Journal of Cleaner Production 156 (2017) 828–837

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Life cycle assessment study of an integrated desktop device -comparison of two information and communication technologies: Desktop computers versus all-in-ones

Karpagam Subramanian*, Winco K.C. Yung

Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong Special Administrative Region

A R T I C L E I N F O

Article history:
Received 25 January 2017
Received in revised form
10 April 2017
Accepted 14 April 2017
Available online 21 April 2017

Keywords:
Life cycle assessment
LCA
All-in-one PC
Desktop computer
Comparison
ELCA
Electronic products

A B S T R A C T

The All-in-one PC (APC), considered as a space saving wonder, represents one of the most recent developments within computer industry which has been replacing conventional desktop PCs at a rapid pace. This work presents the results of the first attempt to analyse the environmental implications of the APC by using Life cycle assessment (LCA). The APC manufacturers also market the eco-friendliness of this product over the conventional desktops considering the fact that all electronic components are in-built into a single monitor and hence is supposed to reduce the energy and material consumption. This hypothesis of whether APC is a model developed to reduce environmental impacts compared to a conventional desktop PC is also tested. In order to conduct the LCA study, hand disassembly was carried out to identify the composition of the APC and Eco invent V2.2 database in-built in the SIMAPRO 7 libraries was used for modeling the product systems. The environmental profile of the APC was dominated by the use stage, followed by the production phase. Within the use phase, home use of the APC in sleep/standby mode was dominant in creating impacts. It is clear that if increased usage in sleep mode is assumed, environmental impacts are observed to be much higher than in the active mode besides the higher energy efficiency of the APC in the sleep/standby mode. Taking into account all the assumptions made in this work, the comparison shows a clear reduction in the environmental impacts created by the APC both in the use and the production phase as against the conventional desktop computers. However to enable much effective comparisons, detailed information on the composition of the involved products must be accessible.

1. Introduction

Electronic products are the real rulers of this world (Balaji Arumugam and Ganesan, 2014). With technology driving people and the planet at an unimaginable pace, and every company or brand trying to outperform the others, we find so many new innovative consumer electronic products in the market every day. All-in-one desktop otherwise called as All-in-one personal computers (APC) or integrated desktops is one such user-friendly version of desktop PCs. Personal computer (PC) has become very popular globally since early 90s. After three decades, we can see such rapid growth and development within this product category. Central processing Units (CPUs), keypads and mouse are no longer essentials to use a computer; we still can work on desktops without any of these at a faster or equal pace like before. The integrated desktop or commonly known as All-in-one PCs have become a household name in recent years. The desktop sales have come down tremendously because of this All-in-one PC segment. This is due to the ability of an All-in-one PC to be used in a kitchen, bedroom or a living room without much hindrance to the surroundings, especially in households with young children; the hassles of handling a huge CPU and keypads can be avoided while using All-in-one PCs (www.compreviews.about.com). And with the newly updated touch screen models, All-in-one PCs are definitely grabbing more attention from both industry and the consumers.

An All-in-one PC integrates all the computer components into a single case called display. The less number of cables needed for use, less heat generating components and lower power requirement are added advantages of All-in-one PCs (www.compreviews.about.com). An All-in-one PC without any

* Corresponding author.
E-mail address: 4u.karpagam@gmail.com (K. Subramanian).

http://dx.doi.org/10.1016/j.jclepro.2017.04.089
0959-6526/

additional devices is supposed to create less environmental implications than conventional desktops that incorporate a separate CPU/tower. In this work, this hypothesis was investigated and quantified considering the life cycle of the products. The environmental implications of the two Information and communication technology (ICT) options are examined using the well-established Life cycle assessment tool (LCA) tool.

1.1. Literature review

To assist industry people to design and develop eco-friendly products and help consumers in their buying decision, systematic analysis tools have been developed. These include LCA or Environmental LCA (ELCA) - for assessing the environmental profile of products. The application of this tool ELCA within electronics started way back in early nineties and is now well-established within the electronics industry (Rhodes, 1993). It has a wide array of applications within consumer electronics products especially ICT devices, the major commonalities and conclusions derived from the existing desktop and laptop related LCA studies in the literature are presented by Subramanian in their work (Subramanian and Yung, 2016). This tool is used in this present work to evaluate the environmental profile of an All-in-one PC and determine whether it an eco-friendly alternative when compared to the conventional desktops.

From an environmental point of view, different kinds of desktops and laptops were all evaluated using conventional LCA techniques to assess environmental impacts or carbon footprint more specifically, using secondary data sources in most cases (Subramanian and Yung, 2016). A Chinese desktop PC was evaluated for its environmental implications; results show that manufacturing and use are the dominant phases (Duan et al., 2009). A Korean PC was examined for its environmental implications using LCA and it was confirmed that recycling of waste PCs clearly reduces environmental loads created by the product (Choi et al., 2004). A desktop PC with 17inch CRT screen was evaluated using hybrid LCA methodology combining process and economic input and output; results showed that computer manufacture is very energy intensive and considering the kind of production rates, it definitely is responsible for a huge annual life cycle energy burden (Williams, 2004a, 2004b). The environmental impacts of a color computer monitor (Seungdo Kim, 2001); notebooks (laptops) in Taiwan (Lu et al., 2006) were both evaluated using LCA; a 2001 Dell Inspiron 2500 was evaluated for its energy use and carbon emissions using hybrid LCA methodology (Deng et al., 2011). A DELL laptop was also evaluated for its product carbon footprint and results were elaborated (Stutz, 2010).

Regional analysis was carried for a group of ICT devices, desktops, office computing systems in some studies. The operational electricity use and carbon emissions relating to ICT products in Sweden, activities like data centers, data transport networks etc that were not studied in previous studies were analysed in this work, PCs were found to be mainly responsible for carbon emissions followed by data centers and then access networks (Malmodin et al., 2014; Malmodin et al., 2010). The significance of geographical factor and uneven distribution of energy consumption during the different life cycle phases of ICT products was illustrated using spatial environmental balance using LCA (Daiyue et al., 2015). Environmental impact assessment of IT/IS solutions with a possibility of defining functional units and build inventory models (Stiel and Teuteberg, 2014) using flow based LCA method. The increasing number of electronic devices in households and its consequences was examined, and whether the newly added products like tablets are really energy efficient options or these just increases the energy consumption due to increase in the number of devices in individual households in recent years was evaluated (Patric and Wager, 2015a, 2015b).

A few environmental studies have compared two competing computer display technologies (CRT and LCD) using ELCA (Maria Leet Socolof, 1999; Noon et al., 2011; Song et al., 2012; Zhou and Schoenung, 2007). It was majorly concluded that LCD monitor disposal has lesser ecoimpacts when compared to CRT (Subramanian and Yung, 2016). Carbon emissions of a range of ICT products was carried out and found the emissions increase with the increase in mass of the product (Kandlikar, 2012), in another study a thin client computing solution was compared to a desktop PC considering carbon emissions only (Maga et al., 2012). Environmental impacts of print media and electronic media were individually evaluated and then compared against each other for its environmental implications (Hischier et al., 2014).

Overall, most of desktop/laptop related studies concluded that, production phase followed by use phase is the dominant one in creating impacts except a few ones in which production phase dominates the use phase; use phase is impacted due to operational energy; Ecommerce when used creates lesser impacts and transportation phase hardly created any major impacts (Subramanian and Yung, 2016). Printed circuit boards and integrated circuits are the dominant modules in desktops that are criticized for creating huge environmental impacts within the manufacturing phase (Kandlikar, 2012).

1.2. Research motivation

From the literature review it is clear that numerous ICT devices have been individually analysed and in some cases compared against each other for their environmental implications using LCA. However, concerning the recently developed All-in-one PC segment no detailed environmental studies are known. The question as to the All-in-one PC's overall environmental performance, especially as compared with the conventional desktops has so far remained open. It has to be taken into account that ICT devices especially computer related products have considerable impacts on the environment. This impact is due to the fast changing technological advancements made in this product category which results in increase in number of devices produced. Production phase is concluded as most dominant phase in terms of creating environmental impacts in many studies (Kandlikar, 2012; Subramanian and Yung, 2016). Moreover, ICT devices can have indirect impacts on sustainable production (supply chains involved in the production of these products), usage pattern and buying decisions of consumers. The end of life of this product category is also very dangerous, as this type of products result in the most complicated waste stream and tackling them is a rapidly growing problem worldwide. Hence researchers and industrialists have become very interested in this field.

Hence this work attempts to evaluate an All-in-one PC for its environmental implications, it is hoped that such initial attempt to evaluate new technologies will contribute to the body of knowledge within the research needs in this sector (ICT) by identifying key problematic areas in the production level and usage patterns that influence environmental impacts. It is to be noted that, two ICT solutions have been previously compared using LCA (Maga et al., 2012), but the focus has mostly been on global warming potential, hence an LCA study enabling a comparison of ICT solutions considering all impact categories is essential. More so, since this product (APC) is rapidly diminishing the sales of conventional desktops, it is essential to understand whether this change is an environmentally friendly transition. Hence a comparison of an All-in-one PC and a normal desktop PC is carried at device level in this work.

1.3. Objectives

The objective of this paper is firstly to analyse an All-in-one PC for its environmental implications and secondly to compare an All-in-one PC (APC) with all integrated components and a conventional desktop PC (DPC) at device level using the LCA methodology following ISO standards. The corresponding results are presented and analysed. From the results, conclusions can be made on the environmental impacts generated by an All-in-one PC throughout its life cycle and most importantly understand whether this new and emerging All-in-one PCs segment has effectively contributed towards mitigating environmental impacts when compared to a conventional desktop PC. This kind of analysis and comparison is essential for the companies that develop these new technologies as well as for the consumers to make a wise buying decision considering the environmental profile of the product.

The rest of the paper is organized as follows: LCA methodology applied to evaluate APC is described in section 2, results of ELCA of APC is discussed in section 3, Interpretation of ELCA results of APC is carried out in section 4; section 5 presents the methods and results of comparison between APC and DPC and finally conclusions are presented in section 6.

2. Methodology

The following section presents the systems and methods applied to evaluate the All-in-one PC. The functional unit, system boundaries, necessary assumptions and the cut off criteria employed are described. All the above details related to comparing the 2 ICT solutions (APC vs DPC) are presented later in Sections 5.1 and 5.2.

2.1. Functional unit and system boundaries

The functional unit for the first part of the study is one HP Omni 120-2-28hk All-in-one PC, manufactured in 2011 in its end of life (EOL), to avoid wastage of a new product. The APC has a 20" LCD panel display. It weighed 6.08 kg. Integrated is an AMD fusion E450 (Zacate) Dual core processor soldered down on the WJ7 Quanta motherboard, 2 GB memory and 500 GB hard drive space. The APC provides 2 USB ports, 6-in-1 memory card reader and an optical disk drive. It also provides W-LAN and a webcam with array microphone. The flow chart for the product system of ELCA for the APC is presented in Fig. 1.

The ELCA of the APC covers its entire life cycle from cradle to grave, including raw material extraction, production of basic materials, pre-products, manufacturing of the end-product, transport, assembly, use and disposal. The components of APC are manufactured in different locations, assembled in China and finally used and disposed off in Hong Kong. Modeling of components like webcam, screws, wires and cables that weighed less than 5 g were excluded as data was not available and these tend to represent a very small share of impacts in the modeling. The informal recycling in China is excluded due to unavailability of data.

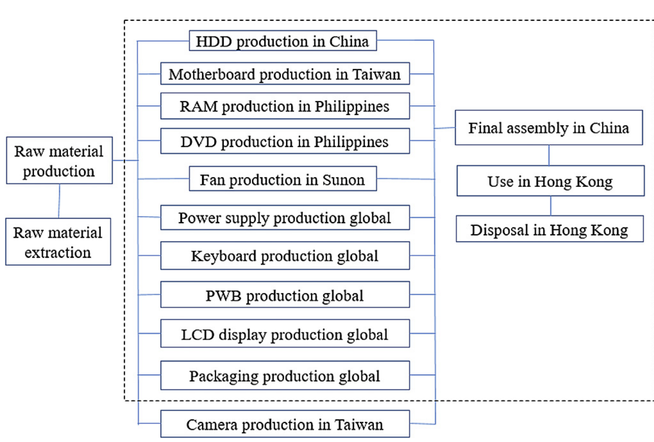

Fig. 1. Product system of ELCA for the APC.

2.2. Data collection, assumptions and quality

LCA is always considered as a data starved field especially when used for complex products like computers. Like all other LCA studies, data collection was difficult for our study also. Due to complete lack of information from the manufacturing companies producing this technology, we bought APC device at its end-of-life, the various components of the device and their respective weights were identified by dismantling this APC as the first step. In this step, to obtain product specific data a HP Omni 120-2-28hk All-in-one PC was dismantled into individual components like hard disk drive (HDD), Optical disk drive (ODD), Fan, Random access memory (RAM) and Main board (MB). In this way, a detailed composition of such a APC device was established and its material composition are summarized in Table 1. In the second step, information from literature sources (Ciroth and Franze, 2011; Deng et al., 2011; Lu et al., 2006; Stutz, 2010; Williams, 2004a) and company websites online (hp) was taken to further detail the composition of this APC device.

In the third and final step, the components and materials identified in this way and the various production processes involved were mapped/linked to the standard LCI database Eco invent v2.2. This database did not contain specific data for electronic modules of APC since it's a new technology, however datasets for electronic modules of desktop and laptop was available. APCs are said to have laptop lineage according to manufacturer information, with few models using notebook style AC adapters, downsized HDDs and ODDs (www.computerworld.com). In this way, the various components mentioned in Table 1 were modelled using laptop electronic modules data sets from the Eco invent. The electronic modules of a laptop in the eco-invent database were first adapted according to our data (weights obtained as a result of disassembly) and then linked. The amount (weight) and type of electronic components obtained as result of disassembly are linked to respective data/processes from Eco invent v2.2. For some components like HDD, ODD, keyboard and mouse the pre-modelled electronic module in Eco invent was used for the product system. Hence for these components, the exact weight could not be used, instead the selected module was a non-mass unit reference which could not be considered for waste/disposal scenarios, but treated as another process within the assembly stage. The key characteristics and assumptions used in this LCA study for various processes of the examined APC device are detailed below.

For the usage pattern, both home use and office use were modelled, since APC has equal usage behavior at homes as well. In this work, we have made an interesting assumption in the use phase. Largely people at home do not have the habit of switching off the computer systems, only the monitor is switched off unlike in office where even if people using it forget to switch off, workers/assistants switch it off as a part of their duty before closing for the day. Hence the office use was calculated with 8hrs/day for 5 days a week (2914 h in active mode, 1061 h standby mode, 8745 h off mode). While for home use, 6hrs/day for 7 days a week in active mode and the remaining 18hrs in standby/sleep mode was assumed. The calculation basis for the aggregated hours of use is outlined in Table 2.

Table 1
Composition of a HP Omni 120-2-28hk All-in-one PC.

Component	Weight	Material	Basic ecoinvent process
Motherboard	300 g		Printed wiring board, mounted, Laptop PC mainboard, Pb free, at plant/GLO U
HDD	584 g		HDD, laptop computer, at plant/GLO U
RAM	8 g		Integrated circuit, IC, memory type, at plant/GLO U
LCD Display	260 g		LCD module, at plant/GLO U
Computer case		ABS,PC, and aluminium	Acrylonitrile-butadiene-styrene copolymer, ABS, at plant/RER; polycarbonate, at plant/RER; Aluminum, primary, at plant/RER
Keyboard	610 g		Keyboard, standard version, at plant/GLO U
Mouse			Mouse device, optical, with cable, at plant/GLO U
ODD	186 g		CD-ROM/DVD-ROM drive, laptop computer, at plant/GLO U
Fan	86 g		Fan, at plant/GLO U
Product packaging			
External	1516 g; 94 g	Corrugated board, Kraft paper	Corrugated board, recycling fibre, single wall, at plant/RER U; Kraft paper bleached at plant/RER U; Polyethylene,
Internal	39 g	HDPE	HDPE, granulate, at plant/RER U

Note: Every activity in the Eco invent has a geographic location and are represented by internationally accepted shortcuts. Such shortcuts are used in Tables 1–4 to represent geographic locations. For e.g. GLO refers to Global, represents activities which are an average, valid for all countries in the world (www.ecoinvent.org) and U represents a unit process. Other geographic shortcuts used are listed in the Appendix.

Table 2
Calculation of use phase.

Mode	Total number of hours	Calculation details	Basic Eco invent Process
Office use	12720 h	8 h/day × 5 day/week × 53 weeks × 6 years	Use, computer, laptop, office use/RER
Active mode	2914 h	0.22917 h/1 h office use	Use, computer, laptop, active mode use/RER
Off mode	8745 h	0.6875 h/1 h office use	Use, computer, laptop, off mode use/RER
Standby/sleep mode	1061 h	0.083333 h/1 h office use	Use, computer, laptop, standby/sleep mode use/RER
Home Use	53424 h	24 h/day × 7 day/week × 53 weeks × 6 years	
Active mode	13356 h	6 h/day × 7 day/week × 53 weeks × 6 years	Use, computer, laptop, active mode use/RER
Standby/sleep mode	40068 h	18 h/day × 7 day/week × 53 weeks × 6 years	Use, computer, laptop, standby/sleep mode use/RER

For product packaging, information (weights in g) available on the HP product specifications, published online was used. Both external (consisting of corrugated board and kraft paper as the major material composition) and internal (included HDPE in the material composition) packaging were modelled. For the total lifespan of an APC the number of 6 years was assumed, followed by a state-of-the art WEEE recycling system (e.g. the one established in Switzerland). It was further assumed that the APC at its EOL is dismantled mechanically or manually at plants in China and then waste streams remaining after dismantling and sent to recycling systems were modelled that, 90% is landfilled and 10% is incinerated. The normal disposal route into the WEEE streams in China was assumed and modelled for keyboard and mouse as well. The EOL processes for the various materials are modelled as established in the WEEE data of Eco invent v2.2: 100% recycling of aluminum and steel parts; 100% incineration of capacitors; 100% cable recycling process; 100% to incineration of corrugated board including production of corrugated board paper from recycled fibre. The disposal scenarios modelled in this work and basic Eco invent process that were used are outlined in Table 3. Apart from the basic assumption that the relevant processes pre-modelled in Eco invent database were adapted according to the own data obtained as a result of disassembly, it was also assumed that all components are compliant with RoHS and contain lead free solders. Figs. 2 and 3 show the pictures of disassembly.

Fig. 2. Front case.

Data quality

Data quality is very essential for any LCA study, especially for a reasonable interpretation of results thereafter (Ciroth and Franze, 2011), more so for a product category like APC for which, this work represents the first full-fledged LCA study. ICT products and its components are continuously evolving and APC is no exception to this trend. Hence the laptop components modelled in the Eco invent dataset might be entirely different to the APC under study.

Table 3
Disposal scenarios.

Disposal Scenarios	Basic Eco invent Process
Disposal of laptop excluding battery (APC does not have batteries)	Dismantling, laptop, manually, at plant/CH U Dismantling, laptop, mechanically, at plant/GLO U
Key board	Disposal, keyboard, standard version, to WEEE treatment/CH U
Mouse	Disposal, mouse device, optical, with cable, to WEEE treatment/CH U

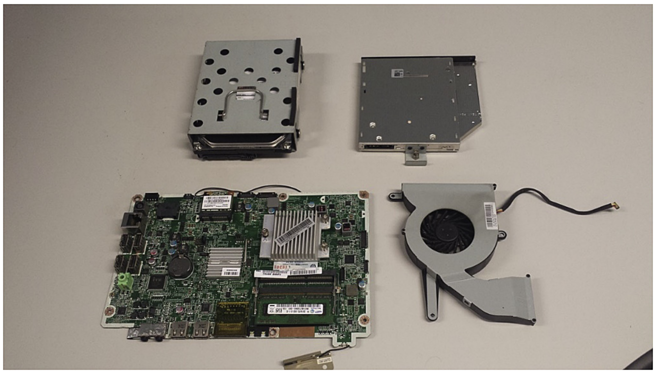

Fig. 3. Hard disk drive (HDD); Optical disk drive (ODD); Motherboard (MB) and Fan.

Hence in this work we dismantled the device for a reasonable adaptation of the foreground processes. In this way a more reasonable and suitable product system can be modelled to a satisfying degree. The process adaptations and assumptions are clearly documented. Minor data gaps such as components like screws, plastics, copper wires, cameras were excluded, assuming they will not majorly affect the results.

2.3. Environmental life cycle impact assessment

For calculation of the environmental impacts of the APC, the method ReCiPe was used. Recently ReCiPe is one of the most used Life cycle impact assessment method (LCIAM) and recommended by LCA experts (Ciroth and Franze, 2011). It contains a resource modeling which combines endpoint and midpoint approach. It is available in 3 versions: egalitarian (long-term), individualist (short term consideration of environmental impacts), hierarchist (combination of both). The hierarchist version which is the default version of the ReCiPe method was used in this work. Both midpoint and end-point categories were used as each has its own pros and cons. The midpoint categories are not so easy to understand for layman, where the results are more accurate with low uncertainties, whereas the endpoint results are easy to understand by the layman (non-LCA experts) but the uncertainty is high. Normalisation was applied for effective comparison and recommendations.

3. Results & discussion- environmental analysis of an All-in-one PC

The results obtained from the LCA study of the APC are presented in this section. The environmental analysis was carried out using the hierarchist version of the ReCiPe method. The mid-point assessment results are presented in section 3.1. and the end-point results are outlined in 3.2.

3.1. Midpoint assessment

For analysis of the characterization, the life cycle was divided into 4 stages: production, packaging, use (home and office), and disposal. The characterization results show that use phase clearly dominates the environmental load in all impact categories (Fig. 4) followed by production stage except the impact category of marine eutrophication. Almost all the impact categories are equally impacted (around 70% during the use phase and 30% during the production phase). Within the use phase, home use is more dominant especially in the sleep/standby mode. The reason could be modeling assumption that APCs are not switched off at home

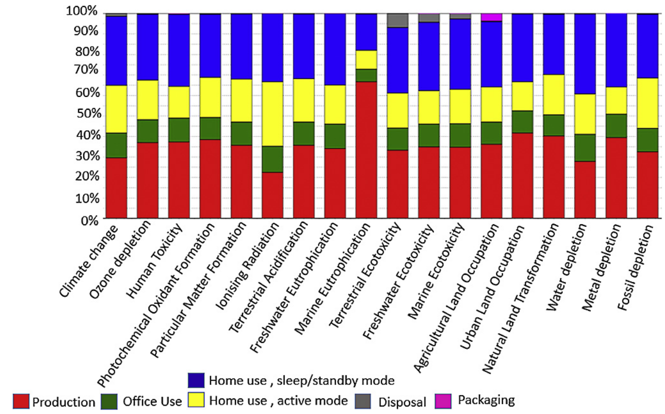

Fig. 4. Characterization results.

and in sleep mode for a longer time and consume energy. Also it can be due to less energy efficiency of the APC model. The packaging and disposal stages have hardly any impacts when compared to the use and production stage. However informal recycling was not considered for modeling; only a landfill and incineration scenarios were modelled due to lack of data. Marine eutrophication is the most impacted category in the production phase and Ionising radiation is the most impacted during the use phase, which is natural due to the exposure of humans to radiations during usage.

To identify the environmental hot-spots (key problematic areas), normalisation was applied. Normalisation is used to relate the impact assessment results to the environmental load of a region. Normalisation set "World ReCiPe H/H" was selected. Fig. 5 presents the normalisation results. Relevant impact categories considered in the product system are human toxicity, freshwater eutrophication, freshwater ecotoxicity, and marine ecotoxicity. Ionising radiation and metal depletion play a minor role. Furthermore, from Fig. 5 it can be seen that, use phase creates the most to environmental impacts. Production phase also is responsible for the environmental implication to some extent unlike the packaging and disposal phases of the product system which hardly have any impact. Human toxicity is the most impacted category during the use phase, indicating the harmful effects of computer usage on humans yet again in this work.

The 4 categories identified as relevant in causing major environmental impacts in the normalisation step were further analysed using the network function in the SimaPro software. Apart from the above, metal depletion category was further analysed, though its impacts are minor since the usage of rare metals in the production

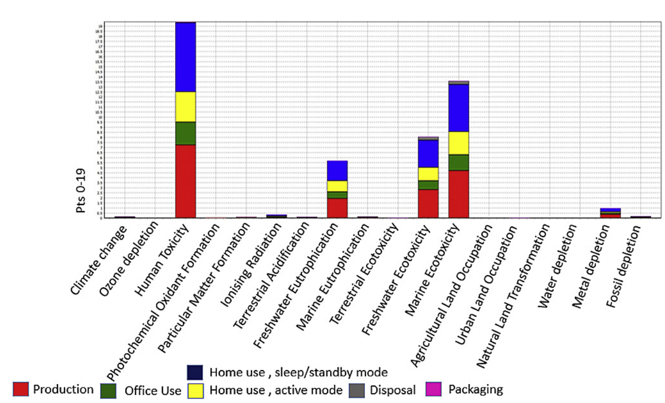

Fig. 5. Normalisation results.

of computer products is often being criticized for its environmental implications. The network display figures use different cut–offs to show the significant processes that mainly contribute to environmental impacts.

3.1.1. Human toxicity

The environmental impacts of the life cycle of APC on human toxicity shows that the mother board production and LCD module causes the major damage within the production of APC, the processes that contribute maximum come from primary gold refining which is used in integrated circuits. The disposal of their (gold and copper) tailings also created huge impacts. The contribution of packaging is very minor and that of disposal to human toxicity is under 5% and hence is not visible since the node cut-off is set as 10%.

Around 35% of the impacts caused by the use phase, is due to the use of APC in sleep/standby mode. It is unusual that impacts created in sleep/standby mode is more than active mode. The processes at the bottom of the network indicate that the reason for larger impacts in use phase is primarily due to the electricity consumption. Firstly, it can be a proof that people do not switch off their APC after use properly, consequently energy consumption increases the impacts. Secondly, the time for which an APC is in sleep/standby mode is definitely more than active mode. The increased energy efficiency of the computers in recent years can also be attributed as a reason for less impacts in the active mode.

3.1.2. Freshwater eutrophication

The environmental impacts of the life cycle of APC on freshwater eutrophication shows that, use of the APC (sleep/standby mode) contributes the maximum with 35.8%, while production contributes to 34%. The major contributor to the use phase when tracing backs at its effects is the lignite mining process for electricity production. The major impacts within the production phase comes from the production of printed wiring board which has its origin of impacts from the gold refining process. The disposal of its tailings is also the determining process in creating huge impacts within production.

3.1.3. Freshwater ecotoxicity

The environmental impacts of the life cycle of APC on freshwater ecotoxicity shows that the production of APC is responsible for around 35% of the impacts and use phase (sleep mode) contributes to 35% approx. The impact of production is mainly caused by the electronic modules, within which motherboard is the major contributor followed by LCD module for reasons similar to that of previous impact categories discussed. The standby/sleep mode dominates within use phase impacts with its origin in the electricity production. The analysis of the network diagram of marine ecotoxicity also gives a very similar result.

3.1.4. Metal depletion

The environmental impacts of the life cycle of APC on metal depletion shows that the production of APC contribute 40%. This is mainly caused by the gold, copper and tin solder used in integrated circuits and printed wiring boards which are the major subcomponents of LCD module, DVD drive and motherboard. In ReCiPe metal distribution is measured in monetary units unlike other IA methods that use MJ equivalents or MJ surplus (Ciroth and Franze, 2011).

3.2. Endpoint assessment

The damage assessment of the entire lifecycle of an APC for the 3 endpoint categories (human health, eco system and resources) is presented in Fig. 6. It indicates that use phase of the APC is the major contributor with an average of 65% followed by the production stage (35%). Home use of the APC in sleep/standby mode is the dominant contributor to environmental impacts within the use phase. Disposal and packaging hardly have any effects according to the single score results presented in Fig. 7.

Also it is evident from the normalized assessment of the endpoint categories (Fig. 8) that on an average human health is the most impacted endpoint category followed by resource depletion and then lastly ecosystem which plays a minor part according to this work. The normalized results in the mid-point perspective are also much similar (Fig. 5). Impacts like climate change, ozone depletion are of smaller importance, whereas impact categories related to humans like human toxicity and ionising radiation are identified as the most relevant impact categories.

3.3. End of life treatment

The EOL phase finally, as described above in the analysis does not cause any major impact, however the results are based on the assumptions used in the model which in turn was based on data availability and reliability. However a normal disposal route into the WEEE streams in China and 90% landfilling as well as 10% incineration after the manual dismantling of integrated desktop parts may not be the actual scenario. Also, currently the most relevant issue related to the electronic products in various forums is regarding the inclusion of material recycling and incineration in the EOL or disposal route of these products. HP (brand of the product analysed in this work) offers 2 kinds of recycling programs: prepaid postage and packaging for the products returned and chance to sell old technology back to HP for a new one. According to Greenpeace (2010), HP is also one of the companies that has moved towards greener products and processes. According to HP's sustainability report of 2015, 76% of materials are recycled into new products and 21% of materials are used for energy recovery (www.8hp.com). Having said all this, still the exact data related to the number APCs recycled is not available. Hence in this work, a few disposal scenarios are assumed, assessed using Recipe-endpoint (H) method in order to determine the worst disposal option. The four disposal routes investigated are:

- Scenario 1: 100% landfilling (All APC sent to landfill)
- Scenario 2: 75% incineration with energy recovery and 25% landfilling (75% of the APC go through incineration for energy recovery and remaining 25% are sent to landfill)
- Scenario 3: 75% recycling and 25% landfilling (75% of the APC get recycled for recovery of materials and precious metals and remaining 25% are sent to landfill)
- Scenario 4: 40% recycling and 60% landfilling (40% of the APC get recycled while remaining 60% are sent to landfill).

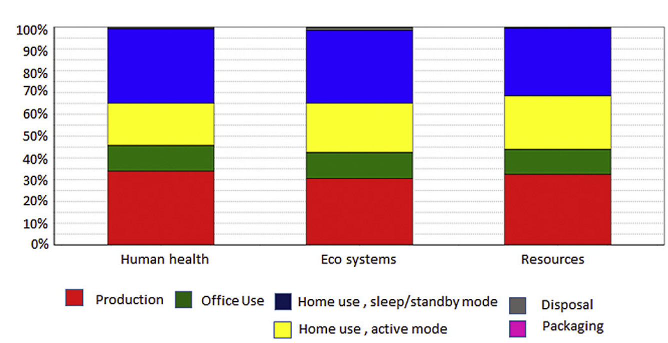

Fig. 6. Results of the damage assessment (in %).

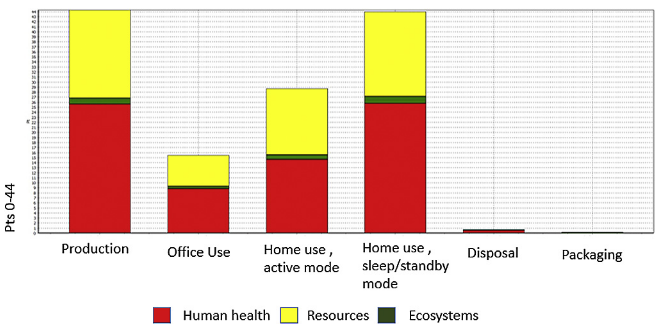

Fig. 7. Results of the endpoint assessment single score (in pts).

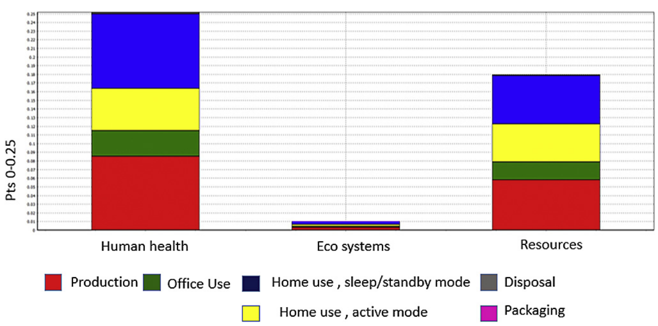

Fig. 8. Results of the normalized endpoint assessment.

The characterization results indicated that Scenario 2 (75% incineration with energy recovery and 25% landfilling) impacted most negatively in almost all categories, while the other scenarios showed slightly lesser contribution to the negative impacts with scenario 3 (75% recycling and 25% landfilling) being the least. When the results were translated to single score results, among the three areas of protection, human health is the most affected followed by ecosystem quality and resource depletion in that order. Going back to Fig. 4, it can be seen that impact categories photochemical oxidant formation, human toxicity and acidification were all not impacted by the disposal phase. The EOL modelled included a normal WEEE recycling in China and hence due to the avoided primary production of aluminium could reduce the negative impacts in case of human toxicity. Overall, scenario 2 is the most favored disposal route for APC which is a partial recycling route while incineration route is not quite a good disposal option. Overall, like in few other studies, it can be concluded that disposal phase does not contribute much to the negative environmental impacts in this work also, however can have benefits if a 100% efficient recycling system is employed.

4. Interpretation of ELCA results of APC

The environmental profile of the APC indicates that the home use of the system, particularly the sleep/standby mode clearly dominates the other phases. While use of APC at home the sleep mode plays a dominant role in creating impacts in the midpoint assessment, in the endpoint assessment, it is found that production also equally impacts the 3 end point categories similar to home use. Packaging and disposal have a rather low impact in the mid-point assessment and hardly any contribution in the end-point assessment. Like all other technologies, environmental profile of APC also reflects high impacts in the use and production phase. The major component that creates more impacts is the production of LCD module due to the subassemblies like integrated circuits and printed wiring boards. Hence the APC must be used as long as possible, since the production of electronic modules creates huge impacts. Also, the major source for high impacts in the use phase comes from not switching off the computer after use and the consequent energy consumption, which depends on the electricity production mix. When non-renewable sources are used for electricity production the impacts will be much higher, hence responsible usage behavior is recommended like turning off the APC completely when not in use.

4.1. Process contribution analysis

Various processes within these phases are the sources of these high impacts. Process contribution specifies the contribution of individual process in the entire life cycle. When the cut off is set as 1%, the processes that contribute more than 1% to the environmental impacts of the APC will be listed. The top 20 processes in that list with their corresponding contributions calculated based on the ReCiPe end-point assessment of an APC are listed below in Table 4. The processes listed below contribute to all the phases (production, use, packaging and disposal). However, contribution of certain process to a particular phase is more while the others are less. For e.g. most contributing process of disposal of sulphide tailings contributes more to production phase than use phase. Contribution of all these processes to the disposal and packaging phase is lesser or negligible compared to use and production phase. Contribution from processes 1, 8, 12 and 17 is more towards production phase and the remaining processes contribute more towards the use phase. The main impact comes from the mining activities and connected processes like disposal of sulphide tailings and hard coal, and production of energy carriers like crude oil within the production phase. Electricity consumption associated with use phase and the related processes contribute to high environmental impacts. Processes associated with production of energy carriers like natural gas, crude oil and hard coal burnt in power plants are all the major source of high impacts in the electricity production (average of over 5 pts). Overall, it can be seen that most of these processes listed are related to mining activities and electricity production.

5. Comparison of APC and DPC

5.1. Goal and scope, data and assumptions

The goal of the study is a device level comparison of the two ICT solutions (APC and DPC). The functional units are: a HP Omni 120-2-28hk All-in-one PC and a conventional desktop PC that weighs 14 kg and consists of desktop computer monitor, LCD flat screen, keyboard and the mouse. In order to compare the 2 ICT solutions, ELCA of the DPC was carried out using SIMAPRO 7 with eco invent v2.2 database according to ISO standards. The premodeled components/products in eco invent v2.2 database were used for modeling the 4 major components of a desktop PC. For the use phase, a similar calculation basis was used in order to enable comparison. Since all the electronic modules modelled for DPC are non-mass units, their waste/disposal scenario could not be considered, however could be treated as another process within the assembly stage. The waste scenarios were separately modelled and the related assumptions were similar to that of APC. The LCA results of DPC system is not presented since is not the primary focus of this work, only the results pertaining to comparison of the two ICT solutions are presented in the next section.

Table 4
Top 20 process contributions.

Rank	Process Name	Total (in pt)
1	Disposal, sulifidic tailings, off-site/GLO U	38.8
2	Lignite at mine/RER U	11.7
3	Natural gas at production onshore/RU U	5.91
4	Hard coal at mine/WEU U	5.24
5	Natural gas at production onshore/DZ U	5.08
6	Hard coal at mine/EEU U	4.91
7	Disposal, Spoil from lignite mining, in surface landfill/GLO U	4.6
8	Clinker, at plant/CH U	3.53
9	Crude oil at production onshore/RME U	3.09
10	Magnesium, at plant/RER U	2.99
11	Lignite burned in power plant/DE U	2.99
12	Hard coal at mine/CN U	2.97
13	Natural gas at production offshore/NO U	2.66
14	Natural gas at production onshore/NL U	2.65
15	Crude oil, at production offshore/NO U	2.48
16	Hard coal, burned in power plant/DE U	2.22
17	Crude oil at production onshore/RAF U	2.22
18	Hard coal at mine/ZA U	2.15
19	Crude oil at production onshore/RU U	2.07
20	Crude oil at production offshore/GB U	2.06

5.2. Comparison at device level

The comparative analysis of the two devices is carried out using the hierarchist version of the ReCiPe method. The mid-point assessment results are presented in section 5.2.1. and the end-point results are outlined in 5.2.2.

5.2.1. Midpoint assessment

The characterized mid-point assessment results of the comparison of the two ICT solutions (APC and DPC) at device level are presented in Fig. 9. The comparison in Fig. 9 shows that DPC model creates more impacts in all the impact categories (18) than the APC model. Ionising radiation is the impacted category which shows maximum deviation between the 2 solutions compared, followed by fossil depletion, climate change and ozone depletion. The explicit deviation in the impacts of production phase can be explained by the different data collection strategies employed. In the case of APC, dismantling of the device was done and the corresponding weights of the components were used to model the product. For the DPC, pre-modelled components in the Eco invent database were used. Normalized mid-point assessment also comes to a very similar result with DPC resulting in higher environmental impacts than the APC (Fig. 10). The relevant impact categories compared are human toxicity, freshwater eutrophication, freshwater ecotoxicity and marine ecotoxicity. Metal depletion and ionising radiation also play a minor role. According to the normalisation results, the most relevant impact category in the comparative analysis of APC and DPC is human toxicity.

5.2.2. Endpoint assessment

The normalized endpoint assessment also shows that DPC contributes more in terms of high environmental impacts (Fig. 11). Fossil depletion is the most impacted category followed by human toxicity and then climate change. Particulate formation and climate change ecosystems play a minor role. Similar to the midpoint perspective, the single score results of the end point assessment (Fig. 12) demonstrate that the DPC impacts the human health and resource depletion categories higher than the APC system. The damage on the ecosystem part is minor, though DPC again results in higher impacts than APC system. According to the damage assessment results, on an average, the DPC system impacts the human health, ecosystem and resources 70% more than the APC system in this study.

5.3. Interpretation of comparison results

The hypothesis that an APC without any additional components other than a bigger display monitor, key board and mouse (for APC which are not touch screen) creates lesser environmental implications when compared to a convention DPC system with a separate CPU tower was analysed and verified by analyzing the two product systems individually and then comparing their results. The LCA study of the DPC was done simply by using the premodeled components for desktop PCs in Eco invent database v2.2. In contrast, the APC was analysed by dismantling the device and taking the primary data referring to the component weights and then mapping them to the eco-invent database accordingly.

The comparative study led to a much expected overall conclusion that APCs are a better solution for creating less environmental impacts than the conventional DPCs. Looking into the details of the LCA results, we can see that there lies a difference in the impacts created by the 2 products on different impact categories, though Eco invent database was primarily used in both cases. The premodeled desktop components might be heavier and contain more integrated circuits and printed wiring boards contributing to more impacts especially due to usage of gold, copper and tin. Though the components identified after dismantling the APC were mapped to the corresponding electronic modules in the Eco invent data base only, the weight of the component might play a significant role in

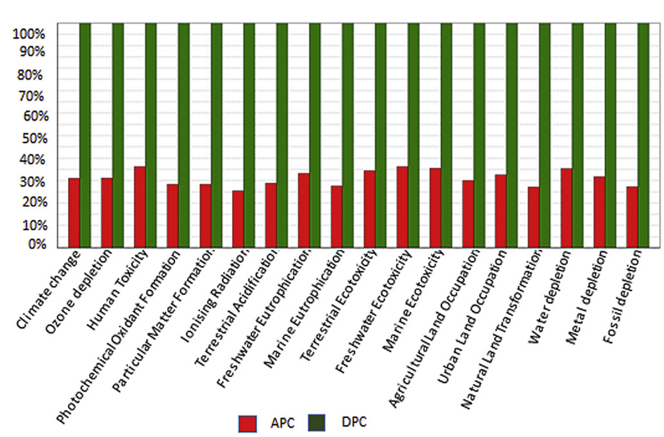

Fig. 9. Characterized midpoint assessment results.

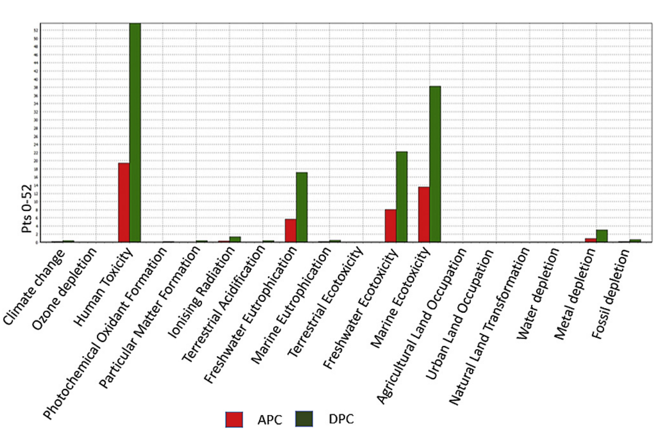

Fig. 10. Normalized midpoint assessment results.

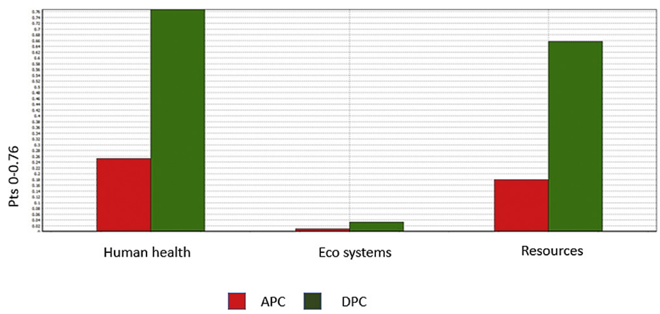

Fig. 11. Normalized endpoint assessment results.

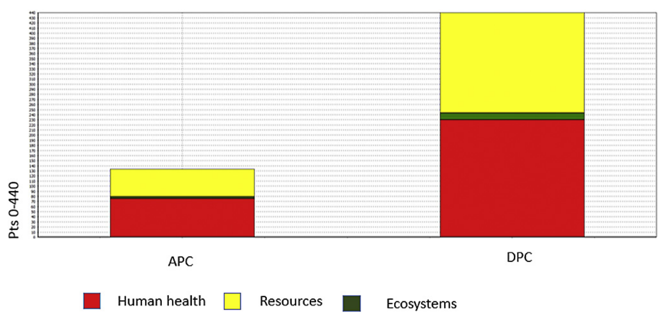

Fig. 12. Single score results.

mitigating impacts within the production phase. Within the use phase, a similar usage scenario was modelled for both APC and DPC to enable comparison. Electricity consumption is the determining factor within the use phase. Hence it is evident that APC demonstrates less electricity consumption compared to DPC, and hence consequently lesser impacts in the use phase compared to DPC. Also it could yet again indicate that manufacturers continue to develop energy efficient new products compared to the existing conventional ones.

6. Conclusions

The conclusions of this work were drawn at two levels: (1) environmental impacts of APC and (2) Comparison of APC and DPC at device level.

(1) The environmental profile of the APC is dominated by the use phase, followed by the production phase both in the end-point and mid-point assessment. The other phases like packaging and disposal hardly have any impacts. The damage created by the use phase is calculated as 65% compared to the 35% damage created by the production phase for all the 3 end-point categories of human health, eco-system and resources. At the component level, LCD module contributes the maximum towards environmental impacts as it includes sub-assemblies like integrated circuits and printed wiring boards. The main impact originates from the extraction of raw materials like hard coal, lignite and involved processes like disposal of sulphide tailings, processes associated with energy production like natural gas, crude oil etc. Interestingly, use phase is dominated by the impacts created in the sleep/standby mode during home use than the active mode and office use. The reason for this could be attributed to not switching off the computer after use at home which consequently increases the electricity consumption. Overall, while considering both endpoint and mid-point perspectives, human health is the most affected followed by resource depletion. Eco-system is impacted less according to this work.

(2) In consideration of all the assumptions made in this work, according to the single score results in Fig. 12., an APC creates 2 times lesser environmental impacts compared to a DPC during its entire life cycle (140pts only compared to the 440-pts calculated for DPC). The comparative analysis indicates that the electronic modules installed in the motherboards and LCD modules of DPC such as printed wiring board and integrated circuits result in higher environmental impacts when compared to APC at production level. For instance, disposal of sulphide tailings one of the connected processes in the production of DPC is calculated to contribute twice than that in the production of APC. Similarly, lignite mining a dominant contribution within electricity consumption in the use phase resulted in higher impacts compared to that of APC.

Overall, this LCA study represents a maiden attempt to evaluate the environmental impacts of an APC and compare it with conventional desktops (DPC), hence for data inventory hand disassembly was carried out to identify the composition and corresponding weights. However, we had to heavily rely on Eco invent database for modeling the product system, hence in future for environmental analysis of such recent developments and to enable an effective comparison with existing products, a more detailed information on the composition; distribution; packaging details; energy consumption and most importantly EOL of the products are needed. Availability of all these details will enable a more complete comparison of the two ICT solutions.

Acknowledgement

The authors wish to sincerely thank Central Research Grant (RTZR), Hong Kong Polytechnic University, for funding this project.

Appendix

Geographic shortcuts used in Tables 1–4 according to Eco invent database

Geography Name	Shortcut
Global	GLO
Europe	RER
Switzerland	CH
China	CN
Russian federation	RU
Western Europe	WEU
Central and eastern Europe	EEU
Middle east	RME
Germany	DE
Netherlands	NL
Africa	RAF
South Africa	ZA
United Kingdom	GB

References

Balaji Arumugam, S.N., Ganesan, Roshni, 2014. Electronic devices – the real ruler of the world. J. Med. Res. Pract. 3 (2).

Choi, B.-C., Shin, H.-S., Lee, S.-Y., Hur, T., 2004. Life cycle assessment of a personal computer and its effective recycling rate (7 pp). Int. J. Life Cycle Assess. 11 (2), 122–128. http://dx.doi.org/10.1065/lca2004.12.196.

Ciroth, A., Franze, J., 2011. LCA of Eco-labelled Notebook-ELCA and SLCA -

Consideration of Social and Environmental Impacts along the Entire Life Cycle. GreenDeltaTC GmbH, Berlin.
Information on http://www.compreviews.about.com.
Daiyue, H., Chao, L., Puel, G., 2015. Spatial environmental balance to information and communication technology products in different regions of China by using LCA. J. Clean. Prod. 91, 128–135. http://dx.doi.org/10.1016/j.jclepro.2014.11.025.
Deng, L., Babbitt, C.W., Williams, E.D., 2011. Economic-balance hybrid LCA extended with uncertainty analysis: case study of a laptop computer. J. Clean. Prod. 19 (11), 1198–1206. http://dx.doi.org/10.1016/j.jclepro.2011.03.004.
Duan, H., Eugster, M., Hischier, R., Streicher-Porte, M., Li, J., 2009. Life cycle assessment study of a Chinese desktop personal computer. Sci. Total Environ. 407 (5), 1755–1764. http://dx.doi.org/10.1016/j.scitotenv.2008.10.063.
Information on http://ecoinvent.org.
Hischier, R., Achachlouei, M.A., Hilty, L.M., 2014. Evaluating the sustainability of electronic media: strategies for life cycle inventory data collection and their implications for LCA results. Environ. Model. Softw. 56, 27–36. http://dx.doi.org/10.1016/j.envsoft.2014.01.001.
Kandlikar, P.T. a. M., 2012. Sources of variation in life cycle assessments of desktop computers. J. Ind. Ecol. 16 (S1), S182–S194.
Lu, L.-T., Wernick, I.K., Hsiao, T.-Y., Yu, Y.-H., Yang, Y.-M., Ma, H.-W., 2006. Balancing the life cycle impacts of notebook computers: Taiwan's experience. Resour. Conserv. Recycl. 48 (1), 13–25. http://dx.doi.org/10.1016/j.resconrec.2005.12.010.
Maga, D., Hiebel, M., Knermann, C., 2012. Comparison of two ICT solutions: desktop PC versus thin client computing. Int. J. Life Cycle Assess. 18 (4), 861–871. http://dx.doi.org/10.1007/s11367-012-0499-3.
Malmodin, J., Moberg, Å., Lundén, D., Finnveden, G., Lövehagen, N., 2010. Greenhouse gas emissions and operational electricity use in the ICT and entertainment & media sectors. J. Ind. Ecol. 14 (5), 770–790. http://dx.doi.org/10.1111/j.1530-9290.2010.00278.x.
Malmodin, J., Lundén, D., Moberg, Å., Andersson, G., Nilsson, M., 2014. Life cycle assessment of ICT. J. Ind. Ecol. 18 (6), 829–845. http://dx.doi.org/10.1111/jiec.12145.
Maria Leet Socolof, M. B. S., Lori E. Kincaid, Jonathan G. Overly,Katherine M. Hart and Dipti Singh. (1999). An environmental life-cycle design tool for assessing impacts of CRT and LCD monitors. Paper presented at the IEEE.
Noon, M.S., Lee, S.-J., Cooper, J.S., 2011. A life cycle assessment of end-of-life computer monitor management in the Seattle metropolitan region. Resour. Conserv. Recycl. 57, 22–29. http://dx.doi.org/10.1016/j.resconrec.2011.09.017.
Patric, A., Wager, R. H. a, 2015a. Grey Energy and Environmental Impacts of ICT Hardware ICT Innovations and Sustainability-advances in Intelligent Systems and Computing, vol. 310. Springer, Switzerland, pp. 171–189.
Patric, A., Wager, R. H. a, 2015b. The Transition from Desktop Computers to Tablets: a Model for Increasing Resource Efficiency? ICT Innovations and Sustainability-advances in Intelligent Systems and Computing. Springer, Switzerland, pp. 243–256.
Rhodes, S. P. (1993). Applications of Life Cycle Assessment in the Electronics Industry for Product Design and Marketing Claims. Paper presented at the IEEE, Arlington,Virginia.
Seungdo Kim, T.H. a. M.O., 2001. Life cycle assessment study of color computer monitor. Int. J. Life Cycle Assess. 6 (1), 35–43.
Song, Q., Wang, Z., Li, J., Yuan, W., 2012. Life cycle assessment of desktop PCs in Macau. Int. J. Life Cycle Assess. 18 (3), 553–566. http://dx.doi.org/10.1007/s11367-012-0515-7.
Stiel, F., Teuteberg, F., 2014. Measuring the environmental impact of IT/IS solutions – a life cycle impact modelling approach. Environ. Model. Softw. 56, 94–104. http://dx.doi.org/10.1016/j.envsoft.2013.12.014.
Stutz, S.O. C. a. M., 2010. Product carbon footprint (PCF) assessment of Dell laptop – results and recommendations. IEEE Sustainab. Syst. Technol. 1–6.
Subramanian, K., Yung, W.K.C., 2016. Review of life cycle assessment on consumer electronic products: developments and the way ahead. Crit. Rev. Environ. Sci. Technol. 46 (18), 1441–1497. http://dx.doi.org/10.1080/10643389.2016.1245550.
Williams, E., 2004a. Energy intensity of computer manufacturing: hybrid assessment combining process and economic input-output methods. Environ. Sci. Technol. 38, 6166–6174.
Williams, E., 2004b. Energy-intensity-of-computer-manufacturing-Hybrid-assessment-combining-process-and-economic-input-Output-methods. Environ. Sci. Technol. 38, 6166–6174.
Zhou, X., Schoenung, J.M., 2007. An integrated impact assessment and weighting methodology: evaluation of the environmental consequences of computer display technology substitution. J. Environ. Manage 83 (1), 1–24. http://dx.doi.org/10.1016/j.jenvman.2006.01.006.