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Abstract: Informatics can make a relevant contribution to sustainable development, if the effects of ICT applications are systematically assessed from a life-cycle perspective and the results of life-cycle assessment (LCA) studies are taken into account by decision makers. The basic scheme of a product life cycle includes the three phases production, use and end of life. In the production phase, raw materials are transformed into the product. In the use phase, the product delivers the service it has been intended for. After the service life of the product ends, parts of the product may be reused or recycled. The rest leaves the system for final disposal or to be recycled in other product systems. Only if life-cycle thinking is applied both to ICT products and to products influenced by ICT applications, is it possible to decide whether a potential ICT application will have a positive or negative environmental impact on the bottom line. With life-cycle thinking, it will be possible to make substantial steps toward sustainable development. Informatics, and in particular environmental informatics as a specialized sub-discipline of it, can contribute to life-cycle thinking by supporting the modelling and data collection process in LCA studies. In addition, dynamic simulation models are useful in prospective technology assessment where LCA methodology reaches its limits.

Keywords: Life Cycle Assessment (LCA); ICT and sustainability; ICT and energy efficiency; life cycle inventory database; life cycle modelling; environmental informatics.

1. INTRODUCTION

The discipline of Informatics (the analysis and design of information processing systems) and its technology (Information and Communication Technology, ICT), have various relationships to the field of Life Cycle Assessment (LCA), i.e. cradle-to-grave accounting of the energy and material flows into and from the environment:

1. Each ICT hardware product has a life cycle which can be assessed with standard LCA methodology and tools. Example: The life-cycle of a PC can be modelled using an LCA tool (such as Umberto [ifu, 2008]) and a life cycle inventory database as a data source (such as ecoinvent 2.0 [ecoinvent Centre, 2008]).

2. Each application of an ICT product has various impacts on the life cycle of other products. Example: MP3 players have an impact on the demand for audio CDs, for CD players, for CD racks, on headphones, on the use of PCs for Internet access (music downloads), etc.

3. ICT applications support life-cycle thinking and thus contribute to sustainable development. Examples: Software tools for life-cycle modelling as well as life-cycle inventory databases help to understand product life cycles and bring the effort needed to do an LCA study down. Such tools can be viewed as applications of environmental informatics [Hilty et al., 2006c].

The following sections give a conceptual overview of each of the three aspects, including examples of existing studies and tools.
2. THE LIFE CYCLE OF ICT HARDWARE

Figure 1 shows the life cycle of an ICT hardware product, which does in principle not differ from the life cycle of any other type of product: It consists of the three phases production, use and end of life. The design phase has been added here pro forma to have this phase in place as a point where the life cycle can be substantially influenced (see section 3). The design phase is generally not viewed as a part of the life cycle in LCA methodology. Each process along this chain consumes materials and energy and uses some infrastructure. Both the materials and energy transformed and the infrastructure have their own life cycles, which have to be accounted for as well. This idea would lead to infinite recursion in life cycle modelling [Hilty and Schmidt, 1997], unless rules for drawing system boundaries are applied. Such rules are part of standard LCA methodology [Frischknecht and Rebitzer, 2005; ISO, 2006a, 2006b]. According to ISO, “the product system should be modelled in such a manner that inputs and outputs at its boundary are elementary flows”. In the case of a life-cycle study of an ICT hardware product, this means, e.g., that the primary production of the metals used in production, the supply chain for the energy used in each phase as well as the final disposal activities are traced through the exchange of chemical elements with the environment.

Viewed from this perspective, it becomes apparent that the current discussion about the energy consumption of ICT and “green data centers” has quite a narrow focus, looking only at energy consumption in the use phase. This is considered an oversimplified perspective because

- the way the electrical energy is generated (electricity supply mix) may be relevant [Frischknecht et al., 2007];
- other life cycle phases may be more relevant than the use phase;
- other environmental impacts may be more relevant than energy consumption.

Although many LCA studies have been done in the ICT field and results are available, this simplistic view is still common in industrial and political initiatives. Life cycle thinking should be part of any Integrated Impact Assessment (IIA) methodology [Ruddy and Hilty, 2007]. Life cycle perspectives are also useful in technology assessment, where risks of prospective applications of new technologies are anticipated [Bauer et al., 2008].

The following studies give typical examples of how the LCA methodology can be applied in the ICT field:

- Several LCA studies on PCs [Atlantic Consulting & IPU, 1998; von Geibler et al., 2003; Hikwama, 2005; Eugster et al., 2007]
- A study on computer screen technologies [Socolof et al., 2001, 2005]
- Two LCA studies on mobile phone networks [Scharnhorst et al., 2005, 2006a, 2006b; Emmenegger et al., 2006] and one on fixed-line networks [Takahashi et al. 2003]
- Several LCA studies on components, such as ICs [Tekawa et al., 2002; Andrae et al., 2004; Andrae, 2005] and batteries [Rydh et al., 2002; Fisher et al., 2006]
- Two LCA studies on the benefits of electronic waste recycling [Hischter et al., 2005; Choi et al. 2006]

Some of the results will be referred to in the following subsections.
Figure 1. The Life Cycle of ICT hardware. All phases cause (direct or indirect) resource consumption and the release of residues to the environment.

2.1 Environmentally relevant aspects of ICT production

Early studies on the ecological impacts of computers (such as that compiled by Hilty et al. [2000]) showed that the production phase matters. The impact of the production phase of computers and other ICT products cannot be neglected in comparison with the use phase.

The most recent study on desktop PC production [Eugster et al., 2007] showed that the Cumulative Energy Demand (CED) of PC production in China roughly equals the CED of three years of use under average conditions. If all relevant environmental impacts are aggregated using the Eco-Indicator’99 methodology, it turns out that the PC even had to be used for roughly six years until the use phase counteracts the production phase. If an energy supply mix with a sizable share of non-fossil energy is assumed (i.e. the PC is used in a country with a lot of hydro-, wind- or solar power), the comparison between production and use becomes still better for the use phase.

Which aspect of the production of a PC has the highest environmental impact? According to Eugster et al. [2007], the production of integrated circuits and other parts containing precious metals is the most energy-intensive part. Assembling the parts is almost irrelevant.

2.2 Environmentally relevant aspects of ICT use

In the use phase, an ICT product delivers its service to the user. LCA studies define a functional unit (such as "1 hour of PC use") to which the environmental impact of the whole life cycle is related.

Given the relatively high environmental impacts of ICT production, the use of ICT hardware has obviously one environmentally relevant parameter: the length of its useful life. If a device is used for six years instead of three years, it can deliver double the amount of functional units, which implies that the share of the production impact attributed to a functional unit is cut by half.

As a rule of thumb, the length of the useful life of ICT devices is more important than their power consumption during use. Short software innovation cycles with increasing hardware

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1 However, in the case of servers in data centers, which are run 7x24 hours a week, energy consumption in the use phase may dominate the life cycle. This is also because indirect energy demand often occurs for air conditioning and for uninterruptible power supply (UPS) units.

2 Extracting precious metals, in particular gold, from the earth crust creates high environmental impacts. This contributes a relevant part to the overall environmental impact of electronics.
requirements have therefore a negative effect: They shorten the useful life of the hardware, which is ecologically disastrous [Hilty et al., 2006b].

2.3 Environmentally relevant aspects of the end-of-life phase of ICT

Electronic waste recycling is a field of great interest in both research and politics [Hilty, 2005; Widmer et al., 2005]. Increasing amounts of Waste Electrical and Electronic Equipment ("WEEE" or "e-waste" for short) make this type of waste and its treatment a rapidly growing problem in many parts of the world.

Although there are methodological challenges involved in assessing the environmental impacts of metal supply [Althaus and Classen, 2005], it can be shown that e-waste recycling clearly pays off in terms of environmental impacts because primary production can be avoided when metals are recovered. Some 20-25% of the energy consumed in the production phase can theoretically be saved by recycling [Hischier et al, 2005]. Hence, it is mainly the reuse of metals that makes WEEE recycling environmentally beneficial.

Unfortunately, this is only true for recycling processes that can handle the pollutants contained in WEEE properly. This is not the case in the so-called informal recycling which is very common in emerging economies. There is a huge informal industry in Asia which recycles WEEE mainly to recover gold and copper, an activity which is very profitable as long as the health and environmental impacts are not accounted for. As an example, Figure 2 shows the extraction of copper from printed wiring boards in a typical backyard company with 12 workers in Delhi, India. This company recovers 1-2 tons of copper per month [Widmer et al., 2005].

Many countries are currently implementing WEEE recycling systems. Unfortunately, ever-larger fractions of electronic scrap may escape these systems if the trend towards embedded ICT systems continues. According to the technological visions of pervasive computing, ubiquitous computing, or ambient intelligence, most ICT products will be integrated into every-day objects and no longer be perceived as discrete ICT devices [Som et al., 2004]; this will create new challenges for recycling [Hilty, 2005]. The diffusion of RFID transponders (also known as smart labels), which is currently just beginning, can be viewed as a forerunner of pervasive computing. Tagging papers, food packages etc. may have consequences for the efficiency of established recycling processes and for the availability of scarce metal resources in the future [Wäger et al., 2005].
3. EFFECTS OF ICT APPLICATIONS ON THE LIFE CYCLE OF PRODUCTS

In order to classify the effects of ICT applications on other products’ life cycles, we will adopt a conceptual framework that was originally created to categorize ICT impacts on traffic:

- **Induction**: ICT applications can induce traffic. Example: People who get to know each other via the Internet may want to meet some day in person.
- **Optimization**: Traffic processes are optimized by specific ICT applications. Example: Intelligent transport systems (ITS) may avoid congestion.
- **Substitution**: ICT-based processes replace traffic. Example: Virtual meetings are substituted for physical meetings.

Although created for the impact of ICT on traffic, this conceptual framework can easily be generalized to other applications fields.

Figure 3 shows how the service provided by using an ICT product can have an effect on the life cycle of another product. There are three types of effects: induction (straight arrow), optimization (dotted arrows), and substitution (bent arrow).

**Figure 3.** Types of impacts of ICT services on the life cycle of another product or service.

*Induction effects* occur when an ICT service stimulates the use of the other product, i.e. more functional units per unit of time are consumed (e.g. the text-processing service provided by a PC system with a printer may stimulate paper consumption).

*Optimization effects* may occur in all phases of the life cycle, as well as in the design phase. CAD tools, for example, can be used to optimize a product for environmental criteria (eco-design). Design has a strong impact of the life cycle because it constrains the optimization potentials that will exist in the production, use and end-of-life phases. For example, if the
variety of materials or the complexity of the product can be reduced in the design phase, it will be possible to reach a higher efficiency level in end-of-life treatment.

Substitution effects occur when an ICT service replaces the use of a physical product, e.g. when e-mail replaces the use of conventional letters.

With LCA methodology, it is possible to quantify the potential environmental benefit of specific optimization and substitution effects. For example, a given conference can be hypothetically virtualized and the difference in environmental impacts assessed. We did so for EnviroInfo 2001, which was held at ETH Zurich, assuming that all travel of participants would have been replaced by Internet connections for video streaming, online discussions, upload and download of presentations, etc., including the estimated environmental impact of the Internet connections. It turned out that the virtual conference would only have caused 2-3% of the actual environmental impact of the physical conference. The main part of this could be attributed to the 6% of the participants who had to take a long-range flight: Their flights accounted for 60% of the overall environmental impact of the conference [Hischier and Hilty, 2002].

4. TOOLS AND DATABASES FOR LIFE CYCLE ASSESSMENT

Life Cycle Assessment (LCA) involves modelling and the collection of inventory data. The life cycle is viewed as a system of processes (exchanging energy and materials) that is modelled in an assumed stationary state. Inventory data specifies the inputs and outputs of each process. In order to do an LCA efficiently, the connection between the modelling system and a comprehensive inventory database is essential.

Two examples of tools which fulfil this condition are Umberto [ifu, 2008; see Figure 4] and SimaPro [PRé consultants, 2008]. Both integrate the life cycle inventory database ecoinvent, which is one of the most advanced collections of life cycle inventories worldwide [Frischknecht et al., 2005a, 2005b, 2005c]. Version 2.0 which was released in November 2007, includes data on electronics, which makes it possible to do LCA studies in the ICT field [ecoinvent Centre, 2008]. The US National Renewable Energy Laboratory provides the U.S. Life-Cycle Inventory Database. The data can be imported into major LCA tools [NREL, 2008].

The Umberto example (Figure 4) shows part of an oil refinery modelled as a network of processes (boxes in the notation used by Umberto) connected by flows. Each process transforms incoming flows into outgoing flows according to a set of linear equations. However, more complex algorithms may also be applied to model a process. The life cycle of any product or service is such a network, albeit much larger than the cutout shown.
The static nature of LCA is not always compatible with the dynamic technological development in the ICT field. In order to do prospective studies of the positive or negative environmental effects of ICT, dynamic models may be needed, as demonstrated in the study “The Future Impact of ICT on Environmental Sustainability” commissioned by the Institute for Prospective Technological Studies (IPTS) of the European Commission [Hilty et al., 2006a]. The System Dynamics model used in this study considered that ICT consumer products will become smaller and more numerous in the future. Dynamic models have proven to be more adequate than LCA when waste generation and recycling are key issues, because stocks of scrap may play an important role in such contexts [Krivtsov et al., 2004; Streicher-Porte et al., 2005].

5. CONCLUSIONS

The life cycle of ICT hardware has a considerable environmental impact. The main causes are the use of scarce metals and toxic components. The former account for a considerable part of life-cycle-wide energy consumption; the latter cause pollution whenever the end-of-life-treatment is inadequate. The software update cycle with its increasing hardware requirements contributes to the overall impact by shortening the useful life of the hardware. However, the environmental impact of the ICT hardware life cycle is still much smaller than that of many materials- and energy-intensive processes (such as traffic or space heating) that can be optimized, and in some cases replaced, by ICT services.

As a tool for systems analysis and decision support, ICT has an important role to play in enabling and promoting life cycle thinking. Here is where environmental informatics [Hilty et al., 2006c] can make a substantial contribution. Environmental informatics can provide
tools that efficiently and effectively support decision makers who want to improve the ecological life cycle of products and services.

REFERENCES


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