LCA Case Studies

Life Cycle Assessment of a Personal Computer and its Effective Recycling Rate

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Abstract

Background, Aims and Scope. Telecommunication and information technology, dramatically emerged during the last decade, has generated environmental problems by accelerating mass production, mass consumption, and mass disposal of personal computers (PCs) in Korea. In addition, it has led the Korean new economy. The Korean government has encouraged researchers and industry to study the environmental impact, adequate disposal treatment, and the reasonable recycling rate of an end-of-life personal computer. The main purpose of this research is to investigate the life cycle environmental impact of PCs and to determine the desirable or feasible recycle rate of an end-of-life PC. An LCA on a PC was performed based on different recycling scenario. Target audiences are new product developers, designers, product recovery managers and environmental policy makers who are interested in the environmental impact of PCs and recycling of end-of-life products.

Methods. A target product is a Pentium IV personal computer made in Korea in 2001, excluding the monitor and peripheral equipment. The procedure of the LCA followed the ISO14040 series. System boundary includes the entire life cycle of the product, including pre-manufacturing (the electrical parts and components manufacturing), manufacturing, transportation, use, and disposal. The LCI and impact assessment database for a PC was constructed using SIMAPRO version 4.0 software and LCI information was compiled by site-specific data and the Korean national database. The LCA was performed on different recycling scenarios: one being that of the current recycling rate of 46%, and the other being the ideal condition of a 100% recycling rate.

Results and Discussion. Abiotic depletion, global warming, ecotoxicity, human toxicity, acidification, ozone layer depletion, photo-oxidant formation, and eutrophication are adopted as the impact categories. The pre-manufacturing stage was a significant stage for all of the environmental parameters, besides human toxicity potential. PC manufacturing consists of rather simple processes such as assembly and packaging. For improving the environmental performance of PCs, environmental management approaches of design for the environment and green procurement are recommended. The use stage had a significant potential due to the electricity consumption produced by burning fossil fuel. The disposal stage's contribution to environmental impact was largest in human toxicity, and second largest in ozone layer depletion potential. The PC recycling was shown to inhibit all environmental impacts with the exception of the ozone depletion and ecotoxicity potential. The increase of light oil, nitric acid, sulfuric acid, and deoxidating agent consumption during the recycling process contributes to the environmental impact of ozone and ecotoxicity parameters. Current recovery and recycling technologies should be taken into account for enhancing the benefits of recycling. Anyway, the effectiveness of recycling was highlighted by this study. PC recycling reduces the total environmental impact of the product. The PC recycling is recommended to be raised up to at least 63% in order to reduce the environmental burdens of a PC in other life cycle stages.

Conclusion and Recommendation. This study implies that design for the environment (DfE) in the product design stage and green procurement are recommended for improving the entire environmental performance of electronic equipment such as PCs. The recycling of waste PCs clearly reduces the environmental burden. There are, however, trade-offs among environmental parameters according to the PC recycling rate. Current recycling methods are not effective in reducing ozone depletion and ecotoxicity environmental impact. The product recovery is another key for efficient recycling. Efficient reverse logistics to collect and transport end-of-life PCs should be taken into account to enhance recycling effects. There were several electrical parts not included in this assessment, due to the unavailability of adequate data. Further studies with more detail and reliable inventories for electrical parts and sub-components are recommended. Furthermore, costs of recycling should also be treated in further research.

Keywords: Computer industry; design for the environment (DfE); end-of-life management; Korean national database; recycling rate

Introduction

As environmental awareness has proliferated across the globe, companies have become increasingly aware of the environmental impacts of their products. Various environmental regulations, which target products directly, are being integrated into new EU policy, such as the integrated product policy (IPP) [1]. Companies have turned their attention to a life-cycle approach in an attempt to understand the entire environmental impact of a given product. Life cycle assessment (LCA) has its own analytical metric or assessment technology. It does not, however, generally link environmental impacts to concrete business decisions. Recently, the concept of design for the environment (DFE), based on LCA, has emerged as a comprehensive tool for environmental management. DFE is defined as the 'systematic consid-

eration of design performance with respect to environment, health and safety objectives over the full product and process life cycle' [2]. DFE should also incorporate the 'systematic consideration of design performance of X' factors: X representing any other objectives, such as higher manufacturability, assembly, disassembly, recyclability, and lower costs, to be true to the nature of business.

The revolution of telecommunications and information technology during the last decade has accelerated mass production, mass consumption, and mass disposal of personal computers (PCs) in Korea and across the globe. This dynamic change in the Korean economy has made the computer industry, its users, and the Korean government turn their attention to the environmental impact of PCs, especially as pertains to their mass disposal[1]. As the PC product life cycle grows shorter, environmental concerns regarding the disposal of end-of-life products, as well as the excessive energy consumption of a PC, are increasing. Including PCs, the electrical and electronic products have become targets of recent regulatory attention, such as the directive on the waste of electronic and electrical equipment (WEEE) [3]. DFE has been developed largely through the efforts of a handful of electric and electronics companies. DFE is rendered a complex and economically undesirable concept in some regards, due to the possibility of a trade-off between environmental performance and economic or quality performance. Furthermore, trade-offs among environmental issues, such as global warming, ozone depletion, human toxicity, and other environmental factors, further complicate matters. For example, one hundred percent recycling of waste equipment at the end-of-life stage is not always desirable in terms of LCA, if achieving it requires excessive corporate investment to improve product recyclability, or if doing so causes other unexpected environmental burdens.

The Korean government has encouraged academic researchers and industry to study the environmental impact, adequate disposal treatment methods, and the reasonable recycling rate of an end-of-life personal computer. The main purpose of this paper is to determine a desirable and feasible recycling rate of an end-of-life personal computer, considering its environmental impacts. For this purpose, we have performed an LCA on a PC, based on different recycling scenarios: one being that of the current recycling rate, and the other being the ideal condition of a 100% rate of recycling. This study is an attempt to answer the question of, "how do the entire environmental impacts of a personal computer differ depending on its degree of recyclability?" The target product is a four-year use Pentium IV personal computer made in Korea in 2001. The procedure of the LCA followed the ISO14040 series – goal and scope definition, life cycle inventory analysis, and life cycle impact assessment [4]. Based on the results of the LCA, this study found some interesting implications for the target audience, namely new product designers, product recovery managers, and environmental policy makers, as well as all those who are interested in the recycling and environmental impact of the personal computer.

[1] Waste computers numbered about 380,000 in Korea in 2001, and increase by 15% each year (The Hankyoreh, 14, January, 2001).

1 Life Cycle Assessment of a Personal Computer

A goal and scope definition, a phase generally pertaining to the main issues of goal, scope, functional unit, system boundaries, and data quality, is the first phase of a life cycle assessment [5]. In this section, the purpose of applying the LCA is to examine the environmental impact of a personal computer.

1.1. System boundaries

Adopting ISO 14041 guidelines and the suggestion of Lindfors et al. [6], we define the system boundary in a spatial, temporal, and technological context. System boundary includes the entire life cycle of a product, including pre-manufacturing (raw material production, the parts and components manufacture), manufacturing (assembly), transportation, use, and disposal (**Fig. 1**). PC manufacturing involves a rather simple process of assembly.

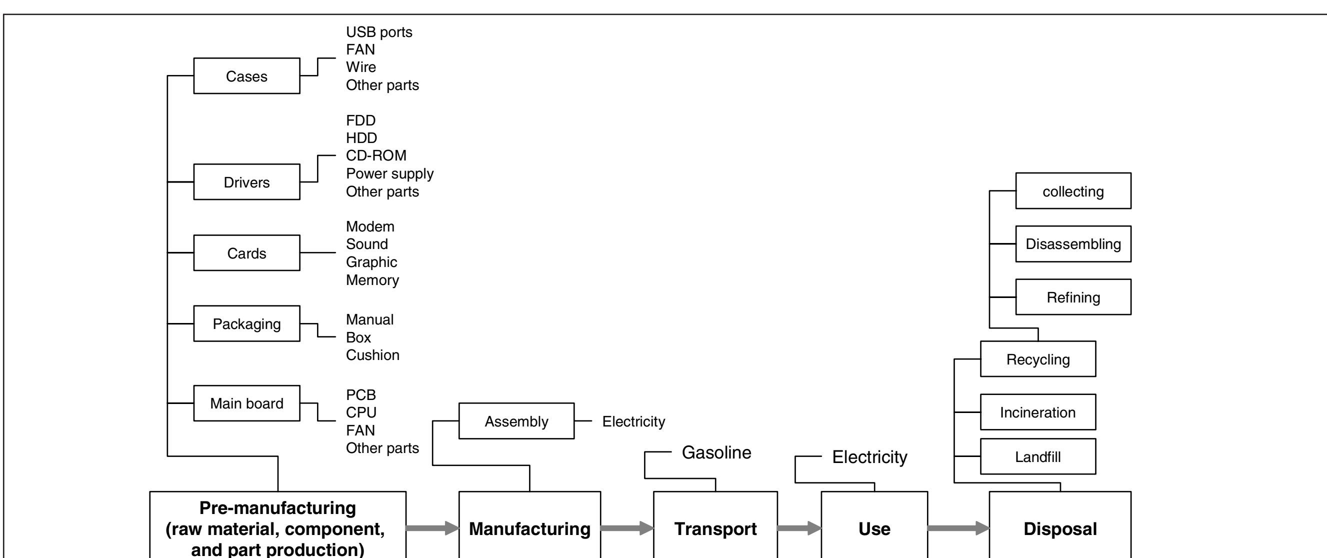

Fig. 1: Personal computer life cycle assessment structure

1.2 Functional unit

The target product is a Pentium IV type desktop PC. This model PC is manufactured by two leading companies that occupy over 66% of the Korean PC market share. A personal computer is defined as a device that computes. More specifically, a PC is defined here as a programmable electronic machine that performs high-speed mathematical or logical operations or that assembles, stores, correlates, or otherwise processes information. We excluded the display and peripheral equipment, such as the mouse, keyboard, and printer for the purposes of this study. The functional unit of the PC is defined as follows:

(a) Spatial context: a personal computer made, used, and disposed of in Korea.
(b) Temporal context: the life span of a PC, as suggested by authorities [2]2, is assumed to be four years.
(c) Technology: a desktop personal computer with Intel Pentium IV 1.7 GHz, 128MB RAM, hard disk drive (HDD), CD-ROM drive,[2] GB hard disk, power supply, 3.5" floppy disk drive (FDD), modem, and keyboard manufactured in Korea in 2001.

1.3 Data origins and LCI analysis

An LCI and Impact Assessment database for a PC was constructed using SIMAPRO version 4.0 software [8]. Briefly, the data required to construct a product LCI were retrieved from various supporting databases as follows:

(a) **Pre-manufacturing.** LCI information on the raw material used was compiled by the Korean national databases provided by the Korean Ministry of Environment (MOE) and the Korean Ministry of Commerce, Industry and Energy (MOCIE) [9–10]. Where data on raw materials were not available from the Korean national databases, the database of the SIMAPRO software was used. A PC consists of many electrical and electronic parts and components. The components of a PC, such as the main board or the hard disk driver (HDD), also comprise many sub-components and/or electrical parts. It is difficult to gather all information on all the parts and components from suppliers. We focused on compiling the LCI data on important components such as the PC case, power supply, HDD, compact disk read only memory (CD-ROM), video cards, and audio cards. However, in cases of poor or inaccessible site data, we used quasi-process information from commercial SIMAPRO software. Materials, electricity, and energy data on electrical parts and components were constructed using the Korean national databases and commercial SIMAPRO database. The LCI of a PC was retrieved from a total of 66 databases such as electricity, light oil, aluminum and cobalt. 29 databases were the Korean national databases and 37 databases were from SIMAPRO and other sources such as IDEMAT 96 and BUWAL 250.

(b) **PC manufacturing.** PC manufacturing is mainly composed of two major processes: assembling the electrical components, and packaging the PC. We used site-specific data regarding input, output, and utilities from two major PC manufacturers in Korea: Samsung Electronics Co., and TriGem Computer Co. We also used the Korean national database for electricity production data.

[2] Although four to six years are generally accepted as the expected life span of a PC in Korea [7], other opinions dispute this.

(c) **Transportation.** LCI data for transportation of the finished product between the manufacturer and domestic wholesalers or retailers was calculated based on 230km traveled by diesel engine trucks in Korea. This distance is the average distance from the two manufacturers to some significant delivery points. The primary transportation vehicle used is a 2.5 tonnage truck, which is capable of shipping 110 personal computers. Information on the transportation is adapted from the 2.5-ton truck database of the Korean national LCI database. This data is of a high quality, and is suitably representative of Korean averages.

(d) **PC use.** In this study, we considered two patterns of PC use. PCs are mainly used at home and at the office. A PC used at home is estimated to be operational for 10.2 hours, and idle for 3.2 hours per week in Korea. The cumulative consumption of electricity of a PC during its life span of 4 years is calculated approximately as 196.53kwh. A PC at the office is estimated to be used for 21.85 hours per week (12.9 hours in operating mode, and 8.95 hours in an idle state) [11]. The total consumption of electricity of an office PC for four years is estimated at 305.21kwh [7]. The Korean MOCIE database was used to estimate the electricity consumption of a PC.

(e) **Disposal or end-of-life PC.** We considered two scenarios for disposal of end-of-life PCs: landfill and recycling. PC recycling consists of four processes: collection, disassembly, pre-manipulation, and refinery processing. A waste PC, completely shredded at pre-manipulation stage, enters the refinery process as raw materials. We used site-specific data on the collection, disassembly, and pre-manipulation processes of a waste PC, which were provided by Korea Computer Recycling Inc. in Korea. Information on the refinery process was retrieved from the Korean MOCIE database. The volume of waste PCs is estimated at over 380 thousand. About 46% of a PC is recycled as raw materials, such as plastics, aluminum, steel, and other materials. 54% of a PC becomes landfill in Korea [7]. Consequently, we estimated the current recycling rate of a PC in Korea at 46%.

1.4 Assumptions and limitations

PCs are generally manufactured using an original equipment manufacturing (OEM) method. PC manufacturers are only involved in certain production processes, such as main board production, assembly, and packaging. A PC is composed of many electrical and electronic components and parts. The system boundaries for LCA on a PC must necessarily be extended when a researcher considers the entire life cycles of all components and parts. Due to limitations of time and cost, this LCA was performed under the following conditions:

- When site-specific data of sub-components or parts was not available, we adopted other similar databases from SimaPro4.0 [8] and the Korean national databases [9, 10].
- All data on electricity was obtained from the Korean national database [10].
- This study did not consider yield and scraps that may have emerged from electrical parts and PC manufacturing.
- We assumed components and parts as an elementary flow, where data on the input and output of materials was inaccessible.

- The assumed current recycling rate of waste PCs was estimated based on the recent study [7].
- All the components and parts were included in this study except a CPU (central processing unit) embedded in the main board. We collected material data of small electrical parts; however, process data of parts on the printed circuit boards such as resistors and capacitors were excluded due to inaccessibility to the data.

1.5 Allocation and impact categories

Allocation has been discussed thoroughly by Ekvall [12]. Allocation may be necessary when a process yields more than one product, i.e. a multifunctional process. Allocation should reflect the physical relationship between the environmental burdens imposed, and the functions delivered, by the System [13]. This study considered allocation in the production of packaging products (e.g. paper boxes), the mounting process, the assembly process of a PC and the steel frame, as well as the recycling process. Firstly, during the packaging process of a PC, cushions and paper boxes are produced at the same time. Secondly, several models of PCs and steel frames are assembled simultaneously during the same process. Data were allocated according to the portions of production volumes and weights of each model. Finally, several models of waste PCs, electronics scraps, and monitors enter the recycling process simultaneously. A skillful recycling expert allocated adequate values to a target PC model for the LCA. Classification and characterization following ISO14042 guidelines were applied to analyze the potential environmental impact of input and output from the LCI.

2 Results of the LCA and Implications for product design

The ecological effects of abiotic depletion (ADP), global warming (GWP), ecotoxicity (ET), human toxicity (HT), acidification (Acid), depletion of the stratospheric zone (ODP), photo-oxidant formation (POCP), and eutrophication (Eut) are adopted as the impact categories. We followed the Korean national guideline [14], when we selected the list of impact categories and assessment methods. **Fig. 2** shows the characterized results of PC production, use, and disposal, which illustrate the contribution of each process to the impact categories.

Intensive material and energy consumption of PC use, as well as pre-manufacturing were major contributing factors of abiotic depletion, global warming, eutrophication, and acidification potential. Most of the material use analysis concentrated on the pre-manufacturing stage, including production of a printed circuit board, cases, and several types of drives, cards, and small electronic parts. Use stage had a significant potential environmental impact as the electricity consumed was produced by burning fossil fuel. However, the recycling of PCs during disposal stage was shown to have a tendency to inhibit the abiotic material depletion potential of a PC. In terms of photo-oxidant formation potential, over 95% of the environmental impact was created during the pre-manufacturing process. The disposal stage's contribution to environmental impact was largest in human toxicity, and second largest in ozone layer depletion and ecotoxicity potential (following the pre-manufacturing stage).

(a) **The pre-manufacturing stage.** This stage was found be the largest contributor to all environmental impact categories, except for human toxicity potential. The manufacturing of small electric parts and several electronic components during this stage requires a substantial amount of materials and energy, and emits substantial quantities of air pollution, waste water, and solid wastes. Fig. 1 identifies the electrical parts with a significant impact on the environmental parameters during the pre-manufacturing stage. The main board was crucial for most of the environmental parameters, with the exception of ozone depletion potential. The main board comprises a printed circuit board (PCB) and

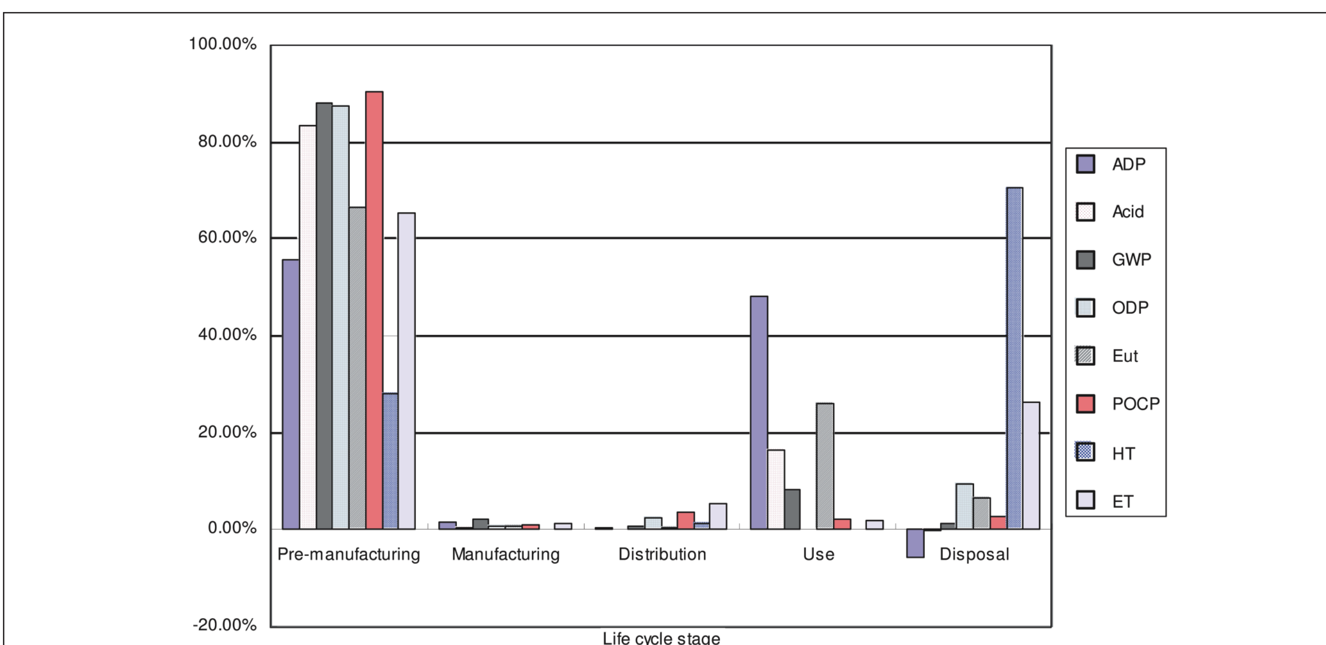

Fig. 2: Environmental impact assessment result for a personal computer

small electrical parts such as resistors, condensers, and connectors. Manufacturing of the hundreds of electrical parts within the main board is the prevalent contributor to the global warming potential of a PC during pre-manufacture, because much of the global greenhouse gases, such as CO_2 and CH_4, were emitted during this stage. The computer case was also critical to global warming, primarily due to the presence of acrylonitrile butadiene styrene (ABS) in the steel and plastic materials used. For eutrophication, the main board and the power supply were most significant, owing to the emission of NO_x, ammonia, and Tot-N during electrical part manufacturing and PCB. CO emissions from the production of electronic parts, and sulfuric acid and compounds emitted during PCB manufacturing, contributed most significantly to the POCP environmental potential. In terms of acidification, Pb-soldering PCBs and small electrical parts of the main board, power supply, and CD-ROM were significant contributors. The ABS of the plastic frame of the PC case, cushions, and paper boxes used for packaging products, had a significant impact on the ozone depletion potential of a PC. Packaging severely contributed to the human toxicity potential. Polycyclic aromatic hydrocarbons (PAHs), Ni, and benzene emissions from paper and cushion production represented over 92% of the total contribution of packaging to human toxicity potential. Potato farina used in the process of cushion manufacturing, and Atrzine, (a kind of herbicide used in the agricultural process of growing potatoes), also had an influence on human toxicity. The critical factors contributing to ecotoxicity potential were: air and water emission substances, such as Cu, Se, Hg, fluoroanthene, and Ni during the electrical parts manufacturing; As and oil emitted during PCB manufacturing and; Cd in wastewater from polyvinyl chloride (PVC) manufacturing.

(**b**) **Manufacturing and transportation stage.** Most environmental impact categories were not greatly influenced by processes during these two stages. PC manufacturing is composed of two simple processes: assembly and packaging. These activities require little electricity, and emit little air pollutants, wastewater, or solid waste. Information on the transportation stage from raw material to pre-manufacturing was insufficient to analyze. However, we might assume that the low environmental impact of transportation would not be changed by additional transportation data in this analysis on the Korean domestic market.

(**c**) **Use stage.** From the results of the LCA, we understood the use stage to be the greatest contributor to environmental impact after the pre-manufacturing stage. Consumption of electricity during the use stage contributed significantly to ADP, Eut, Acid, and GWP, substantially because the electricity consumed was produced by fossil fuels. In this study, we considered two types of consumer behaviors: home type and office type. Office type PC use was found to have at least 50% more influence on environmental impact potential than home type PC use.

(**d**) **Disposal stage.** This stage was found to be a major factor in human toxicity potential. This stage also greatly contributed to the ecotoxicity potential, second only to the pre-manufacturing stage. The disposal stage included collection, disassembly, refinery processes for recycling, and incineration or landfill. Of these processes, landfill may be the most substantial factor leading to human toxicity. For example, metals leak from landfill sites to the natural environment. And ecotoxicity is due to the consumption of several chemicals during the refinery process. PC recycling has a negative, as well as, positive influence on environmental impact potential. Light oil used in the collection process of waste PCs, as well as the nitric acid, sulfuric acid, hydrochloric acid and deoxidating agent consumption in the refinery process were significant causes of human toxicity and ecotoxicity. Nevertheless, PC recycling inhibits the life cycle environmental burden - especially the abiotic depletion potential. CO_2 emissions and recovered energy from the incineration process were not considered in this study. Including these factors may also vary the results of the PC recycling environmental impact potential.

Based on the results of the LCA for a personal computer, several methods were found to reduce the environmental burden of PC products. Although there are several guidelines pertaining to life cycle stages, PC manufacturers might not, for commercial reasons, be able to consider all the recommendations. The pre-production stage was found to be the most significant factor for most of the environmental parameters. However, PC producers cannot affect the operations of all their electrical part suppliers. Some suppliers, such as those of CPUs, or memory manufacturers, are much larger organizations than Korean PC manufacturers. It is beyond a PC maker's decision-making capabilities to change the materials used in the production of the PCB or CPU, in order to enhance the environmental friendliness of a PC. We might suggest, however, some alternatives for a more environmentally friendly PC design, which a PC manufacturer can influence (**Table 1**).

One of our recommendations above is for greater emphasis on environmentally geared supply chain management. This includes green procurement, which may induce suppliers to improve the environmental aspects of production during the pre-manufacturing stage. Through more stringent procurement guidelines, PC manufacturers should assist their suppliers in the substitution of environmentally friendly materials for the hazardous materials, such as Pb, PVC, Se, Hg, and Cd, currently prominent during electrical part production. Pb-free soldering would reduce the potential of acidification. PVC, Se, Hg, and Cd -free products and processes greatly reduce ecotoxicity potential. A new trend of PC design, pursuing slimmer and lighter PCs, should persist. The diminishing average size of PCs and their related components has a positive influence on all environmental parameters, through the reduction of material consumption. To lower the potential of global warming, eutrophication, and acidification, the design of PCs should focus on lowering electrical power consumption during the usage stage. A 10% power consumption reduction would result in a 7% decrease of global warming and resource depletion potentials in this study. A hibernation mode has already been introduced in recent PC models. Other advanced technologies, which enable individual components, as well as the PC as a whole, to hibernate when not in operational mode, are under development. Resource depletion is certainly curtailed by increasing the recycling rate of end-of-life PCs. The impacts of PC recycling on other environmental parameters are presented in the following section.

Table 1: Implications for an environmentally friendlier PC

Life cycle stage	Environmental impact	Design guidelines	Related Environmental Management
Pre-manufacturing	Many small electronic parts, PCB in the main board, and power supply (Pb-solder, NO_x, Co, Cu, Se, Hg, and Ni emission) ABS in plastic chassis PVC parts (Cd, waste water)	Diminishing product size Reducing hazardous materials in parts and materials Lead-free soldering PCB	Green procurement
Production	Low impact		Clean production
Transportation	Low impact		
Use	Electricity consumption (fossil fuel)	Reducing power Consumption	Design for the environment
Disposal	Collection and transportation (fossil oil) Refinery (nitric, sulfuric, hydrochloric acid)	Enhancing recycling	Product recovery Design for recycling

3 The environmental impact of recycling end-of-life PCs

The LCA illustrated that the recycling of end-of-life PCs has helped reduce the environmental impacts of resource depletion and acidification. The influence of recycling on other environmental parameters, however, remained unanswered. In this section, we have examined the impact of PC recycling in detail, and described how the environmental impacts vary, depending on the rate of recycling.

The current recycling rate of end-of-life PCs was estimated at 46%. A comparative LCA for a PC was performed under the scenario that 100% of end-of-life PCs were collected and completely recycled as raw materials. We assumed all other conditions unchanged. **Table 2** illustrates how the environmental parameters changed, depending on the PC recycling rate at the disposal stage. With the exception of the ozone depletion and ecotoxicity parameter potential, PC recycling was shown to inhibit the environmental impacts of resource depletion, acidification, global warming, and other environmental parameters. Interestingly, current recycling methods and technologies were shown to actually contribute to rising environmental impacts of ozone depletion and ecotoxicity, under a 100% recycling rate. The increase of light oil consumption during the collection of waste-PCs, and the transportation of these PCs to recycling plants were found to be the primary causes of enhanced environmental burdens. Additionally, the consumption of nitric acid, sulfuric acid, chloride, hydrochloric acid, and deoxidating agents during the refinery process for extracting raw materials from waste-PCs also greatly contributes to ozone depletion and the ecotoxicity potential. The results suggest a newer approach to recycling – one that takes into account the changing of recycling technologies, rather than merely raising the recovery and recycling rates.

Using the LCA results for different recycling scenario in the disposal stage, we found a linear relationship between environmental impacts and the recycling rate. At a recycling rate over 18.5%, ADP potential at the disposal stage can offset the environmental burdens in other stages. In other words, ADP potential at the disposal stage falls into sub-zero ranges as the rate of PC recycling increases. PC makers are able to reduce global warming and POCP potential by enhancing their efforts to encourage PC recycling. For eutrophication and human toxicity, however, increasing the rate of recycling will have little affect on a PC's life cycle environmental burdens if other recovery and refinery methods and technologies remain constant. However, from an LCA perspective, it is clear that the recycling of end-of-life PCs is a sound method to improve the environmental performance of personal computers. PC manufacturers are recommended to try to increase the recycling rate of PCs to at least 63%, at which point the total environmental impact of PCs will begin to decline. Regardless of the various trade-offs among environmental potentials, the recycling of waste PCs necessarily lessens the overall environmental impact of the product, as summed by normalizing and weighting each parameter (**Table 3**).

Table 2: Comparative LCA result of disposal stage with different recycling rates

Impact category	Under current recycling rate (46%)	Under the scenario of 100% recycling
ADP	–0.00330	–0.00984
Acid	–0.32800	–8.41000
GWP	66.70000	–170.00000
ODP	0.00047	0.00115
Eut.	0.37900	0.32500
POCP	0.04160	–0.32200
HT	0.79800	0.15200
ET	0.00721	0.01360
Total impact[a]	**0.01028**	**–0.02254**

[a] The figures were calculated by normalizing and weighting all the environmental parameters, using a method suggested by the Korea Accreditation Board [14].

Table 3: Linear function of potentials of disposal stage depending on the recycling rate[a]

f (X)	=	a	+	b * X	Even point of recycling rate
ADP	=	0.00223	+	(–0.00012)* R	> 18.5%
Acid	=	6.55667	+	(–0.14967) * R	> 43.5%
GWP	=	268.33333	+	(–4.38333) * R	> 61.2%
ODP	=	-0.00010	+	1.25185E-05 * R	< 8.13%
Eut.	=	0.42500	+	(–0.00100) * R	infeasible (425%)
POCP	=	0.35133	+	(–0.00673) * R	> 52.2%
HT	=	1.34830	+	(–0.01196) * R	infeasible (112%)
ET	=	0.00177	+	0.00012 * R	< 14.9%
Total	=	0.03823	+	(–0.00061) * R	> 62.9%

f (X): environmental potentials as dependent variables
X: recycling rate of end-of-life PCs as the independent variable

[a] For convenient analysis, we assumed that there was a linear relationship between environmental impact and recycling for convenient calculation; Y = a + b * X , here Y represents the environmental potentials, and X stands for the recycling rate. Using the comparative LCA result shown in Table 2, we could derive coefficients, 'a' and 'b'. For instance, the coefficient 'b' of ADP was derived from the equation of (–0.00984 + 0.00310) / (100–46)

4 Conclusions

As the digital economy grows, driven by information and telecommunication technologies, end-of-life electric and electronic products are increasingly cast in the spotlight of environmental impact. Personal computers are one of these concerning products. This study began with some questions regarding life cycle assessment and the recycling of a personal computer: is the recycling of an end-of-life product desirable in terms of all environmental potentials? Is there a feasible and effective recycling rate to which we might aspire? And, what points should be kept in mind during PC design for an environmentally friendlier product? Using life cycle assessment, we analyzed the environmental impact of the personal computer, obtaining meaningful findings on design for the environment and on recycling. We found that the lower the rate of recycling, the greater was the environmental burden of PCs.

This study illustrated clearly that the pre-manufacturing stage was a significant stage for all of the environmental parameters, with the exception of human toxicity potential. For acidification, global warming, ozone depletion, and POCP, the environmental impacts of this stage were about 90% of the total impact of the PC. Transportation and PC production were not critical in terms of environmental impact. PC production primarily consists of assembly and packaging processes. This indicates that environmental management approaches, such as designs with environmental considerations, and green procurement, are critical for improving the environmental performance of PC products. In terms of resource depletion potential, the use stage is the most influential, due to the consumption of electricity (generated by fossil fuels). The disposal stage mostly contributed to human and ecotoxicity potential.

Secondly, the effectiveness of recycling was highlighted by this study. It is widely known that incineration and landfill treatments of end-of-life products are harmful for the environment. PC recycling reduces the total environmental impact of the product. The PC recycling rate is recommended to be raised by at least 63% in order to have a genuine impact on the reduction of the environmental burden of personal computers. Increased recycling rates, however, would not reduce ozone depletion or ecotoxicity potential, owing to the consumption of chemicals and electricity during the recycling process. The change of current refinery technologies is required to enhance the benefits of recycling. In reality, product recovery is a key for efficient recycling. PC manufacturers hesitate to recover end-of-life PCs due to the excessive costs. This is seen in spite of the inevitable trends of extended producer responsibility (EPR) in Korea. Efficient reverse logistics to collect waste-PCs and transport them to recycling plants need to be considered in order to raise the recycling rate. In the beginning stage of the EPR, the government should encourage PC manufacturers' recovery efforts with both financial and non-financial support techniques.

Finally, this study suggested some design guidelines for a better environmental performance of PCs. Hazardous materials should be removed from both products and parts. PC manufacturers are recommended to induce their suppliers to reduce the consumption of chemicals in the production of electric parts and components. During the use stage, the consumption of electricity is significant for some environmental parameters. Designers of PCs are recommended to focus on developing technology that reduces the consumption of electricity during PC usage.

It is difficult to conduct a full and rigorous life cycle assessment on a personal computer. A PC consists of many electrical and electronic parts and components. This study made an effort to access reliable data as quickly as possible on all the life cycle stages: pre-manufacturing, production, transportation, use, and disposal. Nevertheless, there was manufacturing process data of several small electrical parts not included in this assessment due to the unavailability of adequate data. Further studies with more detail and reliable inventories for electrical parts and sub-components are recommended. Recycling, which is crucial for the environment, is dependent on the product recovery infrastructure of the collecting, transporting, and recycling systems. To derive the greatest results from recycling, it is advisable to assess and enhance existing infrastructure and recycling technologies. Costs of recycling should also be treated in further research. Designing products with the environment in mind is likely to become more useful with the addition of analytical tools to find an optimal solution among the trade-offs of environmental aspect potential from life cycle assessment, the recycling rate of end-of-life PCs, and the costs of recycling.

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