	0.219	8.488	0.938	0.27	19.7	0.53	0.154	8.33	0.944	0.27	34.3	0	0
Little toxic emissions	2	0.08																			
Environment	7.67	0.29			1	0.29		0.755	0.219		0.938	0.272		0.53	0.154		0.944	0.274		0	0
Creation of low and semi skilled jobs	2.5	0.09	Amount of jobs	765.9	1	0.09	507.2	0.63	0.06	0.78	0.38	0.04	610.2	0.78	0.07	66.8	0	0	148.9	0.12	0.01
Creation of highly skilled jobs	3.33	0.13	Amount of jobs	68.56	1	0.13	49.05	0.65	0.08	27.11	0.25	0.03	56.34	0.78	0.1	13.13	0	0	20.73	0.14	0.02
Capacity building	3.5	0.13	0, 0.25, 0.5, 0.75, 1	1	1	0.13	1	1	0.13	1	1	0.13	1	1	0.13	0.75	0.75	0.1	1	1	0.13
Society	9.33	0.35			3	0.35		2.28	0.27		1.63	0.2		2.56	0.3		0.75	0.1		1.26	0.16
Total weights	26.5																				
Total utility, unweighted					5.422			4.756			4.412			5.062			3.694			2.73	
Total utility, unweighted normalized					1			0.877			0.814			0.934			0.681			0.504	
Total utility weighted						0.82			0.699			0.682			0.684			0.614			0.33
Total utility weighted & normalized						1			0.853			0.832			0.834			0.749			0.403

Appendix A3: Calculations for the attribute 'involvement/participation of local economy'

Scenario	Processes at	Amount	Treatment		Utility
			within Colombia	outside Colombia	
Ia	CR	54602	100.00%	0.00%	
	CENARE	81354	83.00%	17.00%	
Total (in %)	Life cycle	100.00%	89.83%	10.17%	0.9152
	Transport	100.00%	96.61%	3.39%	
TOTAL value (in %)		100.00%	91.52%	8.48%	
II	CR	29144	100.00%	0.00%	
	CEEX	14000	30.00%	70.00%	
	CIEN	8330	100.00%	0.00%	
	CENARE	56144	83.00%	17.00%	
	OFF (Colombia)	50020	75.00%	25.00%	
Total (in %)	Life cycle	100.00%	79.80%	20.20%	0.8296
	Transport	100.00%	92.45%	7.55%	
TOTAL value (in %)		100.00%	82.96%	17.04%	
III	CR	3960	100.00%	0.00%	
	CEEX	42040	30.00%	70.00%	
	CENARE	47940	83.00%	17.00%	
	OFF (Colombia)	76216	75.00%	25.00%	
Total (in %)	Life cycle	100.00%	66.72%	33.28%	0.7168
	Transport	100.00%	86.57%	13.43%	
TOTAL value (in %)		100.00%	71.68%	28.32%	
IV	CR (User Colombia)	3960	100.00%	0.00%	
	CR (User Overseas)	49459	100.00%	0.00%	
	CENARE	55359	83.00%	17.00%	
	OFF (Colombia)	76216	75.00%	25.00%	
Total (in %)	Life cycle	100.00%	84.61%	15.39%	0.8498
	Transport	100.00%	86.10%	13.90%	
TOTAL value (in %)		100.00%	84.98%	15.02%	
Va	CR (Standard 5)	3960	100.00%	0.00%	
	XO laptop	42040	0.00%	100.00%	
	CENARE	47980	83.00%	17.00%	
	OFF (Colombia)	76216	75.00%	25.00%	
Total (in %)	Life cycle	100.00%	59.31%	40.69%	0.6508
	Transport	100.00%	82.37%	17.63%	
TOTAL value (in %)		100.00%	65.08%	34.92%	
Vb	CR (Standard 5)	3960	100.00%	0.00%	
	PC (new)	42040	50.00%	50.00%	
	CENARE	47980	83.00%	17.00%	
	OFF (Colombia)	76216	75.00%	25.00%	
Total (in %)	Life cycle	100.00%	71.66%	28.34%	0.7743
	Transport	100.00%	94.72%	5.28%	
TOTAL value (in %)		100.00%	77.43%	22.57%	

Appendix A4: Calculations for the attribute 'creation low and semi-skilled jobs', 'creation highly skilled jobs'

	Scenario						I		II						III				IV		Va, Vb	
	Centre						CR		CR		CIEN		CEEX		CRB		CEEX		CR		CRB	
	low-, semiskilled	high skilled	CRs actual situation (2007)	CRB, actual situation (2007)	CIEN actual situation (2007)	CEEX actual situation (2007)	low-, semiskilled	high skilled	low-, semiskilled	high skilled	low-, semiskilled	high skilled	low-, semiskilled	high skilled	low-, semiskilled	high skilled	low-, semiskilled	high skilled	low-, semiskilled	high skilled	low-, semiskilled	high skilled
Production			18000	10665	14000	14000	54602		29144		7778		14000		3960		42040		46000		3960	
Type of job																						
Director of plant (Bogota)		x	1	1	0	0		1		1		0		0		1		0		1		1
Director of centre		x	5	1	1	1		5		5		1		1		1		1		5		1
Supervisor		x	11	7	2	1		33.4		17.8		1.11		1		2.6		3		28.1		2.6
Supervisor (informatic)	x		1	1	0	0	3.03		1.62		0		0		0.37		0		2.56		0.37	
Administration assistent (Bogota)		x	1	1	0	0		3.03		1.62		0		0		0.37		0		2.56		0.37
Assistent (technical support, Bogota)	x		1	1	0	0	3.03		1.62		0		0		0.37		0		2.56		0.37	
Secretary (Bogota)	x		1	1	0	0	3.03		1.62		0		0		0.37		0		2.56		0.37	
Operation depot (fork-lift truck)	x		2	1	1	1	6.07		3.24		0.56		1		0.37		3		5.11		0.37	
Tecnician senior	x		27	16	2	0	81.9		43.7		1.11		0		5.94		0		69		5.94	
Tecnician junior	x		28	16	20	11	84.9		45.3		11.1		11		5.94		33		71.6		5.94	
Tecnician rookie	x		64	34	7	0	194		104		3.89		0		12.6		0		164		12.6	
Tecnician (informatic)	x		1	1	0	0	3.03		1.62		0		0		0.37		0		2.56		0.37	
Assistent depot	x		2	2	0	0	6.07		3.24		0		0		0.74		0		5.11		0.74	
Digitador	x		1	1	0	0	3.03		1.62		0		0		0.37		0		2.56		0.37	
TOTAL, low- and semi-skilled jobs			128		30	12	388		207		16.7		12		27.5		36		327		27.5	
TOTAL, high-skilled jobs			18		3	2		42.4		25.4		2.11		2		4.97		4		36.7		4.97

Appendix B: Data for calculations

Appendix B1: Distances, general weights, adaptations in SIMAPRO and electricity mix of Colombia used for calculations

Distances	in km	Source
CRB - CRC	435	CPE
CRB - CRM	409	CPE
CRB - CRCU	568	CPE
CRB - CRBQ	1008	CPE
China - Colombia	15033	www.imadbx.com
UK - Colombia	8516	www.imadbx.com
Bogota - Cartagena (harbour)	1125	Rodarcarga
General weights	**in kg**	**Source**
CPU	9.75128	Gmünder (2007)
CPU	11.3	Ecoinvent v2.0
CRT monitor	11.122	own measurements
CRT monitor	19.9	Ecoinvent v2.0
Keyboard	1.18	Ecoinvent v2.0
Mouse	0.111	Ecoinvent v2.0
XO laptop	1.5789	Quanta Computer Inc.
SIMAPRO	**in kg**	**Source**
Loudspeaker & Microphone		
Brass, at plant/CH U	0.0003	
Copper, primary, at refinery/GLO U	0.00015	
Steel, low-alloyed, at plant/RER U	0.00022	Roland Hischier, LCA expert (EMPA)
Polystyrene, general purpose, GPPS, at plant/RER U	0.0058	
Nylon 6, at plant/RER U	0.0002	
Robotic mix		author' own assumption
Capacitor, electrolyte type, > 2cm height, at plant/GLO U	0.21	
Connector, PCI bus, at plant/GLO U	0.17	
Light emitting diode, LED, at plant/GLO U	0.008	
Resistor, SMD type, surface mounting, at plant/GLO U	0.002	Ecoinvent v2.0
Transformer, high voltage use, at plant/GLO U	0.5	
Transistor, SMD type, surface mounting, at plant/GLO U	0.06	
Fan, at plant/GLO U	0.05	
Electricity mix Colombia	**kWh**	
Electricity, hard coal, at power plant/UCTE U	0.052050133	
Electricity, oil, at power plant/UCTE U	0.000677864	
Electricity, at cogen 200kWe diesel SCR, allocation exergy/CH U	0.019344786	
Electricity, natural gas, at power plant/UCTE U	0.27099953	
Electricity, industrial gas, at power plant/UCTE U	0.01	Ministerio de Minas y Energia
Electricity, hydropower, at reservoir power plant/BR U	0.6569277	
Electricity, nuclear, at power plant/CH U	0	
Electricity, at wind power plant/RER U	0	
Electricity, bagasse, sugarcane, at fermentation plant/BR U	0.03962	

Appendix B2: Electricity use at the centres and material prices (in Colombian Pesos) paid on the Colombian market

Electricity use	kWh / unit	
Cien	**1.662857143**	
CEEX	**1.662857143**	**CPE**
CRs	9.358568745	
CENARE		CPE
Monitor	0.301731647	
CPU	0.096009264	
Keyboard	0.012639194	
Mice	0.005590413	author's own calculation
PWB (CPU)	0.288181818	
PWB (Monitor)	0.360227273	
Monitor TOTAL	0.66195892	
CPU TOTAL	0.384191082	
Market Colombia	**Material**	**Price paid per kg (in COP)**
	Steel	330
	Copper	12500
	Aluminium	2500
1000 COP = 0.498647 USD (17.12.2007)	Plastic (ABS)	700
	Cables/wires	4500
	PWB to disposal	3500
	Ferrite	330

Appendix C: Expert interviews

Person	Institution/Function	Collected data
Andrea Gardeazabal/ Andres Muñoz	Coordinadora Gestion Institucional	Monitoring, evaluation and transport
Angel Eduardo Camacho L.	CPE (Coordinador CENARE)	General information of CPE and CENARE Future plans and objectives of CPE
Carlos Fernandez Cadavid	CNPMLTA	General information
Cristina Ruiz	(planned) Supervisor CEEX	Operation and processes CEEX
David Molina	ASEI Ltda.	Recycling Colombia, market prices
Dol Momphotez/ Luis Raffael Valderrama	Supervisors CIEN	Operation and processes at CIEN
German Ricaurte	Coordinador Mantenimiento	Operation and processes maintenance
Jaime Prieto	CPE National directorate	General information CPE
Juan Alejandro Montoya	Surenvios	Transport (donations)
Juan Manuel Trujillo/ Cesar Suarez	Rodarcarga	Transport (distribution)
Julian Gomez	Coordinador Área de Monitoreo y Evaluación	Objectives and evaluation CPE
María del Rosario García Jácome	Asesora Área de Gestión	Transport
Mary Lou Jepsen	(former) Chief technology officer OLPC	General information of OLPC
Mauricio Peñalosa Reyes	Director CENARE	Operation and processes CENARE
Omar Espitia	Recycler Bogota	Recycling Colombia, market prices
Oscar Niño	CPE National directorate	Operation and processes at CRB
Sonia Sinanan/ James Fairweather	General Production Manager	General information ComputerAid
Victor Chao	Quanta Computer Inc.	XO laptop specifications