

An LCA-based framework for the analysis of ICT impacts on the environment

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This paper describes an approach to the assessment of ICT impacts on the environment – both in the positive and negative sense – based on the methodology of Life-Cycle Assessment (LCA). The basic idea is that ICT products are used to provide a service (information or communication service) and that the availability of this service may modify the life cycle of *other* products or services. The environmental impact of the ICT product therefore has two components: (i) the environmental impact of the life cycle – production, use and disposal – of the ICT product itself and (ii) the difference in environmental impact of the modified life cycle(s), as far as this difference can be attributed to the information or communication service provided by the ICT product.

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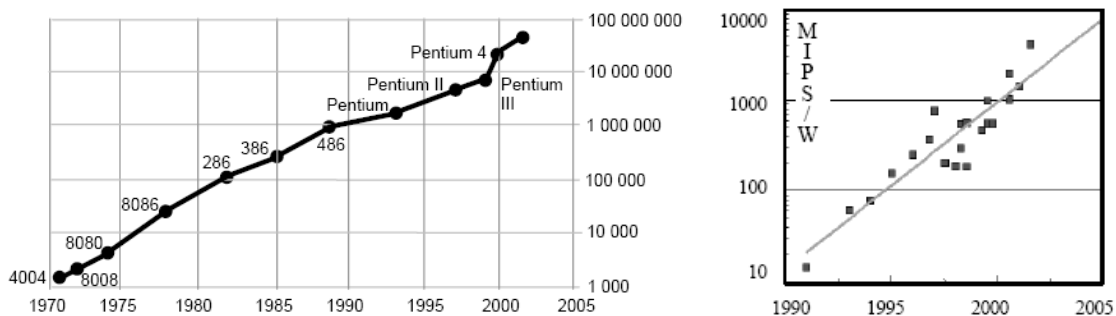
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1. Introduction

1. The impacts of ICT on the environment can in principle be analyzed using a top-down or a bottom-up approach. A top-down approach would start with dividing all economic activities into two complementary sets, ICT- and non-ICT activities, the former set constituting the ICT sector. The environmental impact of the ICT sector can then be assessed using statistical data on the interaction between economic sectors and their environmental implications, as far as available. The bottom-up approach starts with identifying the most relevant types of ICT products and services and describes their environmental impacts at the product level. Based on data on stocks of products or demand for products and services, together with evidence on their average patterns of use, these impacts are then scaled up to the macro level.
2. The conceptual framework proposed in this paper is based on a bottom-up approach with the specification to use traditional Life Cycle Assessment (LCA) methodology at the product level. Traditional LCA methodology is also called SETAC LCA or Process LCA and is defined in the ISO 14000 standard (ISO 14000, 1996).
3. Using LCA for a bottom-up approach has the following advantages: (a) All relevant negative environmental impacts that are accepted through the whole life cycle of an ICT product are taken into account, as opposed to other bottom-up approaches which often consider only energy consumption in the use phase or greenhouse gas emissions caused by production and use, for example. (b) Methodological challenges such as defining the system boundaries, allocation problems and evaluating physical flows with regard to their environmental impacts can be met in a standardized way, leading to comparable results. (c) Existing life-cycle inventory databases can be used to provide the basic data.
4. Using LCA for a bottom-up approach has the following disadvantages: (a) The results can in general not be aggregated to a national macro-level, because LCA does not regard national boundaries (which may be crossed by product life cycles); “indirect flows” can only be separated when the geographic distribution of the life cycle is known (e.g. production abroad, use and disposal inland). (b) The results are not directly compatible with Material Flow Analysis (MFA), because LCA may involve double counting from an MFA perspective in cases where the same material flow has environmental impacts when it enters the system under study (e.g. extraction of fossil fuels) and when it leaves the system after some transformation (e.g. CO₂ emissions from fuel combustion). (c) It is not possible to cover all ICT products and services by LCA studies; an *a priori* decision on the relative relevance of products or services is therefore unavoidable.
5. In LCA, environmental impacts are related to a previously defined *functional unit*. If the product assessed is an ICT product, the functional unit should theoretically be defined as a unit of an information or communication service, such as “1 million computing instructions executed” or “1 Megabyte transferred”. However, using this type of functional unit would immediately lead to the trivial result that the (negative) environmental impact of ICT products per functional unit is decreasing rapidly. Figure 1 shows the exponential growth in materials and energy efficiency which is one of the technological reasons for this progress: The computing power available per microchip or per unit of electric power is doubling every 18-24 months according to Moore’s Law. It is known that the material and energy needed to produce a microchip or to dispose of it is roughly constant, so that the increase in efficiency applies to the whole life cycle.

6. This rapid progress in technological efficiency is fully compensated by the increase in demand of computing power *per device*. It is therefore common practice to use the time of use as the functional unit, such as “1 hour of PC use” or “1 year of average business PC use”. Although it is theoretically unsatisfactory to refer to devices for defining the functional unit for an LCA, this seems to reflect the perception of the consumer, who is usually not aware of the increase in computing efficiency over time. Similar arguments can be found for progress in data transfer efficiency.

Figure 1. Exponential growth of the computing power that can be provided with roughly constant material and energy inputs: Number of transistors per microprocessor (right) and Million Instructions Per Second (MIPS) per Watt of electric power (left) over time.



Source: Mattern (2005)

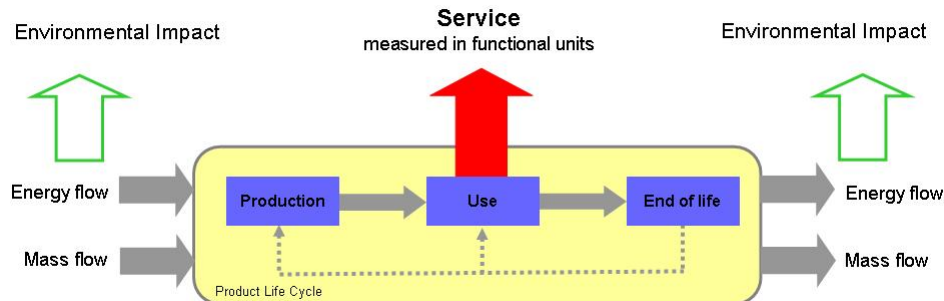
2. Conceptual Framework

7. The conceptual framework proposed here uses LCA to assess two types of life cycles: (i) the life cycle of a given ICT product or service (such as a PC, a mobile phone, an operating system, a telecommunication service) and (ii) other life cycles that are modified through the availability of the information or communication service (IC service) provided by the first life cycle. We introduce the term “linked life cycles” to refer to this concept further on.

8. Figure 2 shows the generic life cycle model that will be used as a basic building block for the linked life-cycle framework. However, any other life cycle model could also be used, provided it views the life cycle as a system that has the purpose of providing a service at the cost of mass and energy that flow through it. On their way through the system, mass and energy are transformed. Roughly speaking, the production phase transforms input resources to a product and the use phase transforms the product to waste while providing the desired service. Both the physical inputs and outputs of the system, i.e. all flows crossing the system boundary, are evaluated with regard to their environmental impacts.

9. All environmental impacts are related to the functional unit chosen, i.e. divided by the number of functional units that are generated during the use phase. This implies that the service life – the length of the use phase – of a durable product is an essential parameter in an LCA. Example: If the system under study is the PC life cycle and the functional unit is defined as “1 year of PC use”, the environmental impact of the non-use phases (production and end-of-life) is cut to half if the PC is used for 6 instead of 3 years.

Figure 2. Basic model of a product life cycle. The purpose of the system is to provide a service, which requires the production, use and disposal of a material product. Product life cycles have a recursive structure, i.e. any phase of the life cycle can involve services, behind which there are life cycles of other material products (e.g. infrastructures used for production, energy supply, transport, disposal). Standards prescribe where to stop the recursion.



Source: Empa

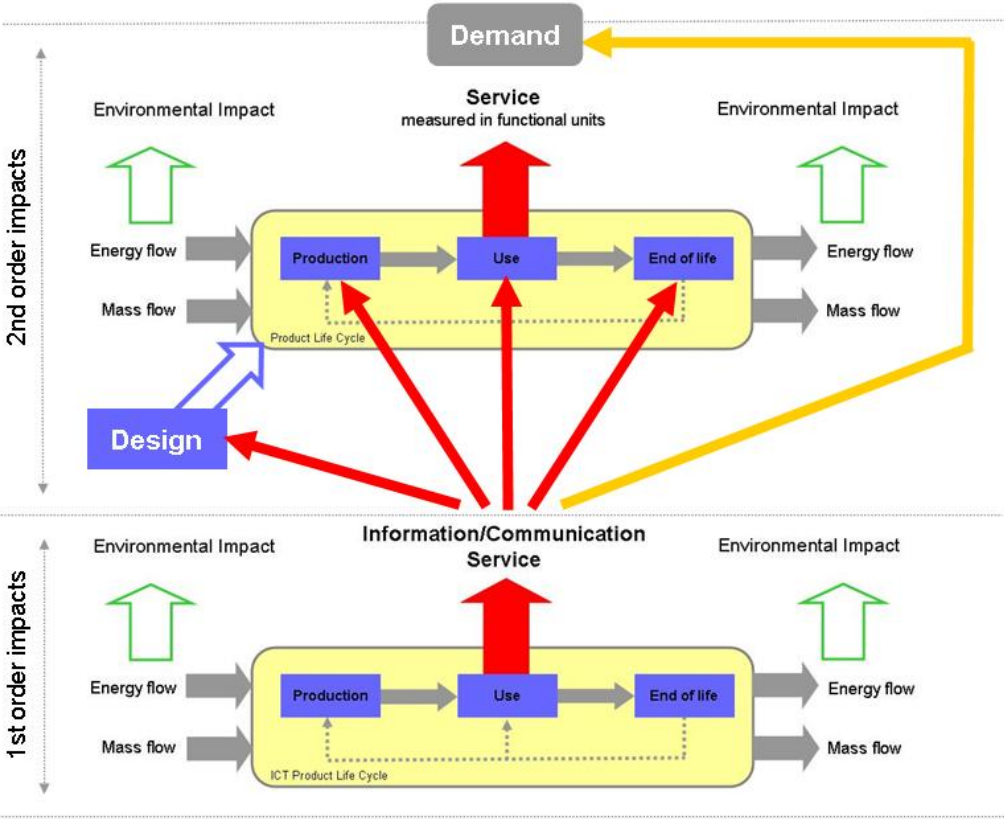
10. The effect of ICT as an *enabling technology*, namely as an enabler of change in production and consumption with the potential to mitigate environmental impacts, can be conceptualized with the approach of linked life cycles, i.e. by showing how the ICT life cycle can affect other life cycles. Figure 3 illustrates the concept. The environmental impacts of the *ICT life cycle* (shown at the bottom) are also called “first-order impacts” or “primary impacts” of ICT. The modification of the impacts occurring at the level of the second life cycle (shown at the top) are called “second-order effects” or “secondary effects” of ICT, because they are indirectly caused through the modification of the second life cycle by the availability of the IC service. The terminology traces back to EMPA (2005) and the sources cited there.

11. The potential modifications of an IC service to a product life cycle can be described generalizing a typology of relationships between telecommunications and transportation that traces back to the 1980ies (Mokhtarian, 1989). The basic idea is to differentiate among optimization, substitution and induction effects: An IC service can help to better organize traffic (optimization), replace traffic (substitution) or generate additional demand for traffic (induction). This typology is no generalized to all ICT applied in any field of application and interpreted from a life cycle perspective.

12. Optimization can refer to any phase of the life cycle in our framework, including the design phase, which usually is not regarded part of the life cycle in LCA methodology but included here as an important link between the two life cycles (see Figure 3). The red arrows refer to effects of the IC service which modify the efficiency of parts of the other life cycle, i.e. they represent optimization potentials.

13. Substitution and induction refer to the *demand* for the service which is affected by the availability of the IC service. If the original service is *replaced* by the IC service, the product becomes obsolete (at least in its function to provide the service), which is a substitution effect. However, the demand could also increase as a consequence of the IC service (such as the demand for paper increases due to the availability of inkjet printers), which is an induction effect.

Figure 3. Illustration of the “linked life cycles” concept. The information or communication service provided by the ICT life cycle at the bottom can modify the life cycle of another product (providing any service) in two ways: by modifying the design, production, use or end-of-life phase of that product (red arrows) or by influencing the demand for the service it provides (yellow arrow).



Source: Empa

14. Table 1 shows how this typology can be interpreted in more detail detail in the linked life-cycle framework. This table can also serve as a checklist to screen a given IC service for potential second-order impacts.

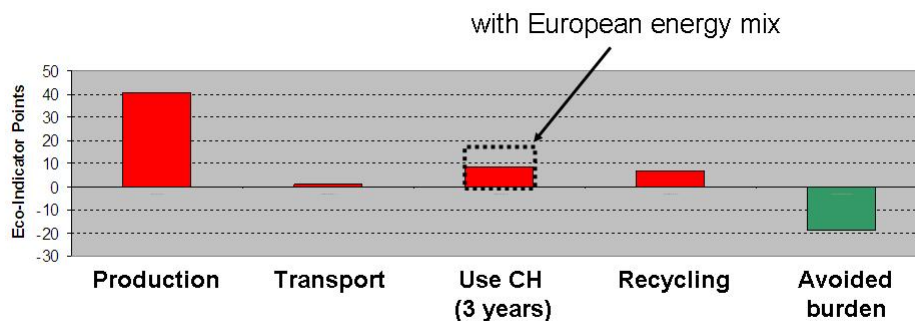
15. A interesting special case occurs if both life cycles are ICT life cycles. In this case, ICT has second-order effects in the ICT sector. Example: The IC service is PC system software, the second life cycle PC hardware. If the software helps the hardware to come closer to the ideal of load-proportional power demand, it has an optimization effect on the use phase. If a new software version demands for more hardware capacity, it increases the demand for PC hardware by shortening the use phase. The latter effect has been called Software-Induced Hardware Obsolescence or SIHO (Hilty, 2008).

Table 1. How an information/communication service can influence the life cycles of another product

Contact point	Effect of IC service	Second-order environmental impact	Examples
Design phase (optimization)	Same design with less effort	Positive, small potential (no multiplication)	Conventional CAD 3D printing
	New design enabling more efficient production	Positive, high potential	CIM Complexity reduction, designing multi-use parts
	New design enabling more efficient use		Energy-efficient architecture
	New design enabling longer use		Design for maintainability
	New design enabling more efficient recycling		Design for recyclability
Production phase (optimization)	More efficient production process	Positive, high potential (unless already used)	Process optimization Integrated process chain Optimized logistics
Use phase (optimization)	More efficient use	Positive, high potential	Energy management of user appliances Intelligent heating, cooling and ventilation Smart grids
	Longer use	Positive, high potential	Remote maintenance and self-maintenance Information systems on replacement parts
End-of-life phase	More efficient end-of-life treatment	Positive, high potential	Smart sorting techniques for recycling
Demand for the service	Replaced by IC service (substitution)	Positive, high potential	Virtual meetings replace travel
	Reduced demand	Positive, high potential	Reduced energy consumption due to smart metering
	Increased demand (induction)	Negative, high potential	Increased paper consumption due to PC printers Hardware obsolescence due to new, demanding software versions

16. The LCA approach on which the framework is based enables contextual factors to be considered in a standardized way. Possibly the most important contextual factor is the energy mix of power production. Figure 4 shows how the energy mix affects the environmental impacts of a PC's use phase.

Figure 4. Example of an LCA result with full aggregation of environmental impact categories. The product under study was a desktop PC, produced in China in the year 2005 and used in Switzerland under mixed private/business conditions. Although these data may vary with different PC models produced in different years, a relatively robust result is that the environmental impact of the production phase (including resource extraction) is higher than that of the use phase. However, the difference decreases if an average European instead of the specific Swiss energy mix for power production is assumed. It would further decrease if the production in China would be powered by renewable energy instead of coal-fired power plants. The green bar represents the environmental impact for producing primary materials (in particular metals) due to the secondary materials output from recycling which substitutes them. This value is subject to high uncertainty due to quality issues.



Source: Combination of data from Empa (2007) and Hirschier (2005)

3. Extension to third-order impacts

17. Optimization, substitution and induction effects of ICT as conceptualized in the linked-life-cycle framework may not only have environmental impacts, but also provoke systemic reactions (e.g. market reactions) due to changes in the price, the necessary expenditure of time or the convenience of a product or service. The environmental impacts of such systemic reactions are called “third-order impacts”. Example: If mobile work becomes more convenient, the demand for public transport could increase, because the time on trains can be better utilized.

18. An important special case of a third-order impact is the well-known rebound effect. Example: If increased energy efficiency makes a service cheaper, this can create additional demand, leading to less energy savings than expected (or zero or even negative savings).

19. The linked-life-cycle framework should be complemented by socio-economic models in order to cover third-order effects. This can be done (a) by continuing the bottom-up approach and modeling market reactions based on elasticities of demand or (b) by combining the framework with a top-down approach (e.g. based on economic input-output tables).

20. The project “The Future Impact of ICT on Environmental Sustainability” commissioned by IPTS and carried out by IZT, Empa, Forum for the Future and Lund University used approach (a) by using elasticities of demand with regard to price and including time-use models with assumptions about the subjective cost of time. Shifts in the price of a service or the time needed to consume it, including multiple uses of time (e.g. for transport and for work) were covered by this model. However, incomplete data on economic elasticities and the difficulty to cover income effects and the general framework conditions (such as the tax regime), which was done by using three scenarios, created high uncertainty (IPTS, 2004; EMPA et al., 2004; Hilty et al., 2006).

21. Approach (b), i.e. combining the bottom-up approach of linked life-cycles with a top-down approach, would be a methodological challenge.

4. Discussion

22. Using a bottom-up approach has the disadvantage of the relevance selection that has to be made *a priori*, since it is not possible to cover all ICT devices (for the first order impacts) and all types of IC services with their potential implications for any other life cycle (for the second-order impacts). Studies exist on isolated ICT products, services and their second-order effects. An advisory group to DG INFSO has recently surveyed the most relevant results, however with a specific focus on increases in energy efficiency, not including other types of impacts and other environmental aspects (European Commission, 2008).

23. However, if one is successful in selecting IC services that have a large leverage with regard to the most material and energy intensive processes in the economy, a bottom-up approach may have more explanatory value than a sector-oriented top-down approach.

24. If a bottom-up approach is used, it should be based on LCA methodology, because restricting the scope to the use phase (both for ICT and for other products and services) or to specific impact categories such as climate change potential, as it is frequently done, creates an incomplete and distorted picture.

25. For causal explanations, it seems extremely useful to think in material ICT products providing immaterial IC services, which in turn have implications for the life-cycle of other products or services. In particular, this view has the advantage to avoid a concept of “ICT infrastructure” which is difficult to confine.

26. The framework created here is focused on the “harder” part of ICT environmental impacts. It is not able to cover “softer” impacts, such as impacts of the Internet on environmental education or on the collaboration within NGOs.

27. There is a confusion in the “ICT and environment” discourse regarding the meaning of the terms “direct” and “indirect”, because these terms are used differently in the various contexts that merge in this discourse. See Table 2 for a clarification. (The list is not exhaustive.)

Table 2. Different uses of the terms “direct” and “indirect” in the “ICT and environment” discourse.

Context	Expression	Meaning
LCA	“direct impact”	Environmental impact of the foreground system, e.g. emissions of a microchip factory or an e-waste recycling facility
	“indirect impact”	Environmental impact of the background system, e.g. emissions of power plant generating electricity for the chip factory, for the microchip in use or for the recycling facility
MFA (OECD, 2008)	“direct flow”	A material flow that enters the system of the domestic economy
	“indirect flow”	A material flows that is caused abroad by the fact that a good is imported, but that does not enter the domestic economy
Energy	“direct energy consumption”	The amount of energy consumed in a device during the use phase.
	“indirect energy consumption”	The amount of energy consumed to provide the device (“grey energy”, “embodied energy”) and/or to provide the energy.
ICT Impacts	“direct impacts of ICT”	First-order impacts of ICT as defined in this paper
	“indirect impacts of ICT”	Second- and/or third-order impacts of ICT as defined in this paper

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