Life cycle assessment study of a Chinese desktop personal computer

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ABSTRACT

Associated with the tremendous prosperity in world electronic information and telecommunication industry, there continues to be an increasing awareness of the environmental impacts related to the accelerating mass production, electricity use, and waste management of electronic and electric products (e-products). China’s importance as both a consumer and supplier of e-products has grown at an unprecedented pace in recent decade. Hence, this paper aims to describe the application of life cycle assessment (LCA) to investigate the environmental performance of Chinese e-products from a global level. A desktop personal computer system has been selected to carry out a detailed and modular LCA which follows the ISO 14040 series. The LCA is constructed by SimaPro software version 7.0 and expressed with the Eco-indicator’99 life cycle impact assessment method. For a sensitivity analysis of the overall LCA results, the so-called CML method is used in order to estimate the influence of the choice of the assessment method on the result. Life cycle inventory information is compiled by ecoinvent 1.3 databases, combined with literature and field investigations on the present Chinese situation. The established LCA study shows that that the manufacturing and the use of such devices are of the highest environmental importance. In the manufacturing of such devices, the integrated circuits (ICs) and the Liquid Crystal Display (LCD) are those parts contributing most to the impact. As no other aspects are taken into account during the use phase, the impact is due to the way how the electricity is produced. The final process steps – i.e. the end of life phase – lead to a clear environmental benefit if a formal and modern, up-to-date technical system is assumed, like here in this study.

1. Introduction

China’s importance as both a supplier and consumer of electronic goods or e-products has grown at an unprecedented pace over the course of the past decade (Wong and El-Abd, 2003). Since its entry into the World Trade Organisation (WTO) in 2001, China’s e-product manufacturing sector has entirely reoriented itself from an industry driven primarily by domestic markets, to a fundamentally export driven sector and the world’s most important supplier of many, if not most, major e-products on the market today. The e-product sector now accounts for 10.2% of the country’s total industrial output value and 6.3% of national industrial profits (NBSC, 2007). The statistical data used (NBSC, 2007) are taken from 2006 survey. While the rapid transition towards global market leadership in the e-products sector has produced significant economic benefits at both the...
national and community levels, it has also placed increasing pressures on the local and global environment (Puckett et al., 2002; Widmer et al., 2005; Wong et al., 2007).

Within the Sino-Swiss cooperation project “Sustainable Development: China and Global Markets”, three major industrial sectors, namely cotton and textile, timber and e-products, were studied, and key sustainability impacts were identified and evaluated from a global level. For the analysis of the environmental impacts in the e-product sector, a life cycle assessment (LCA) study has been carried out. Since the e-product sector is very broad and comprises a vast variety of different appliances, a detailed and modular LCA of a desktop personal computer system (PC system) has been selected as a case study (see the explanations by following passages in this section).

The PC industry is one of the most prosperous electronic industries in China, being the top computer market in the Asia-Pacific region (excluding Japan) with expansion of more than 8% per year. In 2006 the volume of PCs output reached to 89.80 million units, of which above 10% was exported (NBSC, 2007).

However, along with its life cycle, a PC generates a lot of environmental impacts (Atlantic Consulting and IPU, 1998). During the manufacture phase, large amounts of natural resources are needed. The use of a PC consumes considerable amounts of electricity. In addition, the disposal of electronics (i.e. the respective End-of-Life (EoL) treatment) could pose severe impacts on human health and the eco-system when they are not well managed, as many parts of PC contain hazardous materials, such as brominated flame retardants, tin-lead soldering on printed wiring boards (PWB), polychlorinated biphenyl in transformer, and mercury in Switch (Qu et al., 2007; Deng et al., 2007; Liu et al., 2008). Exposure to such chemical substances may increase the risk of developing cancer in people and even cause death (Tekwawa et al., 1997; Socolof et al., 2000).

The increased awareness of the importance of environmental protection and the possible impacts associated with products manufactured, distributed, consumed and EoL managed, have increased interest in the development of methods to better understand and address these impacts. One of the techniques being developed for this purpose is life cycle assessment (LCA) (ISO, 2000; Besnainou and Coulon, 1994; Rivela et al., 2006; Asari et al., 2008). Since the end of 1990s, there have been some studies done on the LCA of PC products or their key components (Socolof et al., 2005; Hikwama, 2005; Choi et al., 2006; Kim et al., 2001; USEPA, 2001). Similar efforts have been taken to apply LCA methodology to other information and communication technologies, such as mobile phone networks (Scharnhorst et al., 2005, 2006). However, contribution from research to LCA studies on e-products in China was nearly blank, particularly with regard to PC product. Just a few papers described the implementation of LCA to conduct eco-design or investigate the environmental impact of technologies for waste management (Yang and Wang, 1996; Zeng, 2006; Wang, 2005).

For this study, a Chinese desktop PC system – using 50% a traditional Cathode Ray Tube (CRT) screen, and to 50% a modern LCD flat screen – is assessed over its complete life cycle, from the extraction of the requested resources up to a state-of-the-art disposal, like currently practice e.g. in Switzerland. The present paper gives a description of the goal and scope (Section 2.1), the inventory data (Section 2.2) as well as the most important results from the impact assessment of these data (Section 3).

2. Materials and methods

2.1. Goal and scope

2.1.1. Objective of the study

The environmental performance of a desktop PC system – assembled in China – is calculated by conducting a LCA study according to the international standards of the ISO 14040 series (ISO, 2000; Rebitzer et al., 2004; Pennington et al., 2004). Within the context of the above mentioned footprint project, the objective of this case study is to establish a scientific baseline that evaluates the key environmental impact related to e-products. The PC system is chosen as this is a very complex electronic device; and its results will allow general conclusions, valuable for the complete e-product industry.

2.1.2. System boundaries

The here examined desktop PC system is taking into account the complete life cycle of such a device, ranging from manufacture (including all steps from material extraction up to the final assembly of the system), distribution (from production site to the use site), functional life span, up to the EoL treatment (including recycling and disposal operations). Hereby the production phase focuses on PC systems assembled in China — while all upstream (e.g. production of electronic components like capacitors, PWB, etc.) and downstream steps (i.e. use, disposal of PC) represent the actual market situation for the Chinese PC assemblers. Hence, only the PC’s assembly phase is limited to China mainland — all other steps are seen from a rather global level (see also Fig. 1 below).

2.1.3. Functional units

The functional unit is a desktop PC system which consists of four different subunits: desktop computer itself, the screen (CRT and LCD technologies), the keyboard and the mouse. The examined PC system (based on a Pentium IV processor) comprises to 50% a CRT and to 50% a LCD screen, it is 4.2 h per day active and 2.6 h per day in either standby or sleep mode (assuming a 40% office and 60% home use of the PC system) during 6 years before the complete system is handed over for EoL treatment. For the distribution and the subsequent use of the desktop PC system, an export amount of 10% of the production volume (to Europe, the United States but also other Asian countries) is assumed, based on the current trade statistics of China (for more details see Section 2.2).

2.2. Life cycle inventory

2.2.1. PC production and consumption — market situation in China

Based on literature review and field investigation (NBSC, 2007; Duan et al., 2007a,b; Li et al., 2006; Tong, 2004; MOFCOM, 2007; China Custom, 2007; Terazono et al., 2006; BCRC, 2005), data information relevant for the here investigated Chinese PC system about the following aspects have been gathered (hereby, China Taiwan and Hong Kong are classified as foreign
trade regions according to China Custom Statistics), which are aimed to establish the inventory data of the various life stages.

- The volume and proportion of finished PC products consumed in domestic and foreign markets, destined countries and regions, and main type and specification of PC;
- The share between CRT display and LCD used in the PC system;
- The proportion of major devices and components (e.g. CRT, LCD, PWB and IC) produced in domestic respectively, imported from foreign markets; including the geographic distribution of original countries and regions where these devices and components are produced;
- Transportation distance estimations between the different producers and suppliers (on the domestic and the foreign markets).
2.2.2. Data — sources, assumptions and limitations

So far, no Chinese national life cycle inventory (LCI) database is available. In addition, very few public data with regard to PC systems (as well as their components) are available. Hence, in order to get a quantitative model, the data sources as well as the assumptions and limitations described in Table 1 have been used in this study here for the various life stages of the examined PC system.

As shown there, the various components and devices have been modelled by using a pre-version of the respective ecoinvent v2.0 datasets (referred in Table 1 as “Empa-internal database”) with a change in the electricity input (Chinese mix) for those parts of these components and devices produced in China. A more detailed view into the used data sources (i.e. its actual values) is not possible. The split between China and abroad is established based on the information shown in Fig. 1.

From this figure, it can be seen that mainly the high-tech products (like e.g. logic Integrated circuits (ICs) or LCD modules) are major parts produced abroad. On the other hand, general parts such as PWB, ferrous-metal and non-ferrous-metal, or packaging materials, are mainly produced directly in China.

2.3. Life cycle impact assessment

As main life cycle impact assessment (LCIA) method, the method “Eco-indicator’ 99”, is used. This method is an example of a multi-step, fully aggregating method, leading to one single number as result. The various environmental impacts that are examined within this method are summed up in one of three damage categories: human health, ecosystem quality and resource consumption. The final normalization and weighting steps are then performed at this damage level (Josa et al., 2007; Geodkoop and Spriensma, 2001; Vlasopoulos et al., 2006). The whole method is an example for the damage-oriented approach.

For a sensitivity analysis of the overall results, the so-called CML method (Centrum voor Milieukunde Leiden) is used in order to estimate the influence of the choice of the LCIA method on the result. This Dutch method is an example of the so-called “problem-oriented” or “mid-point” approach. The method is based on the publication of Guinee et al. (2001), acknowledged as a reference in the field of LCA, and also known as the “CML Table 1 – Assumption and data sources for the various life stages of the PC system

<table>
<thead>
<tr>
<th>Life stage</th>
<th>Data source(s)</th>
<th>Covered area</th>
<th>Assumptions and limitations</th>
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<tr>
<td>Manufacturing</td>
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<td>Global</td>
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<td></td>
<td>Processing of basic materials</td>
<td>ecoinvent data v1.3</td>
<td>Global</td>
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<td></td>
<td>Production of electronic components</td>
<td>Empa-internal database</td>
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<td></td>
<td>Final assembly of desktop PC system</td>
<td>Empa-internal database</td>
<td>China</td>
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<td>Distribution</td>
<td>Transports between different steps</td>
<td>ecoinvent data v1.3</td>
<td>Europe</td>
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<td></td>
<td>Split export/home selling</td>
<td>Chinese trade statistics</td>
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<td></td>
<td>Distances inside China</td>
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<td>Distances of exports</td>
<td>Empa-internal database</td>
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<td></td>
<td>Transport data</td>
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<td>Use</td>
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<td>Electricity mixes</td>
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</tr>
<tr>
<td>End-of-Life (EoL) treatment</td>
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<td>Europe</td>
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<td>Worst case recycling</td>
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<td>Best case recycling</td>
<td>“Avoided” primary production</td>
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* Empa-internal database=according to project specific conditions (production in China) adapted pre-version of those data that have been developed in parallel to this project for the extension/update of the ecoinvent database (ecoinvent data v2.0).

* UCTE-Mix=the Union for the Co-ordination of Transmission of Electricity.
Guide®. This guide provides a list of different impact assessment categories, grouped into obligatory impact categories (i.e. all those category indicators used in most LCA studies), additional impact categories (i.e. categories that have operational indicators, but are not often included in LCA studies) and other impact categories (i.e. no operational indicators available, and therefore impossible to include quantitatively in LCA).

3. Result and discussion

3.1. Environmental impacts of the complete life cycle of a PC

According to the results of the impact assessment of the complete life cycle of a PC, as shown in Fig. 2, manufacturing (including raw material extraction and processing, components production, and PC assembly) and use generate significantly more impacts than the two other life stages. From the total of 41 Eco-Indicator’99 points (EIP) within the manufacturing step, more than a quarter is due to the consumed fossil resources (see also Fig. 4), resulting in an overall impact for the damage to resources that is about 40% in case of manufacturing (compared to only about 27% in case of the use phase). The distribution step contributes very few to the impacts. During the EoL step assuming a state-of-the-art recycling (like e.g. the current Swiss WEEE recycling systems, Hischier et al., 2005), substantial environmental benefits are even generated. The beneficial value of about 22 EIP equals to more than half of the impact during the manufacturing step.

Despite the fact that 10% of China finished PC products are exported to Europe, the United States and other Asian countries – which means long transportation distances within the distribution step (see Fig. 3a) – the impact due to the distribution stays very low compared to all other phases, accounting actually for less than 1%. It was assumed that the PC systems are transported on land with lorries and over long distances on sea with cargo ships.

Due to the electricity consumption of the PC system in the use phase, important impacts are generated within the six years of effective lifespan assumed here. This impact of the use phase is caused by the respective impact of the electricity production. In China electricity is mainly produced by fossil fuels. Due to the fact that 90% of the produced desktop PC systems are used in China itself, the Chinese electricity mix is dominating the impact of the use phase (see Fig. 3b). This fact influences as well the results shown in Fig. 4, where the main contributors to the environmental impact of the three relevant

![Fig. 3 – Split of the environmental impacts of the distribution (a) and the use phase (b) into the amounts from the different markets plus the resulting average (according to the respective market shares), all expressed with the Eco-Indicator’99 method.](image1)

![Fig. 4 – Main contributions to the environmental impacts of a PC system (method of Eco-Indicator’99).](image2)
life stages “manufacturing”, “use” and “EoL” are shown in more details.

In this figure, the impact of the use phase is dominated from the emissions to air, plus the consumption of fossil resources — clear indicators for a high consumption of the latter substances. The high impact due to SO2 emissions is directly linked to the fact, that the Chinese electricity mix is mainly generated from thermal power plants using coal as fuel. Much less important are the various emissions to air for the first step — i.e. the manufacturing. Here, the consumed resources are more dominant. Due to the high energy requirements in the extraction and processing of the metals, fossil resources are showing up much more important than metal resources. The EoL step shows for the resources as well as the emissions to air negative values (i.e. an environmental benefit instead of an impact) due to the fact that recycling can be expressed as “avoided primary production”.

In a second step, the results from Fig. 2 were cross-checked using a second, different LCIA method — the CML method. This is an LCIA method that doesn’t aggregate the various environmental impacts — but keeps them all separated; thus, no overall impact can be calculated here. Nevertheless, comparing Figs. 2 and 5 shows that both methods produced rather similar results. For almost all single environmental impacts reported in Fig. 5, manufacturing and use have a clearly higher environmental impact compared to the other two stages and the EoL stage leads most of the time to an environmental benefit.

3.2. Impacts during the manufacturing of the various devices

As shown in Fig. 2 the manufacturing phase is very important. Hence a more detailed view into this first life stage is established — distinguishing firstly between the various parts that belong to such a PC system — i.e. the desktop PC or CPU (central processing unit) itself, the screen (CRT, LCD), the keyboard and the mouse. In Fig. 6 the resulting environmental impacts of these various parts are shown. In case of screens, the complete impact of either type of screen technology (CRT, LCD) is shown here. The results show that the desktop of PC has the greatest contribution to environmental impacts, followed by the two screens — while keyboard and mouse are of minor importance.

A more detailed view on the first three devices from Fig. 6 — i.e. the desktop PC and the two screen types — is shown in Fig. 7. Here it can be seen that the environmental impacts of a desktop PC (Fig. 7a) is clearly dominated by the motherboard — accounting for 54% of the impacts of the complete desktop PC, or about 11.5 EIP. The actual weight of a motherboard accounts only for 8.1% (Streicher-Porte et al., 2007). Other components of the desktop PC are of much smaller importance. In the case of the two screens, the respective screen material contributes the most to the environmental impacts of these components. In case of the CRT screen, CRT tube itself, electronics components and housing materials together are responsible for more than 80% of the environmental impact of such a device. Hereof, glass in the CRT tube is responsible for the main part, mainly due to its high weight compared to e.g. electronics components. In case of the competing LCD technology, LCD module has by far the greatest contribution to the environment with about 60% of the total impacts of such a device, while assembly process and electronics components only account for about 16% of the impact. Within the LCD module, glass and various coatings are responsible for the high impact.

In case of the CRT screen (Fig. 7b), the CRT tube itself is not the only significant part. Actually, the tube, the electronics components and the housing together are responsible for more than 80% of the environmental impact of such a device, or about 17 EIP. In case of the competing LCD technology (shown in Fig. 7c), the LCD module has by far the greatest contribution to the environment with about 8.5 EIP, accounting for about 60% of the total impacts of such a device, while the assembly process and the electronics components only account for about 16% of the impact.

3.3. EoL scenarios

For the last life stage — the EoL treatment — the actual impact depends upon whether or not the desktop PC system is sent to a landfill or recycled and, if recycled, what processes are used in the recycling process. For this study the following three scenarios have been examined:

(i) Scenario “Recycling, best case”: recycling of all recyclable fractions plus use of a technology that minimizes any releases of toxic substances into the environment (state-of-the-art recycling);
(ii) Scenario “Recycling, worst case”: recycling of all recyclable fractions without special protection of the environment concerning toxic substances (current system in undeveloped countries, like China);

(iii) Scenario “landfilling, worst case”: landfilling of the complete system without prior treatment concerning toxic substances.

Reliable quantitative data on e-waste flows treated under conditions of any of these scenarios are not available. Nevertheless, the scenarios roughly map the three major consumer markets for Chinese PC systems — the EU (high percentage of recycling; advanced facilities), China (high percentage of recycling; taking little care for workers or environment), and the United States of America (high transfer to landfill). In Fig. 8, the influences of the three scenarios on the environmental impacts of the EoL treatment are shown. It can be seen that in the best case the environmental benefits are almost as high as the environmental burden of the worst case. Taking care of toxic substances during recycling processes results in lowering the burden of EoL treatment of about 75 to 80%, and, thus, allows an overall benefit for the EoL treatment.

**4. Conclusion**

The main findings from this LCA study on PC systems can be summarized as follows.

(i) The manufacture and use phases generate with about 41 EIP resp. 43 EIP significantly more impacts than the two other life stages, distribution and EoL treatment. These two firstly mentioned phases are both dominated by the fossil resource consumption (40% of total in manufacturing step resp. 27% in use phase) and the emissions to air (with e.g. SO2 being about 25% of total impact in use phase). If EoL treatment is managed as a state-of-the-art disposal process it has the potential to create environmental benefit in the order of about half of the impact of the manufacturing of the here examined desktop PC system. This is due to the fact that secondary resources from recycling can avoid primary production.

(ii) The impact of the use phase is caused by the energy consumption of the PC system. The Chinese energy mix is dominated by electricity produced by thermal power stations using coal and oil as fuels. Therefore, the environmental impacts of the use phase are dominated by SO2 emissions and other gaseous emissions with a global warming potential, resulting in an overall result that is dominated to about 65% from the human health

**Fig. 7** – Environmental impacts of the production of the various devices within the PC system (from (a) to (c)): desktop PC itself, the CRT and the LCD screen — all expressed with the method of Eco-Indicator’99.

**Fig. 8** – Environmental impacts of the various EoL scenarios, in comparison with the other life stages of the examined PC system — all expressed with the method of Eco-Indicator’99.
damage category — category that contains e.g. the various gaseous emissions to air (like SO₂, CO₂, NOₓ).

(iii) Within the manufacture step of a PC system, the desktop PC itself contributes the most to the total environmental impacts (about 21 EIP), followed by CRT and LCD screens (with 19 resp. 14 EIP) — while keyboard and mouse are of minor importance. Environmental impacts of the desktop PC are clearly dominated by the motherboard — accounting for 54% of the load of the complete desktop unit, or about 11.5 EIP. In the case of the two screens, the LCD module (60% of the impacts of an LCD screen) resp. the CRT tube (33% of the total impacts), are the dominating components of the respective device.

(iv) Within the EoL treatment phase, the environmental benefits from the “state-of-the-art” disposal are almost as high as the environmental impact in the worst case. Sound management of toxic substances during recycling process results in 75 to 80% decrease of impacts, and thus leads to an overall benefit for the EoL treatment.

Based on the findings mentioned above, the following recommendations are considered as priority areas for action for ensuring the long term sustainability to Chinese (or even international) policy makers. The most important environmental impacts arising from the PC products outside the EoL phase are directly related to the high levels of energy use. Thus, to promote the transition to environmentally friendly energy sources and to increase the energy efficiency within various stages will reduce the environmental impacts of a PC system. A second, more directly applicable approach could be the promotion of more environmentally friendly products (eco-design). Also there the strongest support should focus on reducing the overall energy consumption. Eco labeling, energy-consumption standards and green purchasing practices are only some examples. In addition, the present EoL treatment practices in China have to be drastically transformed. In order not to give away the potential which proper EoL treatment of electronics offers, inefficiencies of the existing system have to be eliminated. A comprehensive recycling system for EoL electronics, — comprising collection, dismantling, material and energy recovery, and sound disposal or destruction of hazardous components — is inevitable.

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