ENVIRONMENTAL ASSESSMENT OF ELECTRICAL AND ELECTRONIC EQUIPMENT – THE USE OF APPROPRIATE TOOLS AND ASPECTS OF THE LIFE CYCLE APPROACH

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Abstract:

The electrical and electronic equipment (EEE) sector covers a large number of products. Many of these are part of everyday's life, however, their effect on sustainability (social, economic and environmental) is not always considered. In recent years environmental issues have become a major concern to the general public and the environmental impact of EEE is one of the major topics.

In this thesis sustainability in the context of EEE and in particular of information and communication technologies (ICT) is discussed. Different concepts, methods and tools for environmental assessment are reviewed and advantages and disadvantages for assessing EEE summarised. In this context the life cycle approach is looked at in detail. The length of the life cycle and setting of system boundaries are discussed and illustrated with a case study. The differences between product and material life cycle are also described. Furthermore, the aspects of software tools that help in carrying out an environmental assessment are described.

In order to test the suitability of life cycle assessment two case studies were carried out as part of this thesis. The first case study investigates the impact of an opto-electronic device and shows that a complex method such as life cycle assessment is not suitable for new technologies where considerable data gaps exist and only lab scale figures are available. The second case study looks at the ICT infrastructure of a multi-dwelling estate. Here the impact of providing the service of internet access is analysed. In this case a streamlined life cycle assessment proved to be a suitable tool. This case study shows that the infrastructure itself has a low impact compared to maintaining it.

The conclusion of this research is that electrical and electronic equipment should not be seen as one group of products since their life span, material composition, and use pattern is very different and therefore different environmental assessment tools should be applied. Moreover, it is demonstrated that life cycle assessment is not always a suitable tool for assessing EEE.

Depending on who is carrying out an environmental assessment and how much resource (time, data, expert knowledge, etc.) is available, tools can be classified into simple (for non experts) and sophisticated tools (experts tools). A simple tool can be more appropriate to answer questions and a sophisticated tool will not necessarily give better results if the prerequisites for its use are not fulfilled. Therefore it is important to choose the adequate tool for addressing a specific problem. Otherwise relevant aspects might not be captured and the result will not have the desired quality.

Keywords:
Environmental assessment tools, software tools, EEE, life cycle thinking, optic fibre cable

Kurzfassung:

Die Gruppe der elektrischen und elektronischen Geräte (electrical and electronic equipment – EEE) umfasst eine Vielzahl von häufig verwendeten Produkten. Ihre Auswirkungen auf Nachhaltigkeit werden jedoch nicht immer berücksichtigt. In den letzten Jahren wird mehr Aufmerksamkeit auf die Umweltauswirkungen unseres Handelns gelegt und EEE sind ein wichtiger Teilaspekt darin.
In dieser Arbeit werden die Auswirkungen von EEE auf die Nachhaltigkeit diskutiert und im speziellen auf Informations- und Kommunikationstechnologien (IKT) eingegangen. Unterschiedliche Konzepte, Methoden und Ansätze zur Umweltbewertung werden beschrieben und ihre Eignung für die Bewertung von EEE diskutiert. In diesem Zusammenhang wird auch der Lebenszyklus von EEE analysiert und das setzen geeigneter Systemgrenzen beschrieben. Unterschiede im Lebenszyklus eines Produktes, im Verglich zu dem eines Materials werden veranschaulicht. Darüber hinaus werden wichtige Aspekte von Software tools, die in der Umweltbewertung zum Einsatz kommen beschrieben.
Um die Eignung von Ökobilanzen (auf Englisch Life Cycle Assessment – LCA) zu testen, werden zwei Fallstudien erarbeitet. In der ersten werden die Umweltauswirkungen eines opto-elektronischen Bauteiles untersucht. Die Studie zeigt, dass eine komplexe Methode, wie die Ökobilanz, nicht geeignet ist, um eine neue Technologie zu bewerten, wenn es beträchtliche Datenlücken gibt und nur Labormesswerte zur Verfügung stehen. Die zweite Fallstudie befasst sich mit den Umweltauswirkungen von IKT Infrastruktur in einer Wohnhausanlage. Eine streamlined LCA wird erstellt, um die Auswirkung, die das zur Verfügungstellen von Internetanschlüssen hat, zu untersuchen. Für diese Fragestellung erweist sich eine vereinfachte Ökobilanz als ein geeigneter Ansatz. Die Fallstudie zeigt, dass IKT Infrastruktur an sich relativ geringe Auswirkungen hat, wohingegen der Betrieb beträchtliche Umweltauswirkungen aufweist.
Die Schlussfolgerung dieser Arbeit ist, dass EEE nicht als eine gemeinsame, sondern als zwei Gruppen von Produkten gesehen werden sollte, wenn es um die Bewertung ihrer Umweltauswirkungen geht. Dies liegt daran, dass sich in der Nutzungsdauer, Materialzusammensetzung und Art der Nutzung große Unterschiede zwischen elektrischen und elektronischen Geräten zeigen. Daher sollten unterschiedliche Bewertungsansätze verwendet werden. Es zeigt auch, dass die Ökobilanz nicht immer eine geeignete Bewertungsmethode für jede Arten von Produkten ist.
Die Wahl eines geeigneten Tools hängt neben der Fragestellung auch von den zur Verfügung stehenden Mitteln (Zeit, Daten, Fachwissen,...) ab. Je nach Fragestellung kann sich die Verwendung eines einfachen Tools als sinnvoller und aussagekräftiger erweisen, als die Verwendung eines anspruchsvollen Tools. Ein gutes, aber nicht geeignetes Tool kann falsche Ergebnisse liefern. Daher sollte bei der Wahl des Tools besondere Sorgfalt gelten und ein Tool entsprechend der Fragestellung gewählt werden.

Keywords:
Umweltbewertungstools, software tools, EEE, life cycle thinking, Glasfaserkabel

Publications in context with this study:

Reviewed publications

Paper I Unger N., Wassermann G., Beigl P. (2004): *General Requirements for LCA Software-Tools*. In: Pahl-Wostl C., Schmidt S., Jakeman, T.: iEMSs 2004 International Congress: 'Complexity and Integrated Resources Management', 14. – 17. Juni 2004, Osnabrueck, Germany; Proceedings (Internet, CD), k.S.; International Environmental Modelling and Software Society, Osnabrück, Germany

Paper II Unger N., Schneider F., Salhofer S. (in preparation) *A Review of ecodesign and environmental assessment tools and their appropriateness for electrical and electronical equipment*. Progress in Industrial Ecology (accepted)

Paper III Unger N. (2007) Applying a system perspective to the assessment of materials – a discussion of the limitations of current environmental assessment approaches. In Weil M., Buchwald A., Drombrowski K., Jeske U., Buchgeister J. *Materials Design and Systems Analysis.* May 16 – 18, 2006, Forschungszentrum Karlsruhe, Germany, Shaker Verlag, Aachen

Paper IV Unger N., Gough O. (in preparation) *Life cycle considerations about optic fibre cable and copper cable systems – a case study*. Journal of Cleaner Production in press (accepted)

These papers are reviewed papers and basis for this thesis. They are referenced to in the text as Paper I, Paper II. etc.

Not reviewed publications:

Unger N., Wassermann G. (2003): *The Use of Appropriate Software-Tools for LCA in Waste Management – A Comparison*. In: T.H. Christensen, R. Cossu, R. Stegmann: SARDINIA 2003 – Ninth International Waste Management and Landfill Symposium, 6. - 10. Oktober 2003, S. Margherita di Pula (Cagliari), Italy; Proceedings (Abstract; Langfassung auf CD), pp.193-194

Unger N., Duffy N. (2005): *Considering Environmental Issues - the Pro and Cons of Tools*. In: J. Vickery (Ed.): IMC22 - 22nd International Manufacturing Conference 'Challenges Facing Manufacturing', 31 August - 2 September 2005, Dublin/Ireland; Proceedings, pp.739-744

Unger N. (2005): *A review of ecodesign tools and measures and their appropriateness for different types of products*. In: KERP Kompetenzzentrum Elektro(nik)altgeräte-Recycling & nachhaltige Produktentwicklung: eco-X: ecology and economy in electroniX 2005 „Zukünftige Herausforderungen und nachhaltige Lösungen für den Elektro(nik)sektor", 8. – 10. Juni 2005, Wien; Proceedings, pp.369-383

Unger N. (2005): *A Review and Comparison of the Environmental Impact of Different Materials Across Their Life Cycle*. In: Raffaello Cossu, Rainer Stegmann (Ed.): SARDINIA 2005 Tenth International Waste Management and Landfill Symposium, 3 – 7 October 2005, S.Margherita di Pula, Cagliari, Sardinia/Italy; Proceedings (Abstract; full paper on CD), pp.907-908; CISA Environmental Sanitary Engineering Centre

Unger N. (2006): *Material environmental assessment – pitfalls, obstacles and other aspects*. In proceedings of the International Workshop – Material Design and System Analysis – Integration of Economics and Environmental Aspects into the Development Phase. 16-18 May 2006, Karlsruhe, Germany

Unger N., Salhofer S. (2006) Informations- und Kommunikationstechnologie. In: Herrmann C., Leitner T., Paulesich R. (Eds) *Nachhaltigkeit in der Elektronkindustrie*. Fortschrittsberichte DTV, Reihe 16 Technik und Wirtschaft, Nr. 179 VDI Verlag

Unger N., Salhofer S. (2006*) Life Cycle Assessment and its Applicability for Electrical and Electronic Equipment.* Going Green CARE INNOVATION – From WEEE/RoHS Implementation to future sustainable electronics. Sixth International Symposium and Exhibition, 13-16 November 2006, Vienna, Austria

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1 *INTRODUCTION*

1.1 Background

While some decades ago environmentalists were considered tree huggers, hippies or 'not from this world' this attitude has changed greatly. Today the environmental discussion is no longer considered just an additional aspect to other, more important fields of research but it is an important decision support for authorities, the public, professionals and companies. Environmental issues are topics of world leader summits and can be found in the media on a regular basis.

One of the publicly most discussed issues today is global warming and green house gas strategies, which can be found on the agenda of many politicians and managers. Several politicians, economists and industry representatives denied the environmental impact from human activity for many years although research showed otherwise. Some economists still seem to think that the resources of the planet are unlimited (Schor, 2005) and growth is the highest aim. However, more and more people in public life support initiatives such as greener energy or the protection of tropical rain forests with words or deeds. For artists, managers and politicians it is fashionable to be green. One of the most prominent and accredited person of public life who is strongly promoting the environmental cause and in particular the one of climate change is former US vice president Al Gore. For many years he has been active for the cause of the environment and was even awarded the Oscar by the US Academy of Film for best documentary in 2007 for his film 'an inconvenient truth – a global warning' (Paramount classics 2006). In the same year he also received the Nobel prize for peace, jointly with the Intergovernmental Panel of Climate Change (IPCC).

Besides the political efforts also industry competes for environmental recognition for instance by using environmentally benign materials and reducing the environmental impact of their products. Those achievements are then used for information or commercial purposes. Companies (from small and medium sized enterprises to multinational companies) use different ways of communicating their environmental commitment. Different media are used such as ecolabels (e.g. Österreichsiche Umweltzeichen, Blauer Engel), certifications (EMAS, ISO 14000) and environmental-, sustainability- or Corporate Social reports (CSR).

While the aim to reduce the anthropogenic impact on the environment is well recognised there are different approaches to do this. For that it is important to assess the environmental performance of products, technologies or services and any improvements due to changes. There are a number of concepts, methods and tools available that enable an analyst to estimate the environmental impact. However, each of these has advantages and disadvantages which makes the choice difficult.

1.2 Aim & Scope

In order to assess and analyse the environmental impact of products, services and technologies, concepts and tools need to be applied. A wide range of such environmental tools can be found in the literature. Therefore, when having the task to assess a certain product the analyst needs to decide which of the wide range of tools is most suitable. The choice of the right tool is essential to gain relevant results. Tools (such as Life Cycle Assessment which is probably one of the best known tools) are often seen as the 'universal environmental assessment tool' however, that might not always be the case. Therefore, it is necessary to investigate which tools are suitable for the assessment of certain products and which tools should not be used.

Thus this thesis aims to review environmental tools and analyse their use for Electrical and Electronic Equipment (EEE). A review of the body of literature is performed to understand the types of tools and to gain an overview on tools in use. Special emphasis is given on the reason why tools are considered suitable for some questions but prove not suitable for other problems. Life cycle thinking and its use in assessing the environmental impact is discussed in detail.

In this study EEE is chosen as the scope for the application of tools because it represents a wide range of products that find application in private households as well as businesses and covers small devices such as mobile phones as well as large equipment like refrigerators. Special emphasis is put on Information and Communication Technologies (ICT). This subgroup of EEE is the latest milestone in society development and its impact is often compared with the industrial revolution (Figure 1).

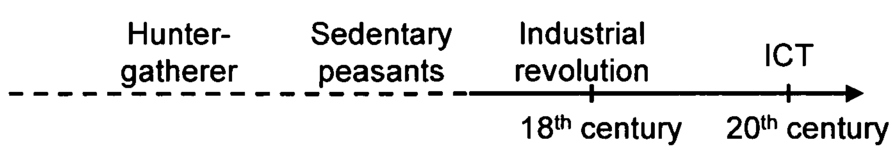

Figure 1: Milestones of society

In addition to the analysis of case studies published in scientific literature, two case studies are performed for this thesis using suitable environmental tools and describing why they were chosen. The first case study analyses the impact of providing ICT infrastructure (internet access) via optic fibre cable and via the traditional copper cable in a defined residential area. This comparison aims to show the applicability of the life cycle approach and the environmental benefit or impact due to the change in technology. A second case study is carried out on a device used in opto-electronics. Again two different (manufacturing) technologies are compared and the suitability of Life Cycle Assessment is discussed.

This thesis covers the following issues:

- Understanding sustainability in the context of Information and Communication Technologies
- Review of environmental concepts, methods and tools
- The use of environmental tools for EEE
- The importance of choosing the appropriate tool
- Life cycle thinking
- The environmental impact of optic fibre cable and copper cable
- Problems in assessing new technologies

1.3 Outline

In Chapter 2 the context of EEE and sustainability is shown. As example ICT are used and a brief review of its impact on society, economy and environment is given. This gives a better understanding of the importance of EEE in today's life.

In chapter 3 methodological considerations are summarised. It starts with an overview of different types of tools and ways of categorising them. Their advantage, disadvantages and applications are described. This leads to a discussion of the life cycle and life cycle thinking. Finally in order to apply the knowledge of methodological aspects of environmental assessments, software tools are usually used. Software tools are standard today and help in modelling and data gathering. However, general requirements need to be fulfilled in order to be of use for the environmental analyst.

In Chapter 4 two case studies are described and the success or failure in applying the life cycle approach described. Chapter 5 summarises and combines results of the research of done in chapter 3 and they are discussed in chapter 6. In the conclusions in chapter 7 the major outcomes of this thesis is summarised in bullet points.

2 ELECTRICAL AND ELECTRONIC EQUIPMENT AND SUSTAINABILITY

2.1 Definition of Electrical and Electronic Equipment – EEE

The phrase 'electrical and electronic equipment' is used in many contexts and can be found in technical and non technical publications. In the Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE) (European Union, 2003) EEE is defined as

'equipment which is dependent on electric currents or electromagnetic fields in order to work properly and equipment for the generation, transfer and measurement of such currents and fields falling [...] and designed for use with a voltage rating not exceeding 1 000 Volt for alternating current and 1 500 Volt for direct current'.

Within the directive EEE is distinguished into the following 10 categories:

1. Large household appliances, e.g. refrigerators, freezers, washing machines, dish washers, electric stoves, microwaves, electrical radiator, air conditioners
2. Small household appliances, e.g. vacuum cleaner, irons, toaster, fryers, grinder, scales
3. IT and telecommunications equipment, e.g. printer, PCs, laptops, calculators, telephones, mobile phones
4. Consumer equipment, e.g. TVs, video and hi-fi recorders, musical instruments
5. Lighting equipment, e.g. fluorescent lamps
6. Electrical and electronic tools (with the exception of large-scale stationary industrial tools), e.g. drills, saws, sewing machines, tools for welding, or gardening activities
7. Toys, leisure and sports equipment, e.g. electric trains or car racing sets, video games, computers for biking, diving, running, rowing, etc., coin slot machines
8. Medical devices (with the exception of all implanted and infected products), e.g. radiotherapy equipment, dialysis, nuclear medicine, freezers, analysers, pulmonary ventilators, fertilisation tests
9. Monitoring and control instruments, e.g. smoke detectors, heating regulators, thermostats
10. Automatic dispensers, e.g. automatic dispensers for hot drinks, bottles, cans, money

2.2 Regulations in context with EEE

EEE plays an important role in today's society and has a wide range of applications. A number of directives issued by the European Union are of direct or indirect relevance for this group of products and address issues such as waste, hazardous substances and ecodesign. The most prominent activities are briefly described:

- **Directive on Waste Electrical and Electronic Equipment (WEEE)**: This directive focuses on the prevention of WEEE, its reuse, recycling and other forms of recovery and on reducing the disposal of waste. A main objective is "producer responsibility" which requires producers of EEE to have the financial responsibility to ensure proper disposal of their products (EU, 2003)
- **Directive on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS)**: This directive aims to severely restrict the content of particular hazardous materials. Avoiding these substances will avoid problems at the end of the product's life. Among the restricted substances is lead, which is ubiquitous in electrical and electronic products (EU,2003)
- **Energy-using Products (EuP)**: This Directive (EU 2005) focuses on the energy use of products. Furthermore it wants to emphasise "ecodesign" since it is assumed that about 80% of all environmental effects associated with a product are determined in the design phase of development (UBA, 2000).
- **Integrated Product Policy (IPP)**: The main objective is that the environmental impact of goods and services should be as little as possible throughout their entire lifecycle. "Life cycle thinking" and the identification of significant environmental aspects are more important than detailed life cycle analysis (Commission of the European Communities, 2001).

2.3 EEE and sustainability – the example of Information and Communication Technologies

2.3.1 Background

Electrical and Electronic Equipment (EEE) such as computers, mobile phones are part of Information and Communication Technologies (ICT) are used in everyday's life. In only a few years these new technologies became an integrated part in modern life. These new products offer features and possibilities like no technology before. Information and Communication Technologies (ICT) are used at homes, for shopping, transport, food, health, clothing, work or leisure time etc. Distances are no longer an obstacle in communication. Thus also habits have and are continuing to change.

Due to this continued rapid and sustained growth of the ICT sector, it is increasingly relevant for the economy and environment (Williams, 2003). But also society is affected by this trend. Thus, it is necessary to view this development from a wide point of view. Figure 2 shows the influence of ICT on each area of sustainability.

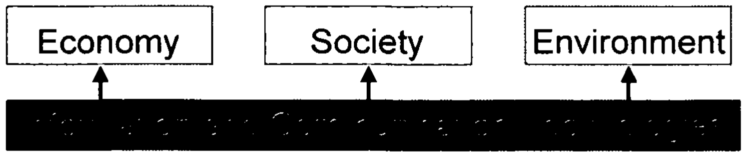

Figure 2: Schematic illustration of effects of ICT on different areas

2.3.2 What is ICT

There are different definitions of ICT. The member countries of the OECD agreed in 1998 to define the ICT sector as a combination of manufacturing and services industries that capture, transmit and display data and information electronically. This definition is based on the internationals standard classification of activities (ISIC Rev. 3) (OECD, 2002). In a wider definition ICT comprises all devices that have a chip, although that would also includes kitchen devices. In literature ICT is often used for all new technologies such as PCs, game consoles, mobile communication and equipment of the entertainment sector. There are some features that are typical especially for electronic devices:

- Miniaturisation: parts and components constantly become smaller
- Very short innovation time: New developments enter the market every few months
- Increasing number of features: e.g. cameras on mobile phones
- Large number of materials used
- Use of precious metals, especially in printed circuit boards
- Shift from tools to life-style objects
- Constantly changing user pattern
- Short use phase

2.3.3 ICT and society

The effects of ICT are often compared with those of the Industrial revolution. Then the invention of the steam engine by James Watt in the 18^{th} century enabled manufacturers to substitute unreliable energy sources such as water, wind or muscles by energy from steam. This, at that time new, technology caused changes in economy and in society. However, they also had heavy impact on the environment. The same is happening today with ICT and again effects on all three columns of sustainability occur. In Table 1 the penetration of ICT in the western world is shown with some examples. Iceland hast most internet users worldwide, with an average of 6.7 per 10 inhabitants. In

Switzerland 7.1 persons out of 10 own a PC. Most mobile phones can be found in Taiwan, Luxembourg and Hong Kong where, in average, every person owns more than one mobile phone.

Internet user per 10 000 inhabitants 2003		PCs per 100 inhabitants 2003		Registered mobile phones per 100 inhabitants 2003	
Iceland	6 747.40	Switzerland	70.87	Taiwan	110.84
Korean Republic	6 034.20	USA	65.89	Luxembourg	106.05
Sweden	5 730.74	Singapour	62.20	Hong Kong	105.75
USA	5 513.77	Sweden	62.13	Italy	101.76
New Zealand	5 262.37	Luxembourg	59.42	Iceland	96.56
Netherlands	5 219.49	Danmark	57.68	Czech Republic	96.46
Canada	5 128.29	Australia	56.45	Israel	95.45
Danmark	5 128.15	Korean Rep.	55.14	Spain	91.61
Singapour	5 043.59	Norway	52.83	Norway	90.89
Norway	5 026.08	Canada	48.70	Portugal	90.38

Table 1: Top 10 countries worldwide in internet, PC and mobile phone usage (Source: http://www.itu.int/ITU-D/ict/statistics/at_glance/cellular03. pdf)

These new technologies also change people's behaviour pattern. E-commerce is a good example for that. Business to Business (B2B) as well as business to costumer transactions are more and more done via the internet. Also for private purchases the internet is an important source for information, books, flight tickets, or a substitute for flee markets and garage sales.

2.3.4 ICT and economy

The development of ICT is responsible for a whole new market. The internet became the marketplace of the future which enables business to "meet" even if they are located in different parts of the world. In this context the phrase 'the new economy' is often mentioned which stands for a new and dynamic economy. In general the main features of new economy are (Meyer 2002):

- Economical and social changes due to ICT
- A shift towards information and service orientated activities
- Use of modern technologies, especially telecommunication, PCs and internet
- Networking with business partners, suppliers and costumers
- Globalisation of the economy
- New Economy is not restricted to a certain branch of industry

Furthermore ICT equipment provides a whole new spectrum of devices for the consumer market. In 2004 ICT expenditures worldwide were estimated 2160 billion Euro of which the United States had the highest share of about 32% (EITO, 2004). The growth rate of ICT and the GDP for the last 10 years are given in Figure 3. It shows that the ICT sector had a growth of more that 10% in the period of 1998 to 2000 when the so-called dot.com enterprises were booming. In 2001 the market collapsed but today it is growing again.

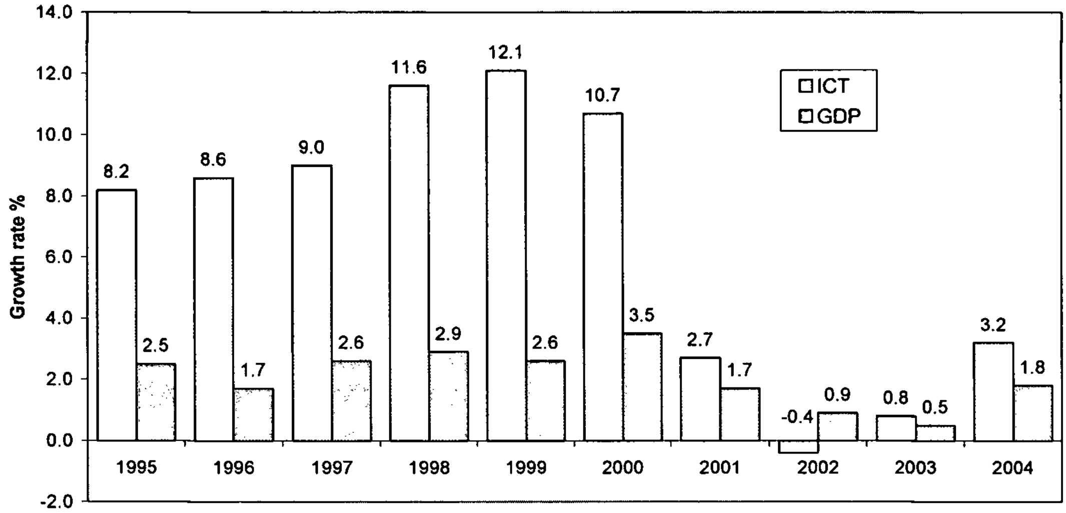

Figure 3: Annual growth rate of the ICT market and the GDP in the European Union 1995 – 2004 (EITP, 2004)

2.3.5 ICT and the environment

For many years it was believed that economic growth is strongly linked with increase in energy consumption. Today this link is getting weaker in the western, industrialised world. In developing countries however economy is still much depending on energy (EIA, 2004). Reason for this difference is the high usage of ICT in the developed world. ICT has (theoretically) the potential to de-link economic growth from energy consumption and its negative environmental impact. While traditional industry was heavily relying on fuels and resources, more factors are of relevance in the ICT sector. There productivity is increased and value added by manipulation of ideas and information (Plebys, 2002), which results in a dematerialisation. Virtual good such as services, software and ideas are important rather than physical.

The impact of ICT can be distinguished into two (Plebys, 2002) to three categories (Hilty et al., 2003; Berkhout et al., 2001)."Primary or direct effects" are those that occur from production, use and disposal – the life cycle – of a device. "Secondary or indirect effects" occur on the one hand due to the use of ICT (e.g. traffic) and on the other hand due to changes in consumer habits and structural changes (tertiary effects). While direct effects mainly affect the environment, indirect effects have a wider impact and affect also society.

In order to assess the environmental impact of electrical and electronic equipment, it is important to look at the whole life cycle of a product. Only an integrated approach can show life stages with a high environmental relevance, so called 'hot spots' and those where a lower environmental impact can be expected. Measures then can be focused on environmental hot spots where they will have the biggest effect.

2.3.6 Environmental impact in production

Production of EEE is characterised by short innovations cycles. Moore's Law (e.g. Kuehr et al., 2003, Hilty et al., 2003) claims that the pace of technological progress is in some sense constant, since the number of transistors that can be put on one chip has doubled every 18 to 24 months for at least the last three decades. Equipment becomes smaller (e.g. mobile phones, laptops) and more efficient. Thus ICT equipment could help to dematerialise economic growth. But the performance improvements in the ICT sector also lead to an increased consumption of ICT products and services, which has numerous environmental implications on different levels (Plepys, 2002). This increase in consumption results in more and more appliances having ICT components integrated (e.g. cars) and this causes a higher penetration of ICT. With an increase in the amount of ICT equipment the price decreases. This is another incentive for people to substitute old equipment with these new developed products with new features. This phenomenon is called the 'rebound effect'. Instead of a reduction in resource use due to more efficient technologies there is an overall increase. For instance an increase in communication technology can on the one hand bring different cultures closer together and on the other hand increase the exchange of goods on long distances. There is also a positive correlation between the use of emails and video-conferences and the number business trips. (Berkhout et al., 2001; Schauer, 2003; Hilty 2003).

In general electronic components production is very energy and material intensive. Often no more than 2% of the material input are actually part of the component, the rest (98%!) are waste (Hilty et al., 2000). For example a computer chip of 2 gram needs 1200g fossil fuel (mainly for energy generation), 72g of chemicals, 700g elementary gasses (mainly nitrogen) and 32 litre of water (Williams et al., 2002). Especially the energy demand in production stage of electronic products is of importance which is often higher than in the use phase. Energy consumption in manufacture of a PC used at home is estimated to be four times higher than in use phase. Electrical equipment usually consumes more energy in the use phase, a fridge for instance consumes in production only about one eighth of the energy it consumes during use (Kuehr et al., 2003).

In manufacture of ICT equipment a steep value increase can be observed. In each processing step materials and parts are more refined and thus value is added. Williams (2003) for instance claims that one kilogram of elementary silicon has a value of 1.70 US Dollar, while one kilogram of silicon in a wafer (part of a chip) is worth 1500 US Dollar.

Infrastructure that allows the use of ICT, such as masts, wiring and even satellites, causes additional environmental impact. However, an accurate allocation to individual products is often difficult, nevertheless, they should not be neglected. For example for the Italian GSM network a material intensity of 134kg per user is estimated, while the T28 Ericsson mobile phone needs “only” 76kg of materials, including all preceding processes (Frederico 2001 in Hilty et al., 2003)

2.3.7 Environmental impact in use

In the use stage ICT equipment mainly consumes energy in form of electricity. The environmental impact depends on how this electricity is generated. Since ICT is used worldwide it is important to have a broader look at it. Fossil fuels, mainly coal and gas, are dominating worldwide (EIA, 2004) In Figure 4 the electricity mixes for different parts of the world are shown.

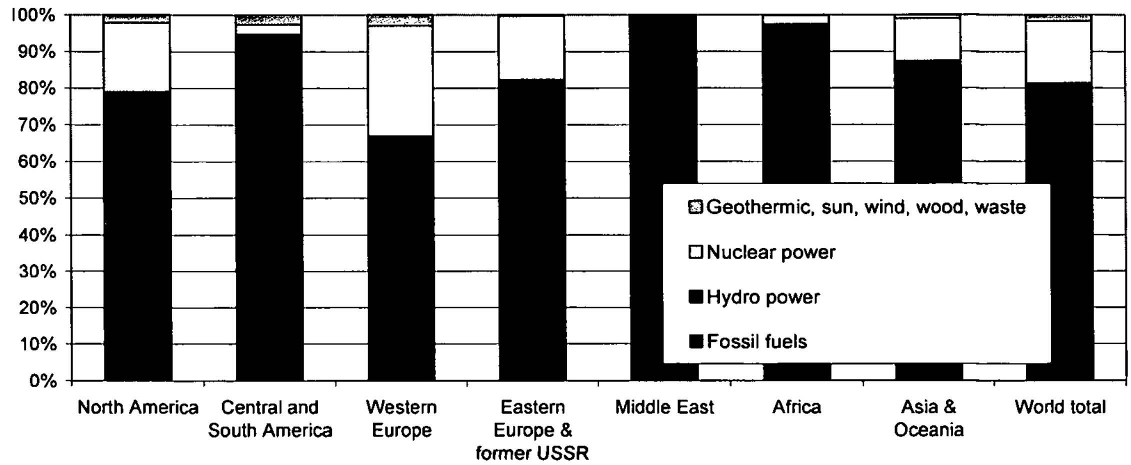

Figure 4: Mix of sources for electricity in different regions of the world and worldwide (Source: Energy Information Administration on http://www.eia.doe.gov/emeu/iea/elec.html)

About 50% of equipment has in addition to a rechargeable battery, energy supply using an electricity lead. This increases mobility and this is often the reason why a product is used, e.g. mobile phone. But batteries can contain a number of hazardous substances. Nickel-cadmium batteries were widely used for many years, today mainly nickel-metal hybrid and lithium-ion batteries are used in products.

Besides the energy consumption the issue of electro-magnetic radiation needs to be mentioned. Being a new form of emission its impact on human health and the environment are still not thoroughly investigated. Some studies suggest that electro-magnetic radiation, can potentially affect brain activity, sleep and cause genetic mutations, but there is still a lot of uncertainty in these results (Hilty et al., 2003).

2.3.8 Environmental impact in disposal

Electrical and electronic waste quantities account for about 4% of municipal waste in the European Union (Berkhout et al., 2001). This number is rising despite the fact that the size of equipment decreases and efficiency increases. One reason is that the use span is nearly always shorter than the technical use span. Short innovation times make a product obsolete soon, or compatibility with other products more difficult. Also fashion and life style trends are responsible for the short use and thus early replacement of still functional products. Small equipment is often disposed of as residual waste and not collected separately. This and the small size of components make a recovery of components and recycling difficult. Therefore, it is important to recognise the environmental risk that is associated with the rising amounts of waste from ICT and to develop approaches that help dealing with it.

Excursus: Exporting Harm

Many countries still do not want to see the problems caused by ICT. The Basel Action Network has published two very demonstrative and often cited reports 'Exporting Harm – the high-tech trashing of Asia' (Puckett et al, 2002) and 'The Digital Dump: Exporting Re-Use and Abuse to Africa' (Puckett et al, 2005). They depict with many pictures the "treatment" of waste electronic equipment in China and Africa respectively. It describes the environmental problems due to contamination of groundwater and hence food as well the hazards people take upon them when working with often highly toxic substances. Since there is a lack of protection (Picture 1 and Picture 2) people are in immediate contact with substances like lead or phosphor dust, as in the case of monitor dismantling. The reports also address the issue of imports of second-hand electronic equipment from Europe and the US which is to a high percentage merely waste.

Picture 1: Typical E-scrapping dismantling operation Guiyu, China. December 2001 (Source: Puckett et al, 2002)

Picture 2: Woman about to smash a cathode ray tube from a computer monitor in order to remove the copper laden yoke at the end of the funnel. Guiyu, China December 2001 (Source: Puckett et al, 2002)

Electrical and electronic waste is also on the agenda of organisations such as Greenpeace (http://www.greenpeace.org/international/campaigns/toxics/electronics/where-does-e-waste-end-up) and a number of journal papers investigate the impact of these recycling activities on the environment and people (e.g. Deng et al., 2007; Qu et al., 2007).

3 METHODOLOGY – REVIEW OF TOOLS

3.1 Types of tools for environmental assessment

The assessment of environmental impacts can be approached by practitioners from different backgrounds, motivations, levels of influence and by different stakeholders. Thus expressions such as method, tool, approach, concept, etc. are used differently by different groups of practitioners and many classifications can be found in literature. Usually 'concepts' reflect the intention and aim of the approach (what), while 'tools' enable the user to do it (how). All types of tools are supported by technical elements such as mass balances which require relevant data. A schematic sketch of the dependencies is shown in (Figure 5). In the group of concepts, for instance, ecodesign, life cycle thinking, clean technology and dematerialisation are often mentioned. There can be big overlaps between concepts and tools such as for Life Cycle Assessment which is sometimes referred to as a concept but which is also a standardised tool. Moreover, there are overlaps between single concepts which often use the same tools. Some of the tools are more detailed and do a thorough environmental assessment of a product, others enable a quick and easy examination of environmental issues, in a manner suitable for non-environmental experts. In this paper the expression "tool" is used in a wider sense because often there is no clear distinction between those different expressions.

Tools used in environmental assessment are very diverse and were developed with different backgrounds (e.g. academic, industry). A large number of tools have been published in literature. Baumann and colleagues (2002) identified more than 150 tools. It can be observed that many companies and institutions involved in environmental and sustainability tend to develop a new tool rather than applying existing ones. Thus, despite the large number of tools, only few have made a significant breakthrough so far (Ammenberg et al., 2005). One explanation for this might be that it is often very difficult to gain thorough and detailed information on how a tool works. Often tools are developed in parallel to a case study and as part of academic work such as a thesis. Thus only few existing tools are improved over time. Moreover, some tools are very useful in one case study, if the study is done by the institution that developed the tool, but considered to be inconvenient if the study is done by another institution or person, because important data is not accessible. Further, the use of not one specific tool, but of a toolbox, a set of different tools, is often used. In this way weaknesses of one tool can be compensated by applying additional tools.

Tools in environmental management can be classified in different ways (adapted from Wrisberg et al., 2002):

- tools that communicate with outside the company,
- analytic tools and
- procedural tools

- Ecodesign tools

The first category comprises all external incentives (legal requirements, requisites from suppliers, requisites from customers,...) as well as all communication from the company to the public like environmental statements and announcements.

Analytic tools are methods that were developed to assess or screen a product's full life cycle, certain stages of the life cycle or certain aspects (e.g. materials, energy). They model the system in a quantitative or qualitative way, aiming at providing technical information for a better decision (Wrisberg et al., 2002). The range of analytic tools reaches from very simple and quick tools to elaborate, data and time intensive ones. Examples for analytical tools for the environment are Life Cycle Assessment (LCA), Material Flow Analysis (MFA), Cumulative Energy Demand (CED), Material Intensity per Service unit (MIPS), Input / Output Analysis (IOA) or Environmental Risk Assessment (ERA).

Procedural tools guide in the process to reach and implement an environmental decision. Procedural tools are, for instance, environmental management systems, environmental audit, Strategic environmental Assessment or environmental labelling (Wrisberg et al., 2002).

Additional ecodesign tools should be considered as a separate group of tools. Ecodesign is often also referred to as green design, ecological design, environmentally sound or environmentally sensitive design, DfE (design for the environment), environmentally responsible design or others (Baumann et al., 2002). As the name indicates, ecodesign is a concept applied in the design and development phase of a product's life cycle. It stands for an environmentally conscious design. Ecodesign can be applied to newly developed products or to redesign of existing products. It is assumed that about 80% of all environmental effects associated with a product are determined in the design phase of development (UBA, 2000 in CEC, 2003). Examples for ecodesign tools are checklists, material exclusion lists, ABC Analysis, or software tools such as the Ecodesign Pilot (http://www.ecodesign.at/pilot).

In Figure 5 a framework of concepts and (analytical and procedural) tools is shown (Wrisberg et al. 2002). It illustrates the relation of different elements in environmental assessment. First the concept needs to be chosen by the analyst. This is determined by the reason (question) why the assessment is done and what should be achieved by it. Then appropriate tools are identified in order to reach the set goal. One tool can be sufficient or a set of tools might be necessary. In a next step technical elements such as the methods of obtaining data, data processing etc. are considered. As a last step qualitative and quantitative data is required.

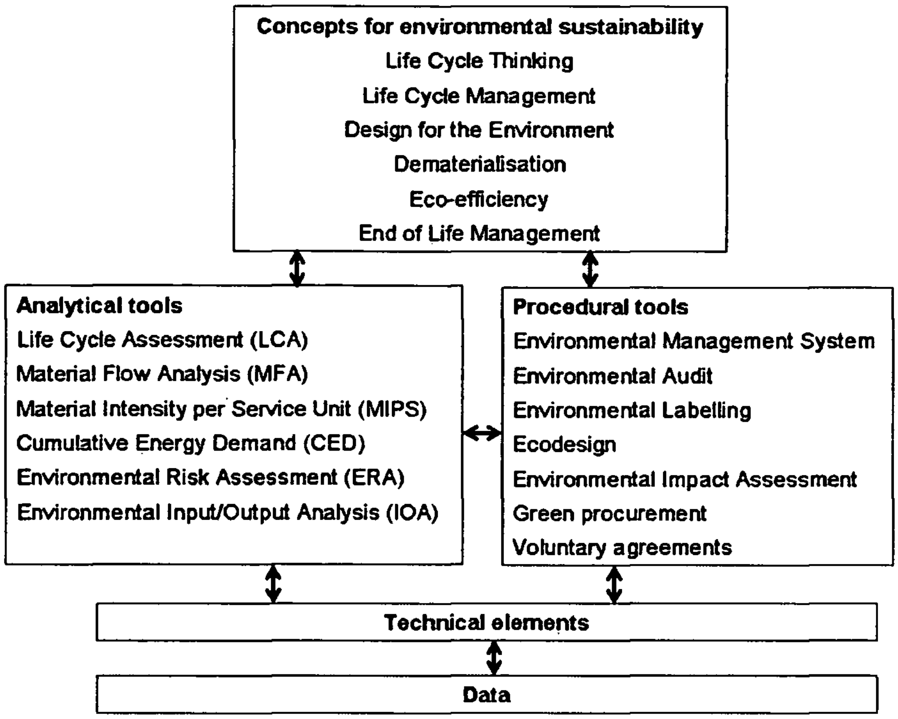

Figure 5: Schematic sketch of the framework of concepts and tools (adapted from Wrisberg et al., 2002)

Another categorisation of tools is given in Baumann and colleagues (2002):

- Frameworks
- Checklists and guidelines
- Rating and ranging tools
- Analytic tools
- Software and expert systems
- Organising tools

Moreover they distinguish different levels of spheres of actions:

- Level 1 deals with the product development process and its tools as such
- Level 2 deals with the product development process in a company context, relating it to business strategy and management, marketing, etc.
- Level 3 deals with the product development process in a product chain perspective, including the interaction with, for example, suppliers, customers, waste handlers, etc.
- Level 4 deals with product development in relation to the policy-making process.

In general tools can be distinguished into 'simple tools' and 'sophisticated tools (see Paper II). Sophisticated tools are tools that require a lot of time, data and experience to carry them out. Example for sophisticated tools are Life Cycle

Assessment (LCA), Material Intensity per unit of Service (MIPS) or Cumulated Energy Demand (CED or Kumulierter Energieaufwand, KEA). Simple tools are, as the name suggests, simple to use. Using a simple tool allows the analyst to obtaining quick results and their use requires only limited amount of data. Check lists, material exclusion lists or Performance Indicators (PI) can be found in this group of tools. In Paper II these and other tools are described in more detail and examples for their use shown.

There is also a number of tools especially focusing on the assessment of EEE. Examples for such tools are

- Prodtect (http://www.prodtect.com/): A software tool that helps in modeling the end-of-life of a product already in the design stage. It calculates a potential recycling rate and the costs of recycling for a product, characterized by material lists, joining technique and other construction features,
- QWERTY/EE Concept: Qualifying Recyclability and Eco-efficiency for End-of-Life Treatment of Consumer Electronic Products (Huisman, 2003). It focuses on the potential recyclability of products not using a weight based approach but based on a scale, ranging between a best and worst case scenario,
- IZM/EE Toolbox: It comprises a number of different tools that can focus on different aspects of electronics (e.g. Toxic Potential Indicator, energy demand) or different life stages (Recycling Potential Indicator). The toolbox was developed by Fraunhofer Institute for Reliability and Microintegration (IZM) to be applied in the design phase of electronic products and processes.

3.2 Software tools for environmental assessment

Beside methodologies for environmental assessment a whole market for software tools has emerged. There are simple software tools that help calculating the environmental footprint, give the amount of greenhouse gases emitted depending on a persons lifestyle or help smaller companies that can not afford to have an environmental expert to advise them in making environmentally benign decisions (e.g. Ecodesign Pilot).

There is also a range of software that helps in using and applying analytical tools, mainly LCA and similar life cycle orientated tools. Among the most commonly used software tools are GaBi by PE Europe, Umberto, by the Institute for Energy and Environmental Science Heidelberg (ifeu) and Institute for Environmental Informatics Hamburg (ifu) and Sima Pro by Pré.

Environmental assessments can involve time and data intensive tasks and software tools can help in modelling in several ways, such as

- Modelling environment
- Transparency
- Database
- Source for data in connection with the methodology
- Communication tool

First of all software tools provide the "environment" where the modelling is done. This is usually an interface that enables to user to connect different processes with material flows. In doing so a single life stage or a whole life cycle is assembled and displayed in a transparent way. In some software tools a hierarchical structure helps in displaying more complex process chains. An example is given in Figure 6.

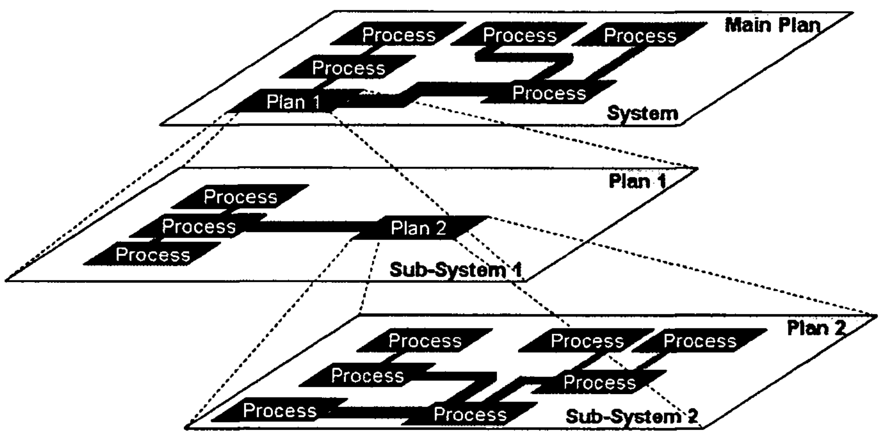

Figure 6: Hierarchical structure in GaBi. Source: IKP, PE: GaBi 4 Software System and Database for Life Cycle Engineering. Copyright, TM. Stuttgart, Echterdingen 1992-2002 (User Guide)

This subdivision of processes improves transparency and enables to modelling of extensive systems under investigation.

Besides these graphic elements, software also serves as data source. It contains inputs and outputs of materials and products of a single process or it contains all inputs and outputs summarised up to this stage; for instance the inputs and outputs of a process that has PET pellets as its output would cover all process steps that occur before as well. The database that is provided with the software should cover a broad spectrum of information, particularly often used data, such as commonly used fuel or materials. Data should be up-to-date and complete. A very important aspect is a good documentation. Here the limits and conditions of use are explained, for which geographical region the data are valid, which allocation rules were applied and the uncertainty of the data. Further its source must be clearly stated.

There is a well-developed market for LCA software tools that ranges from free-of-charge to very expensive and from simple to highly sophisticated. Most of the tools focus on production. More recently a market was discovered for other fields of use, such as waste management or agriculture and many software tools have been made more flexible and adaptable.

Other aspects that are of importance for good environmental software tools are issues like:

- User friendliness
- Service and support
- Costs

However, software can not substitute the methodological knowledge of the analyst. Only when there is a thorough understanding of the methodology the analyst knows how to handle the data and results.

In Paper I requirements for LCA software tools are described in detail.

3.3 The life cycle

Life cycle thinking is the basis for several environmental assessment tools such as LCA. Usually the life cycle is illustrated as linear sequence of processes, from raw material extraction, production, distribution, consumption or use and final disposal. Recycling loops can be part of this system. In Figure 7 an example for such a life cycle is shown. Into each of the processes the inputs are resources and the outputs are waste and other emissions.

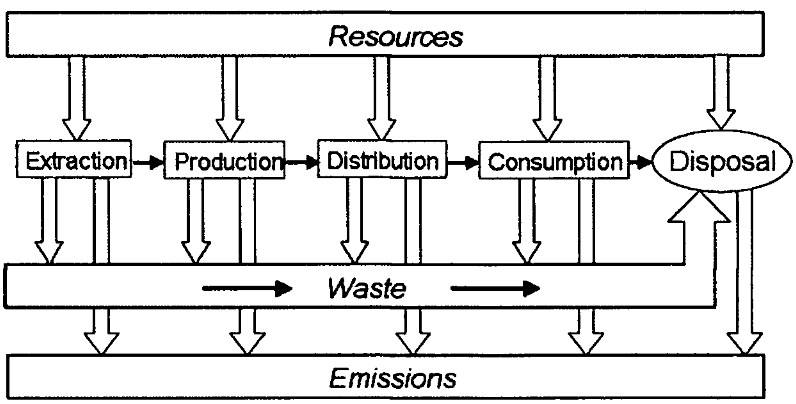

Figure 7: Resource flows through the schematic life cycle

However, this figure is just a simplified version of the life cycle stages of an average product. Although most practitioners will agree that it is impossible to consider all flows in a life cycle approach, it is also difficult to determine the extend of the relevant system boundaries that define the system for the life cycle under investigation.

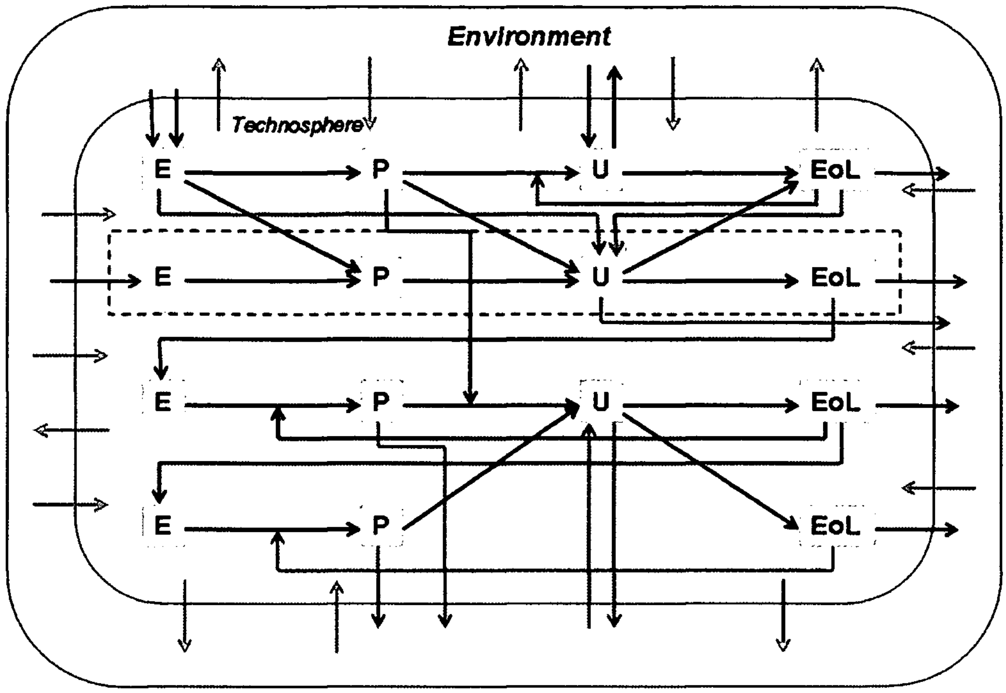

Figure 8: The Life Cycle Net (E: Extraction, P: Production, U: Use, EoL: End of Life)

In Figure 8 this problem is illustrated. Starting from the simple process flow given in Figure 7 a more detailed net of material flows is drawn. It shows that as soon as resources are extracted or treated they become part of the technosphere, where all human activities are captured. The environment in which the technosphere is embedded provides all the resources for the system and acts as the sink for all emissions, i.e. it is both cradle and grave. Several life cycles can be found in the technosphere. They are sketched in a simplified way in Figure 8 showing extraction, production, use and end of life. The life cycle in the dashed box represents the foreground of a specific product. It can be seen that a number of outputs (materials and intermediate products) of other life cycles become part of it in different life stages. At the same time product(s) and emissions are emitted. The latter can either remain in the technosphere and become part of another life cycle, or they are emitted into the environmental again as emission into water, air or soil. Within this net of inter-woven inputs and outputs it can be difficult to determine which process or flow belongs to which product life cycle. That can make the assessment of a certain life cycle difficult and can be the reason for allocation problems.
Furthermore the difference between a life cycle of a product and a life cycle of materials becomes apparent. A lack of a use phase for materials' life cycles is the most significant difference.

This knowledge leads to considerations on where a life cycle starts and ends. The product looses its function at the end of life, i.e. when it is disposed of. However, the life cycle of the materials the product is made of will continue until the material finally leaves the technosphere and is emitted into the environment. This can be at the end of life of a product or after a series of products.

A detailed discussion on the life cycle can be found in Paper III.

4 CASE STUDIES

4.1 Waveguide Area

4.1.1 Background

Optical waveguide components are used to construct planar optical circuits on semiconductor or silica substrates. These compact optical circuits can be designed to perform complex networking tasks. Simply put, the waveguide components guide, split, combine or route the optical signals (light beams) in optical networks. It is a kind of "pipe" that guides the light to a certain point.

In this case study the difference in the environmental impact of a wave guide manufactured using a sol-gel process and chemical vapour deposition (CVD) is compared. There are hardly any case studies on optoelectronic components and no previous case studies on waveguide areas and their impact on the environment were available. As a tool Life Cycle Assessment is used.

A sketch of the manufacture layout of both waveguides is shown in Figure 9 and Figure 10.

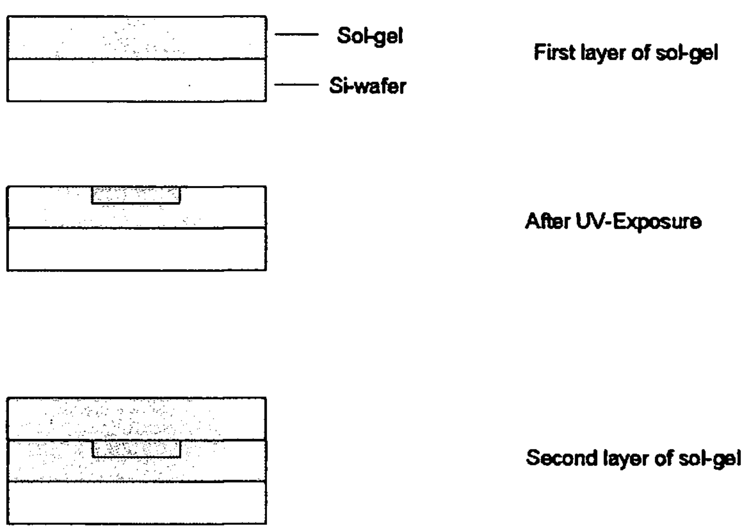

Figure 9: Schematic cross section of a wave guide area manufactured with a sol-gel process

In the life cycle the manufacture has the highest environmental importance due to its use of chemicals and energy. During the use phase no inputs are consumed and no outputs produced. Light is guided though the wave guide without any environmental impact. However, the wave guide is only a component that is part of a product, likely an electronic device, in the use phase. The energy consumption of this device should not be overlooked; however, no impact from it is allocated to the wave guide itself.

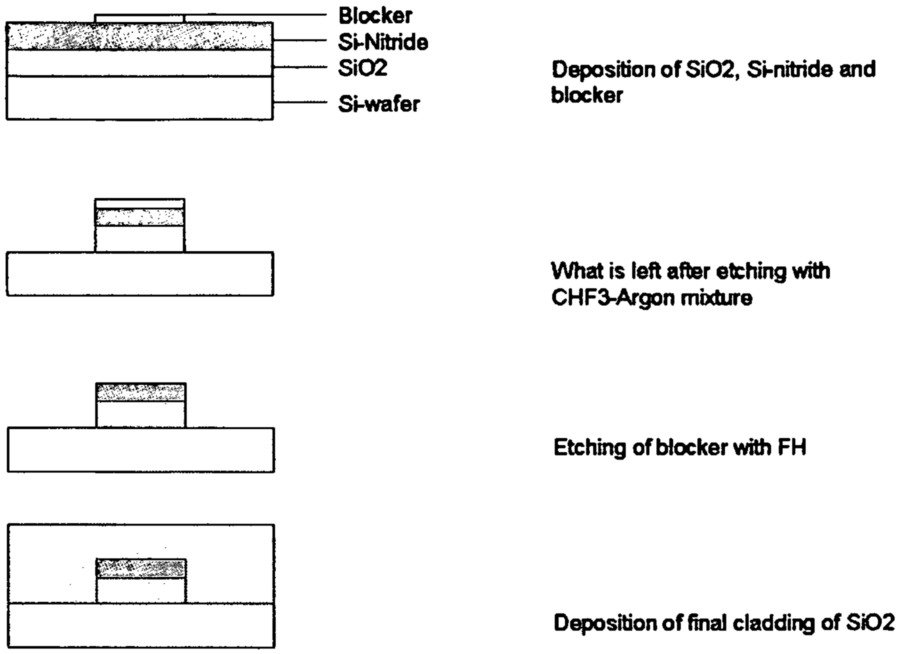

Figure 10: Cross section of the manufacture of a waveguide area

For the end of life stage there are different scenarios possible. The device of which the wave guide is part is disposed together with other household waste or it is separately collected. If the wave guide is part of the household waste stream it is either thermally treated in a municipal incineration plant or disposed of in a landfill (there are other options, but these are the most common ones). If the device is collected separately the same sinks (incineration plant and landfill) are possible. The emissions from both can be considered as negligible, as the wave guide does not contain any hazardous substances and thus can be seen as glass like.

In the case study on **wave guides** a complete LCA was not possible due to lack of data. From scanning the life cycle of a wave guide it became obvious that the production stage is of high environmental relevance, while the use-phase and the end-of-life stage are of more or less no relevance. This is due to the absence of inputs and outputs in the use phase and the inert properties of the waveguide area's materials. Thus the main focus is put on the manufacturing stage.

By having a closer look at the manufacturing processes several aspects that could be of environmental relevance were identified. From that the following environmental indicators can be deduced:

- Mass efficiency: Most of the applied material is lost (97.8% for the sol-gel process, 90% for the CVD resp.).
- Temperature at which the processes take place: the closer to ambient temperature the better, affects energy consumption
- Pressure at which the processes take place: the closer to normal pressure the better, affects energy consumption
- The number of process steps: the smaller the better
- The number of different materials used: the smaller the better

The advantage of these indicators is that they can be used quickly and only relatively easy available data is needed. Thus they are also suitable for use in ecodesign. Furthermore, they allow a quick comparison of different manufacturing alternatives as well as an easy way to assess improvements in production processes. There are still a lot of vague points in this assessment and a lot of data was and is missing.

4.2 Optic fibre cable versus copper cable

4.2.1 Background and scope

In the public view optic fibre cable is seen as the state-of-the-art technology for data transmission. It displays a number of technological advantages over common copper cable, such as low attenuation, less weight or no electromagnetic interference. Capacity (data rate) is one of the aspects most commonly associated with fibre optics, however, it is not the foremost property. Actually, capacity over short distances is comparable to that of copper wiring, since communication engineers have succeeded in applying new technological features to improve performance of copper cable links. Only when it comes to longer distances optic fibre cable show significant advantages.

This case study aims at answering two main questions:

- What is the environmental impact of an ICT infrastructure provided with state of the art technology (optic fibre cable in combination with copper cable) in comparison to no ICT infrastructure?

- What would the environmental impact be if the same service were provided by means of copper cable only instead of optic fibre cable?

The infrastructure as currently present in a student accommodation complex in Ireland was chosen due to its being a well defined and structured area with a high penetration of ICT facilities. The functional unit of this case study is the service of providing internet access to all bed units in the chosen accommodation complex. This comparison was made possible due to the fact that over short distances copper cable and optic fibre cable have a comparable performance.

The student accommodation complex is representative for any accommodation or office complex with a high number of internet access points in Ireland.

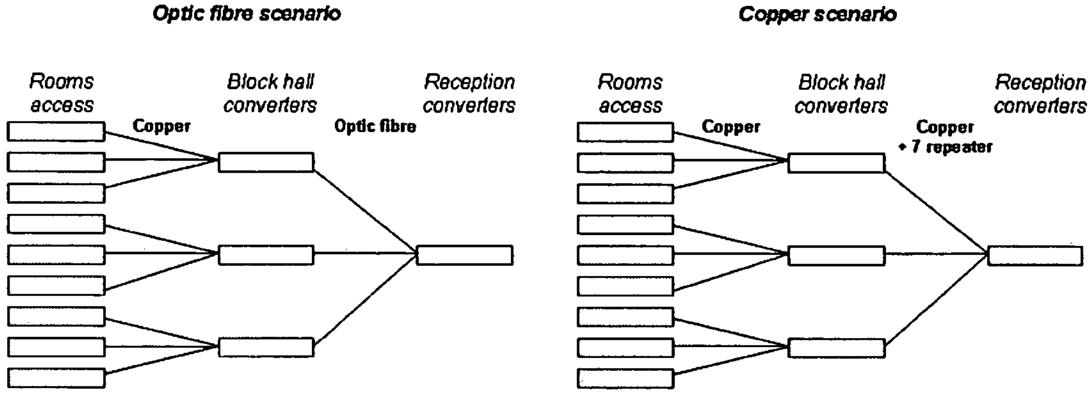

Figure 11: Schematic sketch of the two scenarios

Two scenarios are analysed (Figure 11) which aim on answering the two questions defined in the scope and goal definition. The **optic fibre scenario** is the network as actually implemented in the accommodation complex. Copper and optic fibre cable is used in this scenario.

The **copper scenario** is a fictitious scenario. It represents a merely theoretical measure aimed at illustrating the environmental advantages or disadvantages of optic fibre cable. By applying the scenarios on a large scale, such as the student accommodation complex, a global picture of the degree of environmental impact produced is obtained.

For the comparison of the **optic fibre scenario** and the **copper scenario** LCA proved to be a suitable tool. Both scenarios show similar figures in all categories (Table 2). In both cases electricity consumption in the use stage has a high impact on the results. The results are discussed in detail in paper IV.

	Optic fibre scenario [kg]	Copper scenario [kg]
Global Warming Potential (GWP) [CO2 equiv.]	939.99	1010.84
Abiotic Depletion [Sb-equiv.]	5.47	5.81
Freshwater Aquatic Ecotoxicity Pot. [DCB-equiv.]	13.78	14.94
Eutrophication Potential (EP) [Phosphate-equiv.]	0.29	0.31
Human Toxicity Potential [DCB-equiv.]	95.09	102.17
Photochem. Ozone Creation Potential (POCP) Ethene-equiv.	0.57	0.59
Terrestric Ecotoxicity Potential (TETP inf.) [DCB-equiv.]	0.68	0.74
Acidification Potential (AP) SO2-equiv.	4.97	5.32

Table 2: Selected CML Impact Categories for optic fibre and copper scenario

Paper IV describes the comparison using a simplified LCA performed on optic fibre cable and copper cable.

5 RESULTS

In Paper II different environmental analytical tools are analysed and their suitability discussed. The literature review showed that the choice of a tool and consequently also the choice of measures depends on several different factors. They are:

- Reason for the assessment: Why is the assessment done, what question should be answered? Different stakeholders may therefore find different tools appropriate.
- Time scope: How much time is available to do an assessment?
- Scope of the tool: Some tools focus on certain life stages. The tool must be chosen depending on what objectives should be achieved.
- Resources for the assessment process: Financial and human resources as well as knowledge of methodology.
- Available data

Additionally, the type of equipment needs to be taken into account. Although electrical and electronic products are often seen as one group of products they show big differences and thus different tools show different applicability.

In general **electrical equipment** comprises long lasting appliances, like washing machines and change, in general, only little over time. The materials used in electrical equipment are often commonly used ones and environmental data about them is relatively easy accessible. The composition of electrical appliances is often known or easy to get. The use pattern can be reasonably estimated and does not undergo quick changes. Producers have time to improve the environmental performance with time (e.g. water use and electricity consumption in use phase) without having to change established features of the product from a consumer point of view. Under these conditions sophisticated tools like full LCA can be used for ecodesign approaches. From the results of sophisticated tools, simple tools, like checklists, can be derived and used in guidelines for a certain branch of industry or for a certain type of product for quick decision taking.

The use of ecodesign tools for **electronic equipment** is quite different. Due to the short innovation cycles and thus the quick changes in composition and materials used, it is hard to get reliable information if you are not within the company manufacturing the product. Due to the fierce competition in the electronic sector information about production processes is often regarded as confidential. The materials used are on the one hand common materials like those used for electrical equipment but on the other hand also a large range of highly special commodities, like silicon (semiconductor wafers), precious metals (integrated circuit boards), or potentially hazardous substances (e.g. in liquid crystal displays). For many of those no detailed environmental data is available because their effects on the environment and health are not yet known. Such uncertainties make an assessment harder. Electronic equipment is also characterised by minimisation. The short innovation cycles hardly allow the use of sophisticated tools to help in decision taking, because the time needed to apply these tools is too long. From reviewing case studies it can be observed that some components, that are part of most electronic devices, like printed wiring boards, liquid crystal displays and batteries are often identified as environmental hotspots. Information like that can then be used to derive, for instance, key performance indicators known as KEPIs. Sophisticated tools are more suitable to analyse the environmental features of systems, like a telecommunication system (see for instance Malmodin et al., -). These systems are often very complex and involve many different products and processes.

An assessment by means of a Life Cycle Assessment (LCA) is very difficult due to several reasons. Electronics are a cross sector technology and comprises different types of technology which can not be assessed together. Schischke and Griese (2004) give the following obstacles when doing an LCA:

- Electronics are too complex for full scale LCAs of high data quality, if detailed decision support is intended
- Due to short innovation times the time frame for LCA in electronics is extremely short, if eco-design should be supported
- Lack of data for a high amount of electronic specific inputs (e.g. high purity chemicals) and outputs (impact assessments have to be complemented)
- Toxicity assessment is currently a weak point of LCA methodology
- Further impacts, such as electro-magnetic radiation need to be addressed by a life cycle impact assessment
- Modelling of disposal is very complex since electronics are composed of several hundred substances
- Use patterns of electronic devices are constantly changing (new features, new applications, new life style) making modelling of the use phase difficult without reliable statistical data
- Rapid shifting of functionality towards integration of even more features raises obstacles concerning the definition of the 'functional unit'
- Global supply chains hinder availability of specific LCA data

In Table 3 the data and time demand as well as the strengths and weaknesses of commonly used tools are summarised.

tools	*data demand*	*time demand*	*strengths*	*weaknesses*
LCA	high	high	comprehensive (life cycle stages, impacts), separated calculation of impacts and assessment	data and time intensive, complex results, use patterns hard to model
streamlined LCA	high	med. - high	comprehensive - at least screening of all life cycle stages	data intensive, complex results
MIPS	medium	medium	demonstrative results	only input is considered, not toxic effects included
CED	medium	medium	simple result, energy related to most environmental effects	no toxic effects considered
EF	high	high	simple, demonstrative result	data intensive, data might not be available
MFA	medium	medium	individual material flows can be analysed	no energy or toxic effect are considered
Check lists	low	low	easy to handle, especially in supply chain	origin of data / results not traceable
Performance indicators	low	low	can include major aspects like material, energy and toxicity	origin of data / results not traceable
Material exclusion lists	low	low	easy to handle, escp. in supply chain	origin of data / results not traceable

Table 3: An overview of different tool

6 DISCUSSION

(based on Unger and Salhofer, 2006)

Since it is often difficult to group environmental tools according their function and purpose, it is more appropriate to simply divide tools in two groups – simple tools and sophisticated tools (Unger 2005, Paper II). While the first group gives quick results and needs only little data, skills and time, the latter requires a lot of time, data and experience to carry them out.

Hence simple tools are used for quick decision taking, where environmental hotspots are the focus of assessment. Sophisticated tools are more likely to be used for long time strategic considerations (e.g. the introduction of the third generation wireless communication system, Malmodin et al., -) and assessment of products when they are already in production and results not directly needed for the set up of the production. Moreover sophisticated tools like LCA are the foundation from which simple tools such as performance indicators are deduced. Only when screening the whole life cycle environmental hotspots can be found.

If a manufacturing company wants to carry out an assessment the choice of tools depends on available resources such as time, knowledge, data, financial means etc. (Unger and Duffy 2005). In Figure 12 the use of tools depending on the size of the company and the complexity of the question the application of the tool should answer is shown. Simple tools are used by all types of users since time is often a crucial factor, e.g. in product development. The more resources are available the more sophisticated tools can be used.

Moreover, the choice of tool is a crucial decision. The wrong tool or the right tool wrongly used can give wrong and misleading results. Thus this choice should not be taken lightly. Finnveden and Moberg (2005) suggest that two key aspects determining the choice of tools are the object of the study and the impacts of interest. The other aspects will either influence how the chosen tool is used, or have an indirect influence via the key aspects.

LCA is a sophisticated analytical tool and can be seen as the top tool in the tool hierarchy. The methodology of Life Cycle Assessment is defined in EN ISO 14040ff. However, often modifications to adapt the method to a specific case study are made (see for instance Hunt et al., 1998). In practice, most assessments where the whole life cycle is considered are called LCA, not only those which comply with the standards.

Because an LCA is not a tool limited to a certain type of products (e.g. products where energy is an environmental hotspot) it can be used for theoretically every product or service. Thus, whenever a thorough assessment should be done it is likely that the first thought will be to carry out an LCA. However, there are limitations.

LCA is a suitable tool whenever a comparison is done, either by comparing different products or alternatives, or by comparing different life stages. If results are not compared the interpretation of the results of LCA is very difficult or even impossible. Often LCA is used as a decision support tool where ranking of different options and distance between those options is more important than the resulting numbers. However, LCA is only reasonable if enough resources (as mentioned above) are available.

Another important aspect is the setting of the system boundary. Often results of different LCA studies are not comparable because the boundary is set differently. When doing an LCA a lot of decisions have to be dealt with, such as how to handle allocation problems or where to extend the system boundary. In other studies on the same functional unit decision might have been taken differently. Thus results of different LCA studies vary and make a direct comparison very difficult. However, in general, they should show a similar ranking of options.

Moreover, regional issues need to be considered. Results of a study in one country or region are not automatically transferable to another country or region. Often different sources for energy generation are the main reason for that. Throughout Europe and the world very different compositions of electricity mixes can be found, from high percentage of nuclear power (France) to no nuclear power (in Austria), from high percentage of water power (in Iceland) to high percentage of electricity from oil and gas (in the United Kingdom). These differences are strongly influencing the results of an LCA, especially of EEE where the use phase, and thus energy consumption, is an important factor.

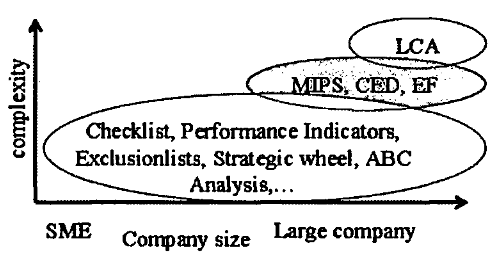

Figure 12: Application of tools (examples) according to the size of a company and complexity (Unger and Duffy, 2005)

LCA is a very valuable tool. It has advantages but also disadvantages. On the one hand complex products such as electronics need a sophisticated tool. On the other hand lack of data is often an obstacle when it comes to a complete LCA. Especially when different options are compared lack and quality of data can have a higher influence on the result than the difference between the two options. Thus LCA is seen as a good and valuable approach but not yet fully suitable for electronics. However, a streamlined or simplified LCA is successfully used. Furthermore an LCA or the LCA approach is a valuable staring point for deducing 'simpler tools' that focus on environmental hotspots because only when starting with a life cycle approach relevant issues can be recognised.

Another problem of electronics is that some important effects are not yet covered in the impact assessment of an LCA. For instance for a comparison of data transmission via optic fibre or copper cable in comparison to data transmission via a wireless connection LCA is not an appropriate tool. This is because electromagnetic radiation, as used for wireless data transfer, has effects on human and nature which are not yet clearly recognised and assessable. Thus a sole LCA could give misleading results if such impacts are neglected.

For electrical equipment a full LCA is more often done. As mentioned before electrical appliances change little over time and common materials are usually used. Thus data gaps are considerably smaller than for electronic equipment. Moreover, usually there are no rapid changes in the products so that more time is available for the assessment and data from other studies are available.

For carrying out an LCA it is important to have a good team and good communication. On the one hand the assessor needs information and understanding of the designer or manufacturer to understand how processes are linked together and to model the process chains. On the other hand the environmental expert too has to be able to communicate the data he needs to the designer or manufacturer.

Concluding it can be said that the question if LCA is an appropriate tool for electrical and electronic equipment has no clear answer. As often in life cycle assessment the answer is 'it depends'. In some cases LCA is a good and appropriate tool while in others an LCA is not suitable. It can not in general be assumed that LCA, just because it is an integrated tool is suitable for every product. Other tools or a mix of different tools (toolbox) might be more appropriate for a certain case study.

In the case study on a opto-electronic waveguide, an LCA, as initially intended, was not possible due to several reasons:

- lack of mass flows: for some input and output materials the used or emitted mass flow could not be determined. This was because both manufacturing processes where done in a research laboratory. Only small amounts were manufactured and many different processes were used in the same lab and with the same equipment. Thus some mass streams could not be clearly allocated.
- lack of data about input material: Many of the input materials are highly specialised commodities. While some of those are common and often used materials where relevant environmental information is available, for others that was not the case. In those cases, only safety sheets which come with chemicals were present. Trying to find producer information was also not a successful path.

- lack of relevant literature: Although a lot of literature about chemical and optical features of such opto-electronic devices is available, no literature with environmental relevance could be found. Thus no experience from other case studies could be used.
- lack of cooperation: to carry out an LCA it is essential that partners support each other and provide sufficient and relevant information. This is only possible if a certain level of interest in the environmental assessment from the side of the developers, as in this case chemists, is present. Especially when quite different disciplines – with the often wide and broad approach of environmental sciences and the narrow and precise approach of chemists – have to work together a certain level of good will to cooperation is absolutely necessary. On the one hand the environmental scientist does need to understand the properties of this particular component to assess and on the other hand the chemist needs to understand that for the assessment inputs in mass are more relevant than inputs according to function. For instance the assessor needs to know the amount of material in a layer of the component (mass) while for the chemist the thickness is of importance. These different approaches and views need to be overcome.

In the case of the analysis of copper cable and optic fibre cable a life cycle approach was chosen from the beginning. A full LCA was not applicable since only secondary manufacture data was available. Moreover, the intention of this case study was not to assess the overall environmental impact but rather to investigate where environmental hotspots may lie and what issues need to be considered when comparing those two data transmission options. Thus for this wider approach a life cycle scan, a qualitative approach with supporting numbers from secondary literature, was best suitable.

7 CONCLUSIONS

- Electrical and electronic appliances are two different types of products that have some things in common (e.g. electricity use) but are very different when it comes to their environmental impact and the environmental assessment process

- There are many tools for environmental assessment beside LCA

- LCA is not always the most suitable assessment tool available

- Tools can be divided in two groups: sophisticated tools for environmental experts and simple tools for non experts.

- On the one hand life cycle thinking is a good approach but it is actually more a life cycle net

- There is no clear difference in the environmental impact between the use of copper cables and optic fibre cables for data transmission over short distances as in an accommodation complex.

- The use of services and its implications (e.g. electricity use of PC) have a higher environmental impact than the medium that conveys the information (copper cable or optic fibre cable)

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Paper I

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General requirements for LCA software tools

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Abstract: In recent years Life Cycle Assessment (LCA) software tools have become increasingly important. Today a large number of LCA programs are available. The large diversity of LCA software tools on offer makes it necessary to first pinpoint some general requirements that determine the quality of an LCA software tool and secondly to describe these requirements qualitatively. The authors last year assessed four different software tools by using each of these programs to model waste management scenarios . This modelling process revealed many differences in the quality of the LCA software tools. These differences are unrelated to the kind of modelled scenario and therefore are relevant for all kinds of LCAs (e.g. product LCA). Using these experiences and by conducting additional research in the literature, we have deduced some general requirements considered essential for good quality LCA software tools. These will be presented in this paper.

Key words: LCA, software, features, quality

1 INTRODUCTION

Life Cycle Assessment (LCA) is today an often used method for assessing the potential environmental impact of products, services or proceedings. Software tools were developed to make the processing and calculation of LCAs easier. The first steps were taken about two decades ago, with the main focus often on the assessment of production processes. Over time LCA software was also applied to other fields such as waste management.

There is a large variety of LCA software tools on the market. The foremost – and for the potential user also often prohibitive – property of a software tool is the price. The price of an LCA software tool can vary between several thousand euros and free of charge. Some tools offer a wider range of features than others. Some are focussed on a specific field of LCA, e.g. LCA in waste management, while others try to cover different application fields of LCA. Also the data and data quality can have an effect on the price of a software tool.

Depending on the purpose for which the user has selected the software, different LCA tools are more suitable for particular applications. However, a number of properties and features are essential for any good quality LCA software tool regardless of the kind of user and the kind of LCA it is being used for. This paper will discuss which features are important and which requirements are desirable for a good LCA application.

The content of this paper is mostly gleaned from experiences with four software tools for LCAs in waste management, as well as from test versions of other LCA software tools.

2 WHO USES LCA SOFTWARE TOOLS?

Different groups of LCA software users can be distinguished. The first group includes scientists and researchers. Users in this group are often experienced with LCA and have a good knowledge and understanding of the context and the features of the LCA method. Thus they make high demands on LCA software tools: They need a flexible software tool that enables them to model "common" often-modelled scenarios as well as scenarios that diverge from the standard. Also the tool should support modelling of complex process chains. The provided data need to be of good quality (see 4.3) and adequate, particularly because, in contrast to business users, scientists usually do not have their own data. It should be possible to create new data sets. In addition, scientists need the freedom to make their own improvements and modifications to existing data, specifications and parameters.

Industry, on the other hand, uses LCA software to improve its environmental performance, for process optimisation and product development. The users want “ready-to-use” software, where many of the specifications are already pre-set with only a few parameters needing to be determined.

Also decision makers use LCA to compare different solution options and hence also LCA software tools. Decision makers generally want an easy-to-understand presentation of the results in terms of which option is the best.

The developers of LCA tools aim to serve both groups of users: scientists and practical users from industry. It is very expensive to develop a software tool and thus it can only pay off when it is sold to the widest possible audience [Rizzoli and Young, 1997].

Not all of the mentioned requirements need to be fulfilled by a software tool in order to be acceptable to a specific user group.

3 WHY ARE LCA SOFTWARE TOOLS USED?

Environmental processes are often very complex and convoluted. This makes it difficult to model an LCA. Additionally LCA is often data intensive. Computers and adequate software tools are thus used to support the user in managing and editing these amounts of data. LCA software further helps to structure the modelled scenario, displaying the process chains and presenting and analysing the results. LCA software tools can be used whenever the method of LCA is applied.

The main reason for using LCA is to calculate the environmental aspects and potential impact associated with a product (ISO 14040). Also environmental hot spots (processes that have a large impact on the environment) can be identified. A more environmentally-friendly production process can thus be developed where they are most effective. LCA can also be used for a cleaner approach to production. It can help to improve and optimise resource management, which leads to a more efficient use of materials and energy.

LCA therefore is used mainly for comparing different options and for deciding which option is best for the environment. LCA and LCA software are thus used as a support tool in decision taking.

4 EXAMPLES OF TECHNICAL AND METHODOLOGICAL REQUIREMENTS

People who wish to use an LCA software tool often face the dilemma of which tool is best for their purposes. There are some software comparisons available that can help (cf. Jönbrink et al., 2000; Frühbrodt, 2002; Unger, 2003). An overview of some properties and features of commercial LCA software tools is provided here. Additional desirable features are pointed out. These can be seen as general requirements that need to be fulfilled by a good LCA software tool.

4.1 Structure and display of processes

A software tool generally consists of a database and a modelling module. The data are handled and modelled on an interface.

The modelling consists mainly of connecting successive processes with material flows. They build the process chain. Each process represents a stage in production and is defined by its input and output (see 4.4). The output from a preceding process builds the input for the next process. Simple process chains can be modelled in one layer. To handle more complex process chains, a hierarchical structure, as displayed in Figure 1, is needed. The main process stages, e.g. extraction, production and disposal, are modelled in the top layer. Each of these stages can be specified more exactly in their own sub-layer. Thus very long and complex processes can also be modelled and displayed in a clear way.

In assessing the life cycles of products the main focus is often placed on the output. The main question is: How can a certain amount of output (product) be produced with a minimum environmental impact (output-orientated calculation)? However, to assess other proceedings, other approaches are more appropriate. For example, in waste management the question “How can a certain amount of waste be treated with a minimum of environmental impact?” is of importance which is an input orientated approach. Good software tools offer the possibility of orienting the calculation towards any process within the process chain.

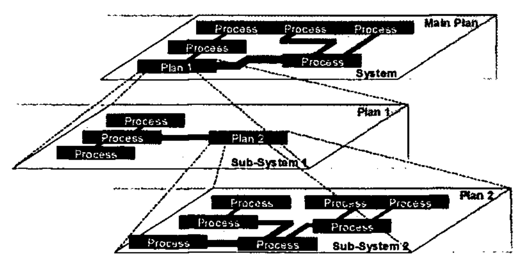

Figure 1. Schematic figure of a hierarchical structure [IKP, PE, 2002].

Some output-oriented software tools allow only one output of a process for the follow-up. Other outputs (by-products) are then addressed as negative inputs, which cannot be followed in the same process chain.

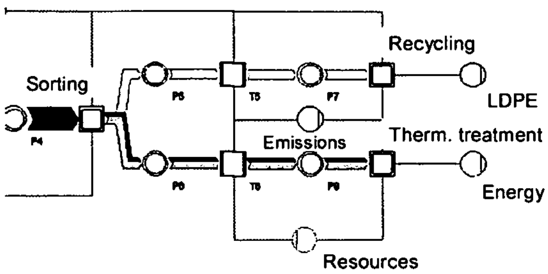

Figure 2. An example of a process chain. (Umberto)

But the user will sometimes encounter process chains with more than one output. Good software offers the possibility of following up different outputs. A simplified example from waste management is given in Figure 2. A sorting process has two outputs: LDPE films, which should be recycled (upper stream), and waste and other plastics that are designated for incineration (lower stream; the two colours indicate two different materials). The software enables the user to continue the process chain using both outputs.

4.2 Transparency, flexibility and user-friendliness

The structure of a software tool is partly responsible for its transparency. The calculation modus is important for a transparent compilation of an LCA. The user should be able to trace back each result in order to find mistakes. The proceedings from the modelling should be chronological and logical. Of vital importance in this context is the user interface, which should be clearly structured and self-explanatory. Modelling the process chain on a graphical interface is a very transparent way of modelling. There processes are arranged (e.g. as plan, network, assembly) and connected with material flows (arrows). The drag-and-drop feature is very helpful in this context.

To improve the user-friendliness many user interfaces have been designed similar to MS Office applications. The user will feel familiar with a number of features from the start. This improves the working quality of the software.

The user will often have to present his results to different groups of people (such as purchasers or the scientific community). Thus the software tools should offer a good presentation toolbox. A sankey diagram (see Figure 2) is a good option for presenting a process chain. The hierarchical structure can help to present the results clearly. Also it should be possible to create diagrams. A uniform layout for printed reports can enhance the software quality. Further the compatibility with other applications such as MS Office is important.

The implementation of a documentation feature is recommended to comply with the ISO 14040 standard, which defines the LCA.

The user should feel comfortable using the software tool. Little features, such as the possibility to change the entry unit, a zoom function for modelling the process chain or the possibility to show the input/output inventory in different gradations of detail, can make modelling more convenient for the user.

It is not easy for software developers to comply with often contradicting features such as user-friendliness and flexibility. Eriksson et al. [2002], for example, state that their software should be seen as a service rather than a computer program. Further they point out that they are continuously working to enhance user friendliness without losing flexibility. This is true for many software tools.

An important aspect in the context of user-friendliness is the time needed to learn how to use the software. The amount of time that has to be invested should be appropriate relative to the level of detail of the LCA.

4.3 Database

Data should be stored separately from the modelling module. It should be created and managed in some kind of database or library. This storage base has to be structured clearly. Very convenient for most users is a database structure similar to the one in MS Windows Explorer, where data can be edited without working in a modelled scenario. Also the import from and export to other applications is easier.

Apart from processes and flows, a database also contains modelled process chains. It should also be possible to file sub-layers in a process chain. They can be reused to model other scenarios. Further it should be possible to file separate data for a specific project so that the user does not need to search the entire database when looking for a specific process.

The data in the database need to be of good quality. They should be up-to-date and from a reliable source. More than one source is desirable in order to limit the danger of making mistakes. The user needs to clearly define the conditions under which the data are valid as well as the region for which they can be applied (e.g. energy for different countries). It can be helpful to include a data quality index to indicate the level of data quality.

An automatic update should be provided as soon as new data or data of better quality are available.

Good quality data should contain following information in the documentation:

- original data source
- age of the data
- composition of the data (number of companies or different literature, where the data are generated).

The user, particularly the scientist, will often use data from the database as well as from his own generated data sets. Processes and especially material flows have to be named carefully. Problems occur if different entries are created for one flow. For example, a process from the database produces the output "CO2." Then the user creates a new process with the output "carbon dioxide." The result is that two different names stand for the same flow. A feature that defines these flows as equivalent is necessary. This is especially important when the user creates his own data and the valuation. A very user-friendly way of communicating that two names stand for the same flow is to define synonyms.

Sometimes the user may want to connect processes where the output and the successive input are different. This should also be possible. An example of this is when the output of a process is "miscellaneous plastics" and the input in the next process is "waste" (plastics).

4.4 Calculation methods, uncertainty and variability analyses

Software tools offer different options for defining the proportion of inputs and outputs of a process. The simplest is to define a mass balance, e.g. the inputs are 1 kg of A and 2 kg of B and the output is 3 kg of C. However, mass balances are usually insufficient. Linear equation systems are an adequate way of modelling processes most of the time. Some tools also offer scripts, enabling the user to calculate non-linear systems like iterations.

Up to now LCA software tools have not usually considered the factors of uncertainty and variability. This refers mainly to parameter uncertainty (e.g. inaccuracy of emission measurements or of normalisation data) as well as the variability between sources (e.g. different emissions of comparable processes) and objects [Huijbregts, 2001].

The spectrum of tools to deal with these potential distortions ranges from simple parameter variations and sensitivity analyses to sophisticated methods, such as fuzzy logic computations, Bayesian statistics or probabilistic simulations.

In particular, simulations based on statistical modelling methods seem to be a promising technique for making uncertainty operational. Two approaches – the Monte Carlo and Latin Hypercube simulations – are currently implemented in LCA software tools [Weidema and Mortensen, 1997].

To perform the Monte Carlo simulation, the uncertainty distribution (normal or rectangular are usually available) of each parameter has to be specified. All the parameters vary randomly within the limits of the given distribution. The randomly selected values are inserted in the output equation. After repeated calculations, the output is represented by a predicted distribution of each output parameter. The Latin Hypercube simulation works in similar way. The main difference is, that the uncertainty distribution of a parameter is segmented in a number of non-overlapping intervals with equal probability. This fact leads to generally more precise random samples than the Monte Carlo simulation [Huijbregts, 2001].

In LCA practice the application of these methods is useful for assessing the influence of the parameter uncertainty on the uncertainty of the model output. The most important consequence of such analyses is the identification of parameters that cause a large spread in the model output. This can help to increase the accuracy of the overall model.

4.5 Methodological Properties

For waste management questions LCA normally leads to the comparison of different treatment options for waste streams with a reference scenario (e.g. landfilling) that provides a functional equivalence. This equivalence can be achieved either by given credits outside of the system or by expanding every system to achieve the same benefits. To use the LCA software tool comfortably it is necessary to provide both methods (the "credit method" and the "basket-of-benefits" method). Especially complex scenarios cannot really be addressed with the basket-of-benefits method. If only "credits" can be provided by inverting existing primary production processes, the assessment will not be comfortable, because outputs are shown in the input table and the other way round. In a good software credits are automatically subtracted from the outputs.

At the international level two impact assessment methods have been established and are most commonly used in Life Cycle Assessment: an operational guide to the ISO Standards (CML 2001 method [Guinée et al., 2001] and Eco-

Indicator 99 [Goedkoop et al, 2000]). Less often used methods, particularly in the German language area, include the Swiss Eco-factors 1997 [BUWAL, 1998] and the German Federal Environmental Agency (UBA) method [UBA, 1999]. The software should at least provide both internationally used methods because they follow different general approaches: problem-oriented methods (CML) and damage-oriented methods (Eco-indicator).

Especially when the CML method is used for the impact assessment, the software needs to provide another aid for interpretation of the results. Weighting the results according to their relative importance often is necessary for the results interpreter. One possibility for results aggregation is normalisation, where calculating the magnitude of indicator results relative to reference information is possible. The software should provide different normalisation parameters.

In general a different quality of results should be given, e.g. a thorough inventory, different valuation results, aggregated values of different impact categories, or a summarisation to just one parameter to afford a ranking of options.

4.6 Service and Support

Service and support are very important aspects of LCA software and should not be underestimated. Software needs continuous maintenance.

The database especially needs a great deal of attention to keep it up to date. The software should also be continuously improved to eliminate malfunctions and improve user-friendliness and software ergonomics.

A telephone or e-mail hotline should be provided to ensure that the user receives qualified help for technical as well as methodological problems. A detailed manual is essential. Many LCA software providers offer special training sessions to introduce the software to the new user. Demonstration versions and tutorials to demonstrate the functionality and features are very helpful in providing a quick overview of the properties of a software tool. Such demo versions should be available for free to demonstrate the advantages of a software tool to potential new users.

Another essential aspect of service is getting relevant information about the software. This aspect should take into account that there are at least two different kinds of users. On one hand there is the LCA newcomer: He needs some general information about LCA and about the advantages of the particular software. This information can normally be found on the software homepage. On the other hand there is the professional LCA user: He needs more detailed information about the different features the software provides and the assumptions included in the database or the methodological solutions, such as which assessment methods are provided and where the database is from. At resent there is a lack of information in this area. Normally one sees this information only after purchasing the software. More detailed information is needed on the Internet for LCA software.

4.7 Other features

As mentioned before, many LCA software tools offer additional features. One group of them focuses on analysing data. One example is a sensibility analysis, which should be implemented in each good software product. The feature of comparing different scenarios can also be called a standard feature.

The cost consideration is also important. Although there are major methodological differences between Life Cycle Cost analysis (LCC) and an LCA, they can be tightly, logically and practically integrated with one another [Norris, 2001]. Some software tools also consider time aspects and social parameters such as working time.

5 CONCLUSION

Many LCA software tools can be considered of good quality. They were often developed for a specific application of LCA but were then improved for a wider scope. Sometimes although the software is generally designed for a wide scope, it is not possible to use this wide scope due to e.g. inadequate calculation methods or an unsuitable structure. Thus it is not enough for single features to be implemented in an LCA tool, but the whole package of features needs to fit together in a good quality software tool. Basic requirements need to be fulfilled by the software to be suitable for a wide audience.

Generally a software tool should operate smoothly and quickly, without errors due to mistakes in the software programming. The hardware requirements should also be adequate. A hierarchical structure is essential for good quality software, in order to be able to work on more complex problems as well. A clear structure ensures transparency and modelling comfort. The starting point of the calculation should be of free choice. Also the modelling of different outputs should be possible. The results should be transparent. A graphical modelling of the process chain is very convenient for the user.

Compatibility of the software with other application should be provided and the user interface should be designed in such a way that the user finds his way around easily and feels comfortable working with the program (e.g. if designed similar to MS Office applications). A good toolbox to present the results is desirable.

The database should be managed and edited separately (creating, deleting, modifying of data). The data should be of good and transparent quality. There should be a possibility of separately saving and organising data used for single projects. The names of processes and materials need to be clear and logical and the problem of synonyms should be taken into consideration.

It should be possible to choose between different methodological approaches for the impact assessment and the aggregation of results as well as for the comparison of scenarios with different outputs.

An Internet homepage with detailed information should be provided for an LCA software tool. It should contain information for newcomers as well as experts. Different versions and a free demo version of the software should be available.

Additional features that help the user to analyse results and allow further calculations are important requirements for some users.

To define the proportion of input and output, linear equation systems will most often be sufficient, although scripts can be essential for some processes.

Good software tools featuring uncertainty and variability analyses such as the Monte Carlo simulation enable the user to identify parameters, which cause a large spread in the model outcome. Thus the accuracy of the model can be increased through support of a more selective procedure.

It is important that an LCA software tool be continually improved and updated with new developments in the field of LCA. Maybe they can even give an incentive to new developments since most life cycle assessments are calculated with an LCA software tool.

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Paper II

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A Review of ecodesign and environmental assessment tools and their appropriateness for electrical and electronic equipment

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Abstract

The electrical and electronic equipment sector is a steadily growing one and thus also environmental considerations about it become more and more an issue. There is a large number of tools that can be used for ecodesign and environmental assessment, but not each tool is equally suitable for all products. Although electrical and electronic equipment are often mentioned together, they show major differences and thus tools will be used differently. The choice of an adequate tool depends on many aspects and thus no single rule on how to choose a tool can be given. However, this paper gives an overview of different well known tools. Case studies from literature and new ones illustrate the process of choosing tools and furthermore show their use on particular products. The applicability of tools for electrical and electronic equipment is then thoroughly discussed.

Keywords: Assessment tools, Electrical and Electronic Equipment, environmental assessment, Life Cycle Analysis

1. INTRODUCTION

The Electrical and Electronic Equipment sector covers a large variety of products which provide a wide range of features and services. In the last couple of years this sector was subject to a number of regulations, like those enacted by the European Union lately (WEEE, RoHS, EuP). They aim at reducing the environmental impact and to improve the environmental performance of such products. However, in order to archive this aim suitable tools need to be chosen.

Ecodesign is often also referred to as green design, ecological design, environmentally sound or environmentally sensitive design, DfE (design for the environment), environmentally responsible design or others (Baumann et al., 2002). As the name indicates, ecodesign is a concept applied in the design and development phase of a product's life cycle. It is assumed that about 80% of all environmental effects associated with a product are determined in the design phase of development (UBA, 2000 in CEC, 2003). Ecodesign can be used for newly developed products or for redesign of existing products. It also has a high potential to facilitate environmental improvement in a cost-efficient way (European Parliament and the Council of the European Union, 2005). Furthermore, ecodesign of products is considered a crucial factor in the Integrated Product Policy (IPP) at European Level. "As a preventive approach, designed to optimise the environmental performance of products, while maintaining their functional qualities, it provides genuine new opportunities for manufacturers, for consumers and for society as a whole." (European Parliament and the Council of the European Union, 2005).

2. *Tools*

2.1. Function of assessment and ecodesign tools

Ecodesign is one of many concepts in environmental design and management; others are life cycle thinking, clean technology, dematerialisation, etc. There are big overlaps between concepts and they often use the same tools. Some of those tools are more detailed and do a thorough environmental assessment of a product, others enable a quick and easy examination of environmental issues, in a manner suitable for non-environmental experts.

In order to design an environmentally benign product or service it is necessary to know where environmental hotspots lie. Environmental hotspots are stages in the life cycle, or certain factors, such as energy, that cause a high environmental impact of a product or service. Thus, focusing measures in ecodesign on those hotspots shows the greatest environmental benefit. Environmental assessment tools are used to identify them and help in getting a picture about the environmental impact of a product.

2.2. Types of tools

The tools used in ecodesign and for environmental assessment are very diverse and were developed with different backgrounds (e.g. academic, company). A large number of tools have been published in literature. Baumann and colleagues (2002) identified more than 150 tools. Often not one specific tool, but a toolbox, a set of different tools, is used. In this way weaknesses of one tool can be compensated by applying additional tools.

Some authors see all tools that help in improving environmental performance as ecodesign tools, while others distinguish different groups of tool in different way (e.g. analytic tools, procedural tools, ecodesign tools, etc.). Those different types of tools are often overlapping and many tools can not be categorised in one single group easily.

Tools also operate at different levels of spheres of action (Baumann et al., 2002). On a low level they only deal with the product development process, while on higher ones also the company context (business strategy, management, marketing, etc.), the product chain (e.g. interactions with suppliers, customers, waste handlers) and the product development in relation to policy-making process are considered.

Ecodesign should aim to address all levels to have a recognisable impact. Measures should be taken where they are most appropriate. The size of the improvement potential is strongly linked to the size of the environmental impact (Zackrisson, 2005). Therefore, in a first step, the whole life cycle needs to be considered. There, "hotspots", life stages with a high environmental impact, are identified. Then measures are taken to reduce these impacts.

Due to overlapping and different ways of grouping ecodesign and environmental tools, a rough grouping into "sophisticated" and "simple" tools is presented here. Sophisticated tools are tools that require a lot of time, data and experience to carry them out. Simple tools on the other hand are, as the name suggests, simple to use. They give quick results and need only little data. They can be used by non environmental experts and experts alike.

2.3. Sophisticated tools

2.3.1. Life Cycle Assessment - LCA

Life cycle assessment (LCA) is used as a concept with a focus on the whole lifecycle as well as a tool specified in ISO 14040. Major steps are a goal and scope definition, followed by a Live Cycle Inventory, where the inputs and outputs of all processes (life cycle stages) are analysed. In a separate step, the environmental impacts assessment, the impacts of the emissions and resource consumption are considered. In a last step the gained results are interpreted. Including all processes as well as several types of environmental impacts makes LCA a very comprehensive, but also time and data intensive tool. Electronic components are especially difficult to assess because there are substantial data gaps. Schischke and Griese (2004) suggest electronic products are too complex for full scale LCA of high data quality, if decision support is intended. They identify, among others, the following main obstacles for life cycle assessment in microelectronics:

- The time frame for LCA on electronics is extremely short if ecodesign should be supported, due to short innovation times.
- Modelling of disposal is very complex because electronics are composed of several hundred substances.
- Lack of data about thousands of different electronic components and their specific inputs and outputs is a continuing problem.
- Use patterns of electronic devices are constantly changing (new features, new applications, new lifestyle), making modelling of the use phase difficult without reliable statistical data.

However, LCA approach is considered suitable for screening the life cycle in order to identify environmental hotspots in a product's life cycle.

2.3.2. Streamlined LCA

A streamlined LCA tries to reduced the complexity and obstacles mentioned above by limiting the scope of the study or simplifying the modelling procedure by eliminating certain life cycle stages (e.g. upstream processes) from the detailed analysis. This can be seen as a part of the goal and scope definition process (see Todd and Curran, 1999). Surrogate data may be used (when the process data cannot be identified) or the effects can be considered for single impacts only. From a streamlined LCA the same type of result is obtained as in a full LCA, although a less comprehensive set of data was used. The screening process, followed by a decision which processes will be left out, needs specific care. A case study with a streamlined LCA is given in section 3.1.2.

2.3.3. Material intensity per unit of service – MIPS

MIPS measures the **input** orientated environmental impact of products and services in kilogramme per unit of service. The whole life cycle (from cradle to grave) is considered and all the material inputs are aggregated in five categories: abiotic or non renewable raw materials, biotic or renewable raw materials, earth movements in agriculture and silviculture (incl. erosion), water and air (Ritthoff et al., 2002). Energy, auxiliary material production, infrastructure, transports, et cetera, are considered in taking the material input that is needed for their production. However, all materials are equally weighted and properties like toxicity are not considered.

The literature review showed that MIPS is, in general, not suitable for the assessment of electronic equipment. However, for larger products such as most electric appliances MIPS can be seen as a suitable tool.

2.3.4. Cumulated Energy Demand – CED

Similar to MIPS the Cumulated Energy Demand (also known as "kumulierter Energieaufwand, KEA" and defined in the German VDI-Richtlinie 4600, focuses on one aspect, **energy**. All primary energy demand in connection with production, use and disposal of a good or service is summed and the result is given in Joule. Beside the energy input in processes also the non energetic demand bound in, for instance, lubricants and also the energy content of materials e.g. caloric value of waste, are considered (Salhofer, 2001). Toxicity is not considered in this pure energy based tool (also see Fritsche and colleagues, 1999).

The Cumulated Energy Demand is often used in connection with other tools or as part of an LCA. CED can be suitable when a major focus is put on energy. However, other environmental issues are not considered and thus CED can only give a very limited picture about environmental aspects.

2.3.5. Ecological Footprint – EF

The ecological footprint is "the total area of productive land and water ecosystems required to produce the resources that the population consumes, and assimilate the wastes that the population produces, wherever on earth the land and water may be located using prevailing technology" (Rees and Wackernagel 1996 in Singhal, 2005). On one hand all direct land-use is considered, like area for mining, land for growing of plants et cetera and on the other hand the indirect land-use for instance needed for CO_2 sequestration is assessed. In this way fossil fuels are accounted for in their emissions. The advantage of the EF is that all inputs and outputs are aggregated to just one aspect – **area of land**.

2.3.6. Material Flow Analysis – MFA

"Material flow analysis is a systematic assessment of the flows and stocks of materials within a system defined in space and time. It connects the sources, the pathways and the intermediate and final sinks of a material" (Brunner and Rechberger, 2004). This way it is possible to trace materials and substances through a system like a manufacturing plant. The amount introduced into the system equals the amount in the sinks. This tool is especially useful to identify the whereabouts of toxic, harmful, dangerous or very precious substances. Stages or processes where large amount of a material are lost can be identified and measures taken. It is related to LCA, but pays more attention to the individual process flows and does not consider the environmental impacts.

2.4. Simple tools

Simple tools are used when decisions have to be made very quickly or for a rough and quick comparison of similar products. Typically the data amount and specific environmental knowledge necessary is small. Simple tools are a more structured approach than verbal-argumentative methods (IFZ/IIÖ, 2003) and are easy to communicate. These tools are often part of "Guidelines". Examples of simple tools that are used for different groups of products and which are also used for electrical and electronic products described in the following.

2.4.1. Check lists

Check lists are catalogues of criteria, questions, et cetera, that help recognise and assess environmental hotspots of processes and products. They give recommendations that reflect certain knowledge (IFZ/IIÖ, 2003). This knowledge can be threshold values for legal compliance as well as other requirements, that help in making a product more environmentally benign. For examples for checklists see the Smart ecoDesign eco-design checklist for electronic manufacturers, system integrators and suppliers of components and sub-assemblies (Centre for Sustainable Design, http://www.cfsd.org.uk/ seeba/ecocheck695%20iss%202.doc), the Designer's Guide to Eco-conscious design of Electrical and Electronic Equipment (http://www. ecodesignguide.dk) or Wimmer (1999).

2.4.2. Material exclusion lists

Material exclusion lists are lists with substances whose use is forbidden or restricted due to their impact. These lists help to comply with legal regulations and to fulfil requirements of guidelines and requirements of customers and suppliers. For example Siemens has published its so-called Siemens Norm which consists of standards to be applied in design and development of environmentally compatible products by all Groups of Siemens AG (http://www.igexact.org/ agu/agu_pub.htm). Also see the Designer's Guide to Eco-conscious design of Electrical and Electronic Equipment (http://www.ecodesignguide.dk).

2.4.3. Performance Indicators

Performance Indicators (PIs) are a small set of indicators that focus on the major environmental issues. The ISO 14031 (Environmental Performance Evaluation) states that Environmental Performance Indicators (EPI) are used "to measure, analyse, assess, report and communicate an organisation's environmental performance against its environmental performance criteria". These EPIs focus on the environmental hotspots of a product and need to be carefully selected. Examples for general applicable environmental indicators are energy consumption, material consumption, water consumption, greenhouse gas emissions or the total amount of waste produced (Verfaillie and Bidwell, 2000).

2.4.4. Other approaches

Strategic wheels (spider net diagrams) are used to display the accomplishment of different objectives (or indicators) on an arbitrary number of axes, typically 5 to 8 axes. The achievements regarding each objective are noted on a scale. The strategic wheel can be used to compare different options (e.g. which product is better) or to illustrate improvement of a company, a process or a product over time. An example is given in Figure 1. Also see for instance the Smart ecoDesign Electronics Strategic Wheel (Centre for Sustainable Design http://www.cfsd.org.uk/etmuel/ tools.htm#stratwheel) and the COMPASS (Kuhndt and Liedtke, 1999) by the Wuppertal Institute.

ABC analysis is a qualitative tool and well known in many disciplines. In an environmental context it classifies issues or problems according to their importance, from high (A) to low (C). Further, different materials can be categorised according to their relevance (e.g. amount of material) using X, Y and Z. Input materials rated A, X are thus ranked highest because they are of high environmental relevance and contribute a major input into a product. Materials ranked C, Z have a low environmental impact and are found only in small quantities in the product. This way a good overview of environmental issues can be gained.

Also 'Common Sense' can be seen as simple tool to identify environmental hotspots. "Stupid questions" like why is something done a certain way can help identify processes and product features that are essential and such that are rather a kind of "tradition". The latter were introduced some time ago and nobody questioned them before because they were always done that way. Why is this material used? Can the same service be gained another way? Is this product really needed?

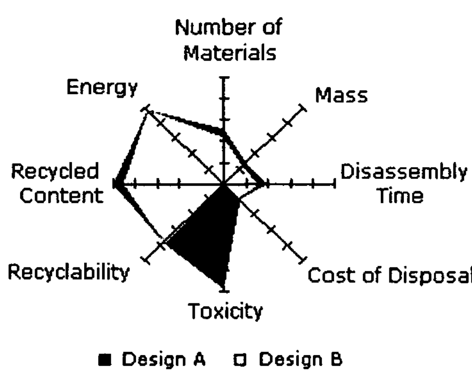

Figure 1: Green Design Advisor (GDA) by Motorola and the University of Erlangen showing that product B has a lower overall impact than product A (Source : http://www.motorola.com/EHS/environment /products/)

2.5. *Examples for specialised tools*

There are several sophisticated tools that focus on electrical or electronic equipment which often use indicators. For example 'Prodtect',is a software tool that helps in modeling the end-of-life of a product already in the design stage. (http://www.kerp-engineering.com). It calculates a potential recycling rate and the costs of recycling for a product, characterized by material lists, joining technique and other construction features. Another approach is the 'QWERTY/EE Concept' - Quantifying Recyclability and Eco-efficiency for End-of-Life Treatment of Consumer Electronic Products (Huisman, 2003). It focuses on the potential recyclability of products, not using the weight based approach but a scale, ranging between a best and worst case scenario. Also well known is the IZM/EE Toolbox which comprises a number of different tools that can focus on different aspects of electronics (e.g. Toxic Potential Indicator, energy demand) or different life stages (Recycling Potential Indicator). The toolbox was developed by the Fraunhofer Institute for Reliability and Microintegration (IZM) to be applied in the design phase of electronic products and processes.

3. *APPLICATION AND APPROPRIATENESS OF TOOLS FOR ELECTRICAL AND ELECTRONIC EQUIPMENT*

3.1. *Examples of choosing a tools*

The following three examples should illustrate the process of choosing an appropriate tool for a certain product. There is no single rule on how to choose a tool. However, all "relevant" aspects should be considered. What is considered "relevant" depends for instance on the actors, the complexity, the uncertainty, the level of improvement, the aspiration of the decision-maker and the cultural context (Finnveden et al., 2005).

3.1.1. Battery system

An example for the choice of a tool is a case study on battery systems (Rydh, 2001). The goal of this study was to identify activities of battery systems with significant environmental impact. A battery system has a high degree of complexity and a comprehensive picture of the system is needed in order to make a reliable assessment. This study aimed to include environmental impacts in relation to the input and output flow of both materials and energy. Thus LCA was chosen as the suitable tool because it presents a comprehensive evaluation of flows of materials and energy, both being important aspects for batteries. Furthermore LCA can be applied to hotspot identification in product system, product development, product comparisons, green procurement and market claims. Other tools which could be used, like Substance Flow Analysis or Cumulated Energy Demand had not been considered, as the applied LCA approach included aspects of both of them. Using only Substance Flow Analysis would have given only rough indicators and CED does not consider the environmental load of different forms of energy.

3.1.2. Eco mouse

In order to demonstrate both the methodology of ecodesign and the advantages of ecodesign products, an ecodesign product was developed and assessed (Schneider and Salhofer, 2005). As a widely used and not too complicated product, a wireless computer mouse was chosen. For the newly developed ecodesign product ("eco mouse") changes were made for the housing material, the energy supply and the soldering material. A common mouse has a housing made of acrylonitrile-butadiene styrene (ABS), is operated by two mignon-sized batteries and is assembled by using lead-containing soldering paste. For the eco mouse a housing made of lignin and hemp fibres was used and three double layer capacitors provide the energy. Satisfying the RoHS directive a lead-free soldering paste was used for assembly.

As the aim was to compare the eco mouse to a common mouse, it was decided only to consider those processes along the life cycle where the two products show different impacts on the environment. In a screening, for both products all life cycle stages were analysed. Processes which turned out as not diverging for both products (e.g. the assembling process for the housing material) were not further considered. Diverging life cycle stages are:

- The extraction, production and end-of-life treatment of the housing material.
- The production and the usage phase for energy supply options.
- The mining, production and the end-of-life treatment of the soldering paste, as well as the assembly stage for the two soldering pastes.

The assessment tool used should allow the summation of the results of the three separate parts to a single result per impact category for each product. Due to this consideration a streamlined LCA was chosen as some of the processes had to be excluded due to a lack of data (end-of-life treatment of the energy supply and the soldering material) and for others only one of several options was modelled (e.g. end-of-life treatment was modelled as waste incineration, although also other options exist).

For the evaluation of environmental impacts, the CML methodology and corresponding impact categories were used. The modular approach allows the identification of hotspots of each individual part (housing, energy, soldering) in quality and quantity. Thus optimisation can focus on processes with a high environmental impact and even processes with a lack of data can be considered by substituting them with similar processes. In addition, the results of one module can be transferred to other products without the other two.

3.1.3. Waveguide

Optical waveguide components are used to construct planar optical circuits on semiconductor or silica substrates. These compact optical circuits can be designed to perform complex networking tasks. Simply put, the waveguide components guide, split, combine or route the optical signals (light beams) in optical networks. It is a kind of "pipe" that guides the light to a certain point. In a case study an appropriate tool to assess the environmental impact of a waveguide area had to be chosen (Unger et al, 2006 not published). The main characteristics of the wave guide area are that it consumes no inputs in the use phase (similar to a pipeline) and that it consists mainly of silicon based materials, which are, in short, quite similar to glass. No environmental information about this particular type of product could be found. A complete LCA is not possible because of lack of data for the use phase and the end-of-life, as well as lack of data about a number of input materials. Thus a life cycle screening (scan through the whole life cycle in order to estimate roughly the relevance of different life stages, process steps or materials) was done. The result was that the use phase and the end-of-life stage showed little environmental relevance. This is due to the absence of inputs and outputs in the use phase and the inert properties of the waveguide area's materials. Thus the main focus is put on the manufacturing stage. To get a picture of the environmental impact of the manufacturing stage a comparison of two manufacturing routes, the sol-gel process with UV exposure (the one to assess) and Chemical Vapour Deposition (CVD) is carried out. This allows omitting certain aspects that both scenarios have in common, such as the silicon wafer base. The comparison is done by identifying indicators. This is because of the lack of some detailed data and the fact that the collected first hand data is taken from lab-scale processes which show some differences to large scale processes. The indicators show the hotspots of the manufacturing process, such as energy consumption (e.g. caused by ambient conditions, such as temperature and pressure) or mass efficiency. These indicators thus allow a quick comparison of different manufacturing alternatives as well as an easy way to assess improvements.

3.2. Examples for the use of tools for Electrical and Electronic Equipment

In the following some examples for the use of tools are given. In Table 1 the main aspects of some commonly used tools are summarised.

tool	*data demand*	*time demand*	*strengths*	*weaknesses*
LCA	high	high	comprehensive (life cycle stages, impacts), separated calculation of impacts & assessment	data and time intensive, complex results, use patterns hard to model
streamlined LCA	high	med. - high	comprehensive - at least screening of all life cycle stages	data intensive, complex results
MIPS	medium	medium	demonstrative results	only input is considered, no toxic effects included
CED	medium	medium	demonstrative result, energy related to most environmental effects	only input is considered, no toxic effects included
EF	high	high	simple, demonstrative result	data intensive, data might not be available
MFA	med. - high	med. - high	individual material or substance flows can be analysed	material or substance flow is considered, not impacts
Check lists	low	low	easy to handle, especially in supply chain	origin of data / results not traceable
Material exclusion lists	low	low	easy to handle, especially in supply chain	origin of data / results not traceable
Performance indicators	low	low	can include major aspects like material, energy and toxicity	origin of data / results not traceable

Table 1: An overview of different tools

A recent case study (Singhal, 2005) deduced that **LCA** is not a fully reliable method for definition of the environmental impact of complicated electronic devices like mobile phones. The reasons presented are the short product development and innovation timescales, the immense potential scope of data that has to be collected, the lack of available data for many substances and components like rare earths, and the lack of data on the toxicity issues related to the end-of-life phase. Moreover, when LCA is used to compare two similar products the differences are likely to be so small that they get buried in the assumptions that need to be made. In the experience of this study's author LCA has proven to be a very difficult tool for environmental improvement of product design. However, several examples for LCA case studies exist, for instance, Malmodin and colleagues (-) on a Third

Generation (3G) Wireless Telecommunication System, a case study on PCs (Atlantic Consulting and IPU, 1998) or simplified LCAs for electronic components (Stutz and Tobler, 2000).

A case study on mobile phones (Autio and Lettenmeier, 2002, in Singhal, 2005) showed that **MIPS** did not prove to be a suitable tool although the material composition data was available. Götz and colleagues (2001) also found that MIPS is not suitable because a pure mass consideration is a too rough measure for problem identification when two technical approaches are compared. However, another case study on mobile computing (Geibler et al., 2003) using MIPS found that most of the material inputs were available. Only for specific materials of the Printed Wiring Board and the Liquid Crystal Display were assumptions and estimates necessary, although for more than 99% of the materials the MI have been made available. The CD-ROM and floppy drive as well as batteries had to be omitted since no material intensity could be made available. Also the end-of-life phase could not be considered.

One of the key issues in comparing tumble driers (air vented and condenser tumble driers) in different ambient conditions was the **CED** (Rüdenauer and Gensch, 2004). So far, energy efficiency labelling of tumble driers takes into account the electricity demand when used under standard conditions (EN 61121). However, under real life conditions in a household additional parameters influence the energy demand. The results should build a scientific background for suggested correction factors for the energy demand of the two drier systems under real life conditions. Other case studies are, for instance, the comparison of printer colour containing solvents and water based printer colour (Götz et al., 2001).

The **ecological footprint** was used in a case study on mobile phones (Frey, 2002, in Singhal, 2005). The ecological footprint was found not to provide a good method for use in the electronics industry at present. The main reason for that is that this tool is relatively new and has only been used for one electronic study (i.e. Frey, 2002). Therefore also the risk of misinterpretation is high and results can not be verified (Singhal, 2005).

A good example for **PIs** are the environmental performance indicators especially for the production phase of mobile phones (KEPIs Key Environmental Performance Indicators) (Singhal et al., 2004). They allow a quick assessment with few, often easy accessible data, such as:

- Amount of precious metals, specifically gold, in the phone
- Total area of the printed wiring board (including all layers)
- Areas of the fabricated dies which are processed with the same number of mask steps
- Amount of bromine in the phone
- Area of LCD in the phone
- Amount of solder paste in the phone
- Amount of copper used in charger and its cable

Most electronics manufacturer use simple and comprehensible tools such as **guidelines** and **certificates** to show their concern about the environment. For instance Apple state on its website to use of guidelines, like the energy star or the Code of Conduct on Efficiency of External Power Supplies, introduced by the European Commission, to increase energy efficiency. This results in a significant cut in power reduction in the sleep mode of the newer products (Power Mac G5 in comparison to Power Mac G3 about 66%) and also in the off-mode power by improvements in the Integrated Circuits (parts on the printed wiring board).

Another electronics manufacturer (LG) states on its website that in order to conduct eco-design, LCA was introduced ten years ago. From it, Eco-Design guidelines and checklists as well as a Design for Recycling software were developed. Examples of products where these were applied are plasma TVs, mobile phones or DVD writers. They also have a Green Partnership Program with their own certification for suppliers (partnered firms and subcontractors) to ensure they purchase environmentally friendly materials and parts.

4. Discussion

The literature review showed that the choice of a tool and consequently also the choice of measures depends on several different factors. These are:

- The reason for the assessment
- Scope of the tool
- Resources for the assessment
- Time frame
- Data availability

Before an assessment is done the reason for the assessment must be clear to all stakeholders; why is the assessment done, what question should be answered, who is the audience for the answer? Many tools are intended to be used as a support in decision making. Thus the context and the question that should be answered will influence the choice of tool. Other aspects will influence how the tools are used, e.g. if a simplified or detailed study will be done. Finnveden and Moberg (2005) suggest that "*the two key aspects of the decision context determining the choice of tools are the object of the study and the impacts of interest. Other aspects will either influence how a tool is used, or have an indirect influence via the key aspects.*" Different stakeholders may therefore find different tools appropriate. These considerations also help in defining the scope of the assessment. While some tools may focus on the whole life cycle or a certain life stage, e.g. end-of-life, others focus on certain types of indicators, e.g. materials or energy. The tool must be chosen depending on what objectives should be achieved.

Other aspects that influence the choice of tool are available resources for the assessment. In many cases the size of the company will determine the available financial, personal, time and data resources. The more time there is, the more sophisticated and integrated the tool can be. In the design and development stage simple, quick tools are more likely to be used. The tool used must be appropriate for the company so that an environmental improvement can be gained. Larger companies are more likely to influence suppliers and to promote their environmental image to customers than small and medium sized companies. Large companies are also more likely to gain access to first hand data since they either own the relevant sites or are more influential than small and medium sized companies. How much, type and quality of data will also influence the choice of tool.

Additionally, differences can be seen by the type of equipment. Although electrical and electronic products are often seen as one group of products they show big differences and thus different tools show different applicability.

Electrical equipment comprises long lasting appliances, like washing machines and change, in general, only little over time. The materials used in electrical equipment are often common and environmental data about them is relatively easy accessible. The composition of electrical appliances is often known or easy to get. The use pattern can be reasonably estimated and does not undergo quick changes. A refrigerator, for instance, is plugged in when bought and will show relatively constant energy consumption over its life time. Electrical appliances are hardly ever very small but, on the contrary often bulky and heavy. Due to their bulkiness they are very likely to be disposed in special collection points or taken back by the retailer (as also required in the new WEEE directive). Thus an adequate end-of-life treatment can be assumed for many of them. Producers have time to improve the environmental performance with time (e.g. water use and electricity consumption in use phase) without having to change established features of the product from a consumer point of view.. Thus, also sophisticated tools like full LCA can be used for ecodesign approaches. From the results of sophisticated tools, simple tools, like checklists, can be derived and used in guidelines for a certain branch of industry or for a certain type of product for quick decision taking.

The use of ecodesign tools for **electronic equipment** is quite different. The electronic sector is characterised by short innovation time and continuous changes. The number of features, for example, of mobile phones increases constantly and thus the consumer behaviour in the use phase changes. The model of last year is already considered an old model today. Due to the short innovation cycles and thus the quick changes in composition and used materials, it is hard to get reliable information if you are not within the company. Due to the fierce competition in the electronic sector information about production processes is often regarded as confidential. New models of equipment show often changes in details which are hard to assess. Assessments are, due to the above mentioned reasons, often carried out by the environmental departments of the manufacturer, or on behalf of the manufacturer. The results are published in environmental statements where they are summarised to a few numbers, in general giving a positive opinion that can be used for marketing purposes. Because of that reason, it is often difficult to access the underlying data and thus to use the experience of such studies for other studies. The used materials are on one hand common materials as are also used for electrical equipment but on the other hand also a large range of highly special commodities, like silicon (semiconductor wafers), precious metals (integrated circuit boards), or potentially hazardous substances (e.g. in liquid crystal displays). For many of those no detailed environmental data is available because their effects on the environment and health are not yet known. Such uncertainties make an assessment harder. Electronic equipment is also characterised by minimisation. This trend can be seen with laptops or mobile phones. Thus only small amounts of certain materials are used, which is a desirable effect, but which increases uncertainty and can make adaptation of end-of-life treatment more difficult. The short innovation cycles hardly allow the use of sophisticated tools for decision taking, because the time needed to apply these tools is too long. From reviewing case studies it can be observed that some components, that are part of most electronic devices, like printed wiring boards, liquid crystal displays and batteries are often identified as environmental hotspots.

Information like that can then be used to derive, for instance, performance indicators, as can be seen in the example of KEPIs. Sophisticated tools are more suitable to analyse the environmental features of systems, like a telecommunication system (see for instance Malmodin et al., -). These systems are often very complex and involve many different products and processes.

5. *Conclusions*

Although the word "tool" and also some retailers of assessment software give the impression that it is easy to assess even complex products, this is not true. The choice and application of tools can be very difficult and sometimes many decisions have to be taken. If the wrong tool is chosen for a particular product or if it is used inadequately, the results will be misleading. The tool has to be fit for the type of product to assess as well as for the person applying the tool.. Thus it is important to see the difference between electrical products (slower innovation cycles, common materials and composition, well known use patterns and end-of-life treatment) and electronic equipment (with short innovation time, changing use patterns and highly special materials).
Moreover, the choice of tool depends on the "question" which the use of the tools should answer – should it assess the overall environmental impact; should it help in taking quick decisions, etc.? Thus a qualified person has to choose the tool. Looking on previous case studies can help in taking the decision, because they illustrate the advantages and disadvantages of a particular tool in a certain scenario. It is not possible to say that a tool is the best tool for a certain type of product.

Acknowledgement

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Paper III

Unger N. (2007) Applying a system perspective to the assessment of materials – a discussion of the limitations of current environmental assessment approaches. In Weil M., Buchwald A., Drombrowski K., Jeske U., Buchgeister J. *Materials Design and Systems Analysis.* May 16 – 18, 2006, Forschungszentrum Karlsruhe, Germany, Shaker Verlag, Aachen

Applying a system perspective to the assessment of materials – a discussion of the limitations of current environmental assessment approaches

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Abstract

This discussion paper explores the concept of life cycle thinking drawing on examples from the electronics sector. Although the phrase 'life cycle' is regularly used in the context of environmental management, analysis frequently focuses only on individual life stages or simplified linear sequences of production processes. This paper illustrates the true complexity of the 'life cycle' and suggests use of the term 'net' as a more fitting description. Further the difference between a material and a product life cycle is explained. This serves to illustrate how legal regulations, which focus on the material rather than the whole product can result in a shift of environmental burden from one life cycle stage to another, rather than an overall improvement in environmental performance.

Keywords

Life Cycle Thinking, LCA, system analysis, system boundaries, allocation

1. Introduction

Although approaches exist for the integration of environmental aspects in system analysis (e.g. Life Cycle Assessment, EN ISO 14040ff) full product systems are hardly ever examined (Sim et al. 2006). Often a cradle to gate approach is used where the life cycle of a product is analysed from extraction until it leaves the manufacturing site gate. Theoretically, the life cycle starts with the extraction of raw materials and their refining. In the production stage raw materials are combined to make a product and in the use stage they provide the desired service. At the end of a product's life, some kind of treatment may often be performed before the product or its material parts are finally disposed of. Thus the whole life cycle – from cradle to grave – is taken into consideration. Indeed, this sequence of processes is often the basis for environmental assessment such as an LCA. However, this suggests that product life cycles are discrete linear process chains, which in the real world rarely exist. This current modelling paradigm is illustrated in Figure 1. The (horizontal) linear process chain crosses several (vertical) flows. These are the (more or less linear) process chains of materials and products that enter the main (horizontal) life cycle at different life stages. Recycling loops may occur but do not dominate the flows. All life stages consume inputs such as fuels, electricity or other ancillary materials (e.g. lubricants). They also require infrastructure. The number of crossing flows considered by the analyst depends on the system boundary and therefore the cut-off criteria applied.

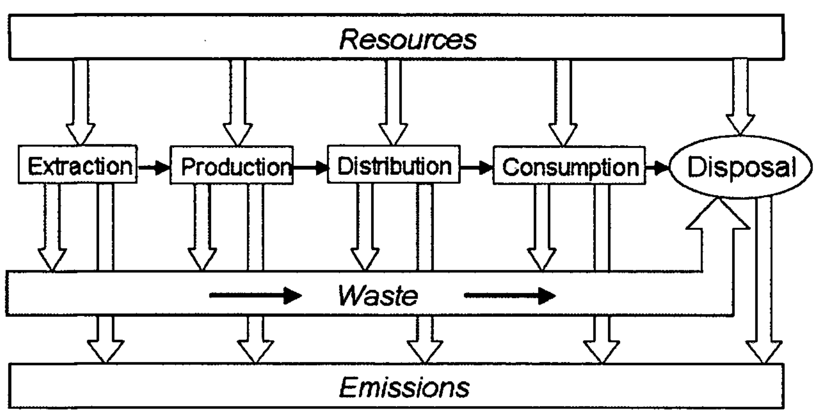

Figure 1: Resource flows through the schematic life cycle

2. Current life cycle modelling

The sequence of processes which combine to form the product life cycle all take place within the technosphere. This is the economic and technical space in which human activity takes place. We can see from Figure 2 (adapted from Clift et al. 1998) that the technosphere is a wholly owned subsidiary of the environment.

This is because the environment provides all the resources for the system and acts as the sink for all emissions, i.e. it is both cradle and grave. According to LCA standards (EN ISO 14040ff) only elementary flows from the environment should enter the technosphere and only elementary flows should leave it.

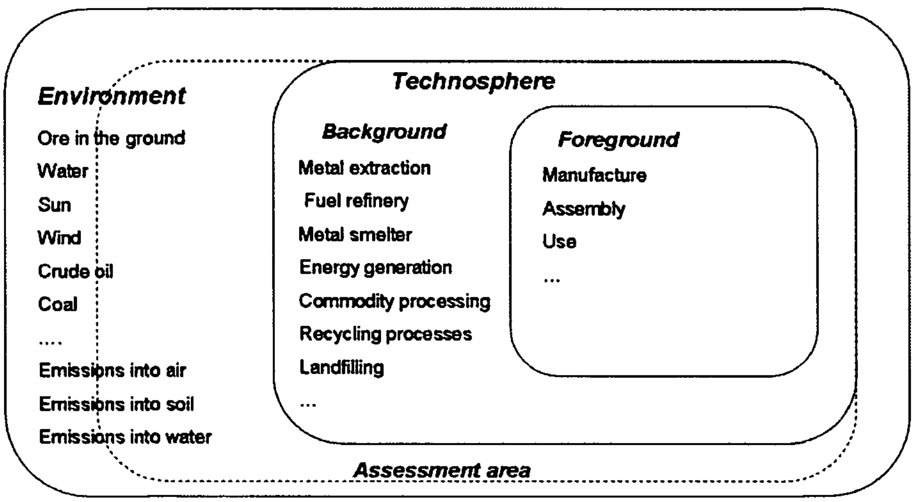

Figure 2: The Foreground and Background System

The technosphere can be divided into the fore- and the background (Figure 2). The foreground consists of life stages whose regional location and temporal scope are normally known; for instance manufacture, purchase and use (Clift et al, 1998). Inputs to the product system and ancillary processes are often found in the background. Such processes may include extraction and refining of raw material and intermediate products and the end of life treatment (EoL). The background may include commoditised materials whose exact origin may not be known (e.g. copper from different mines which has been smelted at one site to be traded on a global commodity market; see e.g. Ayres et al. 2003, Goonan, 2005 and Vexler et al. 2003). In general, the exact location of the background processes is of less importance in environmental assessment; one exception is electricity generation. Thus the background processes are more likely to be assessed using average data while foreground life stages will normally be assessed using site specific data.

The distinction between fore- and background proves to be a useful aid to modelling, but difficulties arise in managing system boundaries and cut-off points (i.e. the cross-cutting flows shown in Figure 1) illustrated with a dotted line in Figure 2. Normally the problem must be dealt with by applying allocation rules such as system expansion or allocation by physical relationship or economic value (see e.g. Weidema 2001, Tillman and Baumann, 2004). Indeed, these 'loose ends' are one reason why environmental assessment can prove to be challenging.

Moreover in certain cases of environmental assessment some stages of the life cycle are left out of the assessment altogether (e.g. streamlined or simplified LCA, Christiansen 1997). This is acceptable only where life stages are of no, or negligible, relevance for addressing the objective of the assessment. It is important to explain the reason for omitting a life stage, stating why the results are still believed to be valid. (EN ISO 14 041).

3. Differences between product and material life cycles: implications for environmental assessment

While products are characterised by the function they provide, materials are defined by their chemistry or composition and are usually measured in weight. For example, a kilogram of metal would be classified as a material; however in the shape of a screw both function and value have been added resulting in a product. Whilst product cycles may comprise any number of life stages, there are three main segments: production, use and end-of-life treatment. However, the life cycle of a material has just two main segments: extraction and refining, and end-of-life treatment. In the use phase the material is part of a product where it neither consumes resources nor produces emissions itself. If a material is used up during the use phase of a product, this may actually be viewed as a form of disposal (EoL); e.g. burning of fuel or wear of a car tyre on the road. However, where materials are not consumed during the use phase of a product, different life cycle paths are possible for these materials when the product is decommissioned. The end of a 'life cycle loop' can either be the 'grave' or the start of a new loop (Figure 3); the phrase 'cradle to cradle' is often used to describe the latter. However, this terminology is not advocated by the author because the cradle is positioned outside the technosphere in the environment whilst recyclate remains within the boundaries of the technosphere (see Section 2). Figure 3 illustrates this: one unit of metal is extracted from the environment, incorporated into a product and eventually treated in some way (within the technosphere) at the end of the product's life. For instance it may be incorporated within different electrical and electronic equipment, toys, vehicles and in kitchen utensils. A number of end-of-life scenarios are possible for each of these product groups including reuse and recycling. Only when these materials are finally treated as waste will emissions from their disposal cross the boundary between the technosphere and the environment. Such flows are considered in material flow analysis (e.g. Brunner et al. 2003).

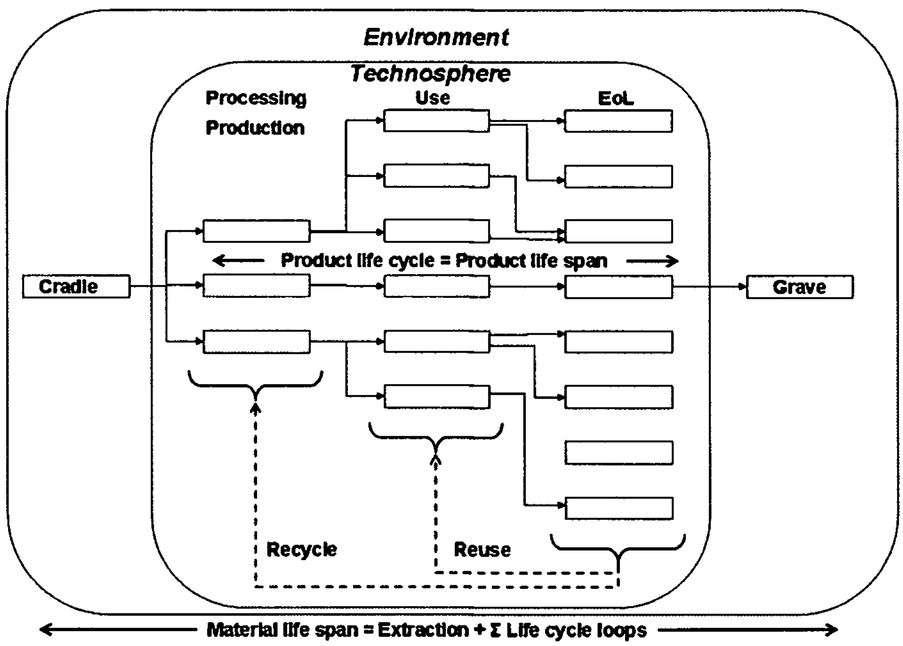

Figure 3: Schematic sketch of cradle to grave with life cycle loops

4. An alternative perspective: the Net

It is clear from the discussion above that the tendency to model life cycles as linear systems creates numerous problems for the identification and management of cross-cutting flows. Recognising this, it may be more appropriate to consider product systems (e.g. those elements encompassed within the dotted lines in Figures 2 and 4) as part of a 'net' in which numerous materials and products join and diverge at different stages in space and time (Figure 4). At each stage of the net outputs of other life stages are incorporated whilst products, materials and emissions are diverted to other life cycle or the environment.

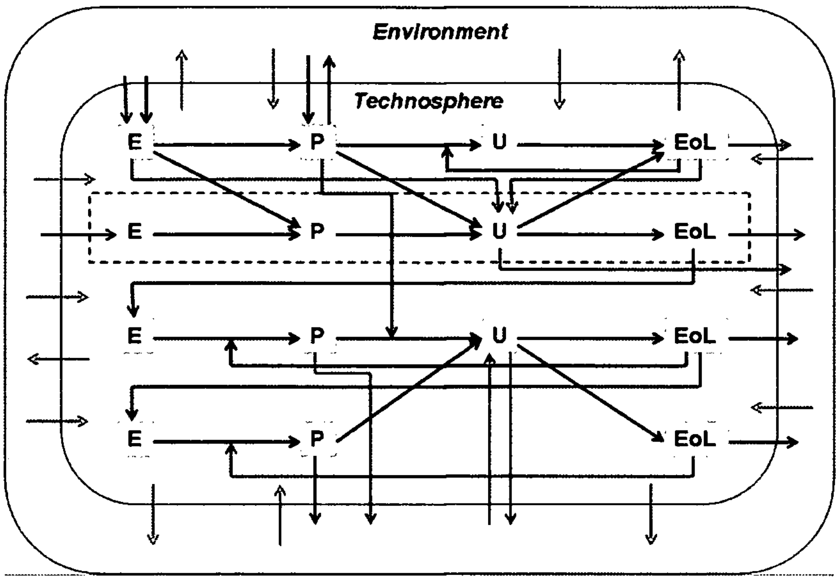

Figure 4: The Life Cycle Net (E: Extraction, P: Production, U: Use, EoL: End of Life)

5. Example: Mapping the paths of two different products

This section presents an example of the use of the net to illustrate the material flows of a lead-containing soldering paste (Sn63Pb37) and those of a lead-free soldering paste (Sn96.2Ag2.5Cu0.8Sb0.5). The data (shown in Figures 6 and 7) have been taken from a recent study on an environmentally friendly computer mouse (Schneider et al., 2005, Figure 5). The need for this comparison arose as a consequence of the RoHS directive (Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment, EU 2003) which has had considerable impact in the electrical and electronic sector. Within this directive, the use of lead, in addition to a number of other substances such as cadmium and mercury, is severely restricted due to its potential health and environmental risks, even assuming disposal through adequate recycling routes. One such restriction is a ban on the use of lead in soldering paste: alternative soldering pastes are now used.

Figure 6 illustrates the net of flows for the lead-containing soldering paste. Only material flows which are in the foreground are shown. Some flows, such as energy generation, are summarised. The input materials are extracted from the environment and combined to form a paste; both processes require energy. The paste is then used in the assembly of the Printed Circuit Board (PCB) of the mouse (soldering process). As shown in Figure 6, there are no flows related to the paste in the use phase, when it is part of the mouse. Three different End-of-Life options are considered. In the case of separate collection, approximately 95% of lead is recycled (dotted line in Figure 6) thus forming a life cycle loop, while the other input materials are lost and released as emissions to the environment. However when the municipal solid waste incineration (MSWI) and landfilling options are chosen, all materials cross the technosphere's boundary and are released into the environment.

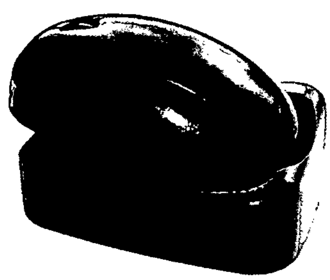

Figure 5: The Eco mouse

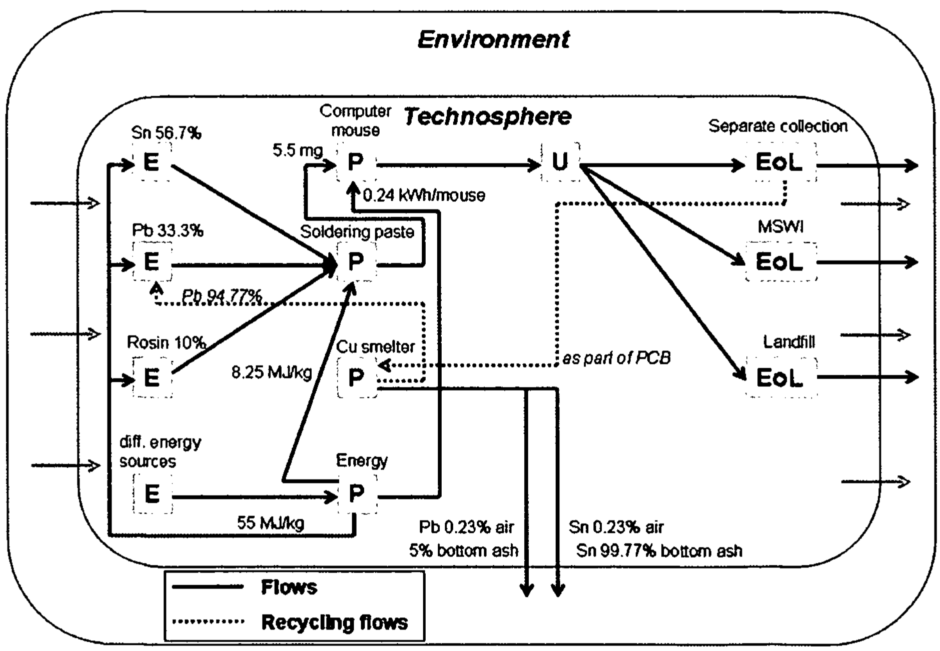

Figure 6: Net of flows for a lead containing soldering paste (E: Extraction, P: Production, U: Use, EoL: End of Life)

In Figure 7, the net of flows of the lead free soldering paste is shown. The energy needed to extract and refine the used metals is significantly higher than for the lead-containing paste. This is due to high energy demand for silver production. Moreover, the energy required for soldering increases due to the fact that lead free soldering paste has a higher melting point than a paste containing lead. For the End-of-Life, the same options as for the lead containing paste are considered. In the case of separate collection, copper and silver are recovered and reused (loops) while the other input materials of the lead-free soldering paste become emissions to the environment. Again, all materials leave the system following MSWI and landfilling.

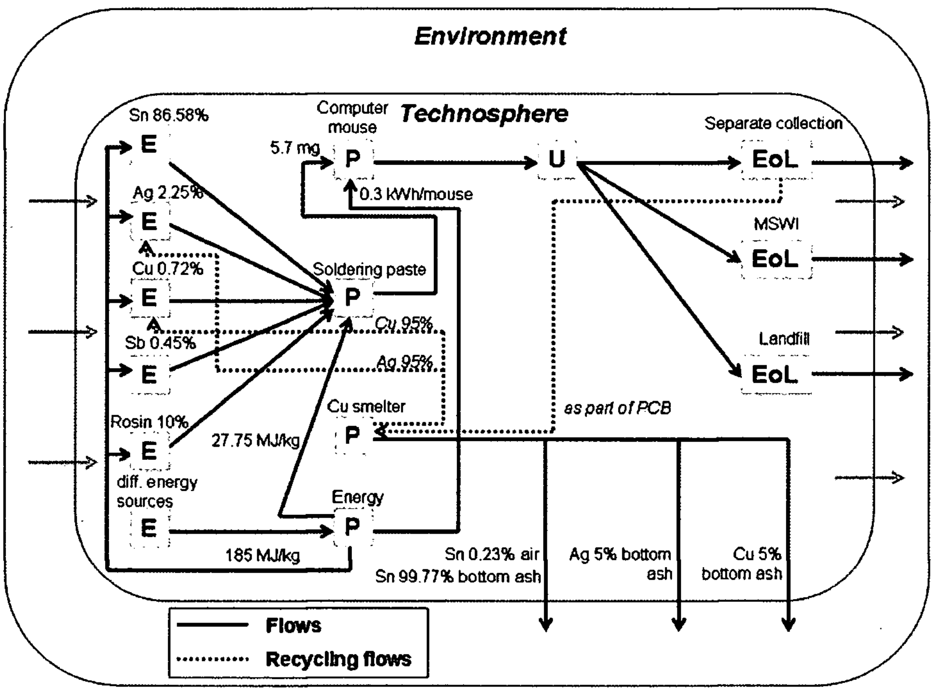

Figure 7: Net of flows for a lead free soldering paste (E: Extraction, P: Production, U: Use, EoL: End of Life)

As shown in Figures 6 and 7, the flows related to a single input (soldering paste) in a product life cycle are indeed rather complex. However, the picture becomes even more complicated when further interconnections are considered. Metals, for instance, hardly ever originate from a single, clearly distinguishable raw material source. In general a mix of different metals can be found in ore. Figure 8 illustrates some interconnections; for example, significant parts of silver production are by-products from lead and copper mining (Huisman, 2003). Such interconnections should therefore be combined with the net of flows of the soldering pastes. This would result in a denser net with a greater number of linkages to other life cycles.

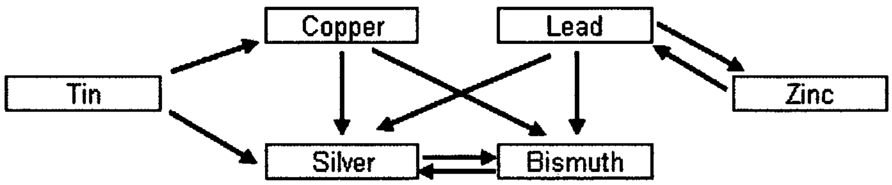

Figure 8: Interconnection of base metal products (Huisman, 2003)

This comparison of soldering paste shows that the lead containing soldering paste has clear environmental benefits in respect of Global Warming Potential, Acidification, Eutrophication, Ozone Layer Depletation Potential and Photochemical Ozone Creation Potential (commonly used impact categories in Life Cycle Assessment). The higher impacts of the lead-free soldering paste are mainly due to a higher melting point of the paste and to the fact that the metals, mainly sliver, which replace those used in the lead mix are found in lower concentrations in ore resulting in more waste during the refining process. However, applying the Toxic Potential Indicator (TPI) and the Toxic Emission Potential (TEP) (of the Institut für Zuverlässigkeit und Mikrointegration, Fraunhofer Institute) lead-free soldering paste shows lower impact (Müller et al. 1999). This comparison illustrates that a shift from one 'toxic' material to other substances that have lower toxicity may result in higher impacts in other environmental categories. In order to recognise this mechanism of burden shifting, it is important to understand the connections between single materials and the broader net of which they are a part. Therefore, there is a need to consider the full net when determine system boundaries in assessments which aim for overall improvements in environmental performance.

6. Recommendations

It is recognised that to model a full net would be a data intensive and time consuming task especially given that problems already exist when conducting environmental assessments because time and data is often not readily available.

Moreover, it is usually not the objective of the assessment to attempt to model product systems with infinite detail, but rather to identify possibilities for environmental improvement. However, it is recommended that practitioners should at least investigate the complexity of the net in their initial scoping activities to enable them to make more informed judgements when setting their modelling system boundaries. This will help them to ensure that all relevant life stages are considered in the environmental assessment, thus helping to avoid burden shifting (Section 5). One way for analysts to investigate this complexity is through site visits, both of processes occurring in the fore- and background, rather than relying solely on their compilations of secondary data.
In addition, more work needs to be done in the field of classifying materials according to their environmental impact (e.g. Rydh et al 2005, Unger 2005), particularly with the aim of informing the development of regulation. This would help in the setting of system boundaries either to include or exclude cross-cutting material life cycles so that burden shifting is avoided.

7. Conclusion

This discussion paper illustrated that life cycles are often far more complex than the words suggest. The term 'net' is a more fitting description of the interwoven product and material life cycles which actually exist in the 'real world'. In order to mange the challenges associated with modelling system boundaries in environmental assessment (e.g. allocation), it is important to consider the true breadth of technical activities and the linkages which bind them. The net is proposed as one way of illustrating this wider analytical perspective.

8. Acknowledgement

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Paper IV

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Life cycle considerations about optic fibre cable and copper cable systems: a case study

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Abstract

Q1 Optic fibre cable and copper cable are important media for data transfer, the latter especially for shorter distances. However, the environmental implications of this facility are rarely looked at. The present paper investigates and discusses the life cycle of a cat5e copper cable and that of a 4-core multimode optic fibre cable. It shows that the difference in the environmental impact depends on the type of end-of-life treatment and that there is no clear advantage to either type of cable. Moreover, the question is raised if providing the infrastructure for internet access will have a higher impact than the mode of data transmission.

Keywords: Optic fibre cable; Copper cable; Information and communication technology; Life cycle assessment

1. Introduction

Modern society has become increasingly dependant on the numerous information and communication technologies (ICT) available. They are now commonly used world over. ICT have changed and affected not only our means of communication but also have exerted a considerable influence on economy, society in general and the environment (see also, e.g. Refs. [1–3]). However, communication has been an important issue throughout the centuries, not merely over the last decades. The notion of using glass fibre to carry optical communication signals was first proposed by Alexander Bell [4]. Today it is state of the art to use optic fibre cable as well as copper cable, the latter especially for shorter distances – "the last mile".

Optic fibre cable is one of the principle communication media used today. Optic fibres are suitable for replacing conventional copper cable in communications systems with few modifications. The former, however, display several significant technological advantages over common copper cable.

Although capacity (data rate) is one of the aspects most commonly associated with fibre optics it is not the foremost property. Actually, capacity over short distances is comparable to that of copper wiring, since communication engineers have succeeded in applying new technological features to improve performance of copper cable links (e.g. DSL over telephone cable, Gigabit Ethernet over UTP cable). Only when it comes to longer distances does optic fibre cable show significant advantages. While in copper cable the signal has to be repeated or amplified to restore its power and remove the noise at quite short intervals (100 m–2 km), fibre optic cable can cover much longer distances without a drop in signal strength, thus requiring a considerably less frequent regeneration of the signal (repeaterless distances of 200 km are common). The dimensions – diameter and consequently weight – required for optic fibre cable are notably smaller, thus facilitating installation, and resulting in lower costs for installation. Although bending of optic fibre cable is at times problematic, the smaller dimensions afford reasonably good flexibility.

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Additional advantages of optical systems when compared with electrical systems (copper cable) include the fact that with the latter "ground loops" caused by potential differences between the ground at different locations may occur. Moreover, optical networks and connections need not be protected from harming people as is the case with electrical installations. Optical cabling also shows advantages due to the absence of electromagnetic interference with electrical and electronic installations. In this way optic fibre cabling can be laid close to electrical cables; for instance, plastic optical fibres are used in the car industry where space is very limited and more and more electronic features such as entertainment equipment are installed [5].

2. The case study

2.1. Goal and scope

Fibre optic cable is reputed to be preferable to copper cable from an environmental point of view because it provides far more information transmission capacity per environmental load than copper cable ([6,7]).

This paper aims to assess this environmental advantage by carrying out a case study on optic fibre cable and copper cable. To do so the life cycle is discussed and a simplified LCA carried out. Moreover, the impact of modern information and communication technologies (ICT) will be illustrated.

The paper intends to answer two main questions:

- What is the environmental impact of an ICT infrastructure provided with state of the art technology (optic fibre cable in combination with copper cable) in comparison to a no ICT infrastructure?
- What would the environmental impact be if the same service were provided by means of copper cable only instead of optic fibre cable?

The alternative of wireless access was not included in this study which intended to focus only on the two types of cable.

In order to address the above questions, two different scenarios were assessed and compared. A student accommodation complex in Irelandwas selected for evaluation, due to its being a well defined and structured area with a high penetration of ICT facilities. The complex had been recently built and consists of 13 blocks accommodating 175 apartments for a total of 586 beds (Fig. 1, each block is named after an Irish author). Each bed unit has direct access to the network. In addition there is a further access point in the apartments' common room. All installations were carried out during the initial construction, thus no extra building activities were necessary for the ICT wiring. The distances within the accommodation complex are shown in Table 1. The cable runs from the bedrooms to the hall of each block. The average distance is 40 m (the wiring within the block is calculated by the number of beds + the number of common rooms × 40 m). The cable is subsequently directed to the reception of the student accommodation complex. In one part of the complex (on the left of the sketch) the wiring was put in the roof of the underground parking lot. In this way it can run under the buildings, while on the other side (on the right of the sketch) the wiring runs around the perimeter of the buildings. The complex is connected to the college network from the reception area. This connection is beyond the scope of the present case study.

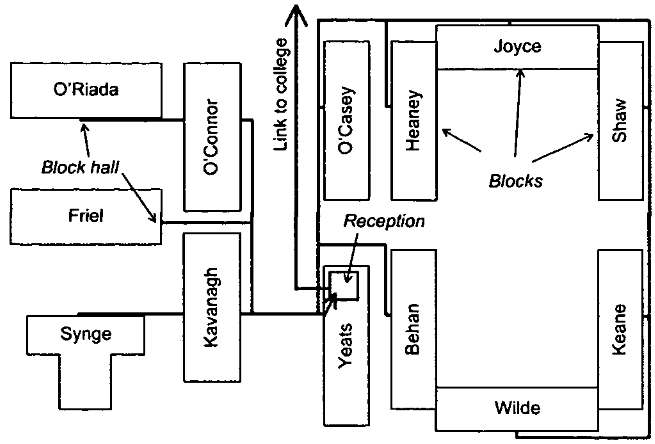

Fig. 1. Sketch of the outline of the student accommodation complex.

2.2. Methodology

As environmental assessment method a streamlined Life Cycle Assessment (LCA) was chosen. An LCA is a tool commonly used to assess the potential environmental impact of a product or a service throughout its whole life cycle. The life cycle starts with the extraction of raw materials and includes all life stages such as production and use stage until the end-of-life of a product, its disposal – from cradle to grave. A streamlined LCA is not as detailed as a standard LCA.

The functional unit of this case study is the service of providing internet access to all bed units in the chosen accommodation complex. This study was made possible due to the fact

Table 1
Distances [m] within the accommodation complex

Block name	Number of		Room–block hall [m]		Block hall–reception, total distance [m]
	Apartments	Beds	Distance	Total distance	
Yeats	11	41	40	2080	3
O'Casey	16	48	40	2560	49
Heaney	12	36	40	1920	116
Joyce	12	46	40	2320	120
Shaw	10	30	40	1600	177
Keane	10	30	40	1600	212
Wilde	12	36	40	1920	266
Behan	12	36	40	1920	56
Kavanagh	16	55	40	2840	27
O'Connor	16	55	40	2840	69
O'Riada	16	55	40	2840	87
Friel	16	55	40	2840	91
Synge	16	63	40	3160	58
Total	175	586		30,440	1331

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that over short distances copper cable and optic fibre cable have a comparable performance. The student accommodation complex is representative for any accommodation or office complex with a high number of internet access points in Ireland. Thus a streamlined LCA rather than a full LCA was done and average data from public sources were taken for the inventory. For the calculation the software GaBi 4.0 (LBP University of Stuttgart and PE Europe GmbH) was used. Data sources were the GaBi databank, the Ecoinvent databank (Swiss Centre of Life Cycle Inventories), data from literature and personal measurements of the composition of cables.

2.3. The scenarios

In the *optic fibre scenario* the network as actually implemented in the accommodation complex is analysed. This should answer the first question, as to what impact the provided ICT infrastructure produces.

The network is formed by the two different types of cables. As shown in Fig. 2 the connection from the rooms to the block hall is provided by a copper cable (Cat5e operating at 100 Mb/s) while the connection from the block to the reception area is made by optic fibre cable (each operating at 1 Gb/s). Connections between the different types of cable are achieved by means of media converters. These are devices that change the format of the information to render them compatible with the standards used, e.g. Fast Ethernet to Gigabit Ethernet and electronic information into optical information. The converters in the block halls combine the cables leading from apartments into just one cable connected to the main reception area. Likewise, the cables from the individual blocks are combined into one data cable connected to the college.

The *copper scenario* is a fictitious scenario. The copper scenario represents merely a theoretical measure aimed at illustrating the environmental advantages or disadvantages of optic fibre cable. The connection of the blocks to reception is therefore envisaged also by means of copper cable as a substitute for optic fibre cable. Optic fibre is used due to the numerous advantages (size, price, etc.) afforded, as mentioned in Section 1. The main aim of this case study, however, is to evaluate the environmental aspects. It is technically possible to provide the same facility afforded by optic fibre over short distances using a copper cable. This is normally not the case in view of the advantages offered by optic fibre cable, but which scenario is preferable when taking into account only environmental issues? This scenario should help to illustrate differences between the environmental impacts of copper and optic fibre. By applying the scenario on a large scale, such as in the student accommodation complex, a global picture of the degree of environmental impact produced is obtained.

The 'Room–Block hall' connection is identical in both scenarios. In connecting the blocks to the reception area optic fibre cables can be substituted with copper cables without any problem up to a distance of 100 m. For distances exceeding 100 m a repeater has to be inserted into the cable to ensure good data quality. A total of seven repeaters would be needed to connect the blocks with the reception.

The connection to the college was not assessed in any of the scenarios. This connection had been achieved using a 4-core single mode optic fibre cable. A copper alternative would not be feasible (10 repeaters would have been required) and was deemed too unrealistic for comparison. A wireless connection, e.g. WiMax could represent an alternative to optic fibre, however, as the present study focused exclusively on the two types of cable.

2.4. The life cycle of the optic fibre scenario

2.4.1. Production phase

The cabling of the optic fibre scenario consists of the following components:

- Copper cable
- Optic fibre cable
- Converters

In the optic fibre scenario copper cable as well as optic fibre cable was used. The copper cable is described in greater detail in the copper cable scenario (Section 2.5).

2.4.1.1. Optic fibre cable. The optic fibre cable consists in general of a core, cladding and a primary coating (150–500 μm thickness). The cladding has a slightly smaller refractive index than that of the core which causes the light to be reflected at the core-cladding boundary, thus confining the

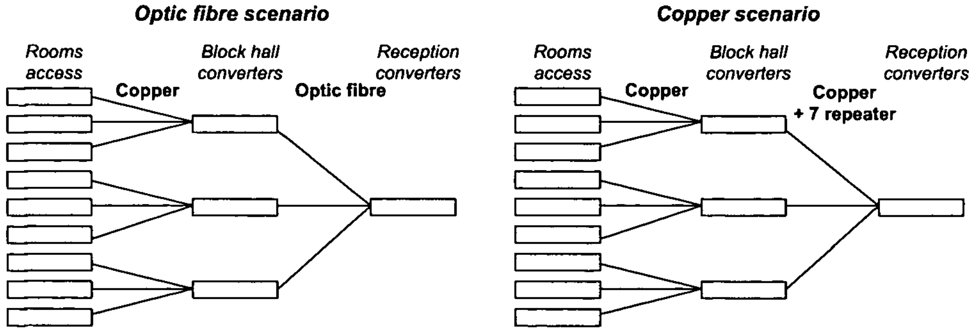

Fig. 2. Schematic sketch of the two scenarios.

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light signal within the core. The cladding is usually made of pure SiO_2 while the core lightly doped with germanium to alter the refractive index. In general optical fibre consists of 96% of silicon dioxide and 4% germanium dioxide, with small amounts of other elements [8]. Between the cladding and primary coating there is normally a coating of 2–5 μm to protect the fibre from humidity. The primary coating is made of materials such as silicon or nylon [7].

The optic fibre itself is obtained from a preform, a cylinder of silicon dioxide matching the radial structure of the resulting fibre (typically 10 cm in diameter and 1 m in height which yields about 120 km of optic fibre) [7].

Although there are a number of optic fibre cable manufacturers, very few companies actually manufacture the optic fibre itself. The composition of the loose tube optic fibre cable used in this case study is given in Table 2. The optic fibre itself is protected by a buffer cable consisting in a layer of aramid yarn. The outer coating is made from polyethylene (PE).

2.4.1.2. Converters. In order to connect the different cables and to encode the information accordingly, 13 converters (one in each block) were required (e.g. Netgear ProSafe 48 Port 10/100 L2 managed Stackable Switch (FSM750S), suitable for use, with slight modifications, in both scenarios). Although their envisaged functions and use is different, they can be deemed comparable in view of their similar assembly implicating a similar impact from an environmental point of view. They consist of a housing, a circuit board and wiring. For the assessment an average composition of a printed wiring board (PWB) was taken. The housing is steel manufactured.

2.4.2. Use phase

No detailed data was available on the life span of optic fibre cable. However, for the cables an operational life span of 20 years has been assumed. This was done on the assumption that major refurbishment and restructuring of the buildings is likely to take place and the wiring adapted and renewed for renewed needs. The converters are assumed to have an operation life span of 6 years. This is the mean time between failure value. Warranty lasts for 5 years, thus the devices are more likely to be replaced with new models than repaired. Throughout the use phase the only energy consumed is that required by converters (max. 90 W). In addition to energy consumption heat generation also occurs; this is not, however, taken into account in this study as, on the one hand, it is not used, and on the other hand, no additional cooling is required in the blocks. In this case study the maximum energy consumption was taken as being 24/7.

Table 2
Composition (in grams) of 1 m 4-core optic fibre cable

Optic fibre	0.29 g
Gel	2.22 g
Inner cladding	4.25 g
Aramid	3.1 g
Outer sheath	24.13 g
Total	33.99 g

2.4.3. End-of-life phase

2.4.3.1. Optic fibre cable. In comparison to metal containing cables where the recovery of metal is economically reasonable, there are no valuable materials in optic fibre cable that would encourage recycling. In particular, the presence of sticky gel makes cost-effective recycling hard to achieve [9]. Although research is underway to improve recycling techniques, they have not yet been widely applied.

Accordingly, it has been assumed for the purpose of this case study that used cables are disposed of by incineration. While the silicon based materials will produce a negligible impact, energy credits will be achieved by thermal treatment of plastic components. It has been assumed that incineration takes place in Germany since there are no suitable facilities in Ireland.

2.4.3.2. Converters. A number of different end-of-life options are available for converters, switches and waste electrical and electronic equipment (WEEE) in general, such as reuse of selected components, recovery of some materials or incineration.

However, not all these possible treatments can be performed on a large scale. Printed wiring boards (PWB) are the foundation of electronics. Electronic components such as capacitors, resistors and chips are located on the PWB as are electrical interconnections between the components.

There are too many differences in the intrinsic physical and chemical properties of the many materials and components present in scrap PWBs and scrap in general to permit recycling into individual fractions [10]. Recycling is applied almost exclusively for metals. Over the last years the content of precious metals in electronic goods has decreased (e.g. Refs. [11,12]). This trend is expected to continue in the future [13].

Metals that are economically attractive for recycling are for instance gold, palladium, platinum, silver, copper, tin and nickel [13]. More than 90% of the intrinsic material value of boards is in the gold and palladium content [10]. In addition, lead, mercury and cadmium – although the EU's RoHS Directive [14] has recently severely restricted their use in EEE – are of relevance due to their high environmental impact.

For the purpose of this case study it is assumed that converters are separately collected, disassembled and the steel housing subsequently recycled while the printed wiring board is thermally treated in a municipal waste incinerator. In thermal treatment, organic components (plastics) are used as fuel while hazardous substances such as furans and dioxins are filtered to a large extent. It is assumed the end-of-life treatment takes place in Germany since there are no adequate facilities in Ireland.

2.5. The life cycle of the copper scenario

2.5.1. Production phase

The wiring of the copper scenario consists mainly of the following components:

- Copper cable
- Converters

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2.5.1.1. Copper cable. The copper cable is of the type "cat5e" (Category 5 UTP) cables (such as those used to connect a PC to the network). It is an unshielded-twisted-pair cable (UTP) that has eight copper wires, each in a plastic cladding. A schematic sketch is provided in Fig. 3. The type of copper cable used in this case study is a cat5e cable. An average composition for this type of cable is illustrated in Table 3.

Copper is a very important commodity worldwide. In 2000, the production of copper mines amounted to approximately 13 million tons [15]. Althaus and colleagues [16] cite for the year 2000 a worldwide production of 14.9 million tons and Ayres and colleagues [17] for 1998, 12.3 million tons of mine output and 13.9 million tons of refined output, which exceeds mining output due to the inclusion of old scrap recycling which varies around 15%.

Due to strict environmental constraints, the production of secondary copper is cheaper than extracting primary copper from ore, particularly in view of the fact that primary global resources of this metal are estimated to become depleted in less than 30 years [18]. Other estimations refer to a period of 60 years at current demand [16].

The mining of copper produces a large amount of waste rock. Nearly all copper mined in the 20th century contained less than 2% copper. The different process steps (mining, milling, smelting, refinement, etc.) are described in detail in literature (e.g. Refs. [17,19]) or on the websites of organisations focusing on metal and copper such as the U.S. Geological Survey or the International Copper Study Group.

Only little recent information is available concerning the quantity of copper used for ICT wiring. For the year 1990, it was estimated that 8% of global copper is used for telecommunication wire ([19,20]). Although numerous new technological features have been developed in recent years this figure may provide a useful guide for estimation. The reason for this is because, on the one hand, the ICT market is on a rapid increase, whilst on the other hand a lot of new cabling has been laid using optic fibre cable. Today copper is mainly used for the "last mile", the connection to the individual households (as can also be seen in the optic fibre scenario).

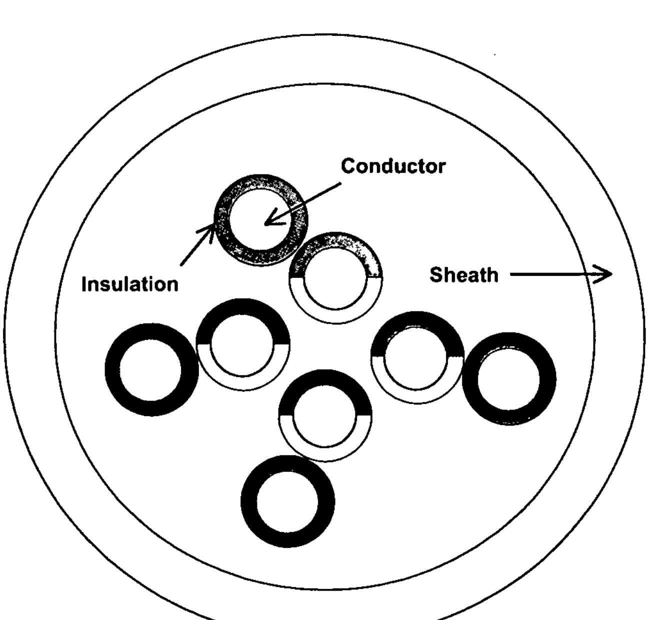

Fig. 3. Schematic sketch of an unshielded-twisted-pair cable (UTP).

Table 3
Composition (in grams) of 1 m cat5e copper cable

Copper	15.7 g
Inner cladding	5.0 g
Outer sheath	12.0 g
Total	32.7 g

2.5.1.2. Converters. In addition to the converters (a total of 13 in the block halls) described previously in the optic fibre scenario, seven additional devices (switches) were needed in the copper scenario. These enabled the use of copper in covering distances greater than 100 m to connect the blocks with reception. The latter are relatively small devices, about the size of a cigarette box (e.g. Zyxel 5 port Desktop Gigabit Switch GS-105A http://www.zyxel.de/product/model.php?). Again they mainly consist of a housing, a circuit board and wiring. Subsequently, converters in the blocks and additional switches used in the copper scenario are referred to as converters.

2.5.2. Use phase

Telecommunication wiring has an estimated use span of 50 years [19]. However, as in the optic fibre scenario a use span of 20 years is assumed, due to the probability of renewal of the ICT infrastructure after a 20-year period. For the converters an average life span of 6 years is assumed (based on Mean time Between Failure – MTBF value). The maximal energy consumption of the converters used for cables exceeding 100 m in length is 7.5 W, while the converters in the blocks consume up to 90 W. Otherwise the same assumptions apply as in Section 2.4.1.2.

2.5.3. End-of-life phase

2.5.3.1. Copper cable. Copper is an important commodity, however reserves are limited and thus recovery and recycling are becoming more and more important. Energy savings from recycling copper in comparison to primary production range on average from 60 to 80% [18]. In 2000, only 13% of the worldwide refined copper was secondary metal [17].

In Europe (EU-15 plus Poland) a total of 920,000 t of post consumer copper waste per year of copper are generated and about 300,000 t per year imported. On average 2 kg of copper waste is generated per person and year. Approximately 48% of the domestic copper waste is recycled. The remaining 52% is either landfilled or lost to the environment. The latter accounts for approx. 5000 t per year and is lost mainly via sewage sludge and bottom ash used in agriculture and road construction, respectively. The recycling efficiency of copper in waste electrical and electronic equipment (WEEE) is assumed to be around 50% [21].

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It is estimated that 25% of telecommunication wiring is recycled, while 75% is treated as waste [19]. In recycling copper cable two common (mechanical) procedures, stripping and shredding [9] are applied. For the stripping process the cable is cut open and the metal extracted. This requires a great deal of manual work, especially when the cables are bent. Cable stripping machines can process only single strands of cable at rates up to 60 m/min or 1100 kg/min with cable diameter ranging from 1.6 mm to 150 mm [22]. However, this process is only suitable for relatively thick cables, such as power cables. For copper cable as used in this case study treatment providing for shredding of the cable and subsequent separating of plastic and metal components by sieving and density separation was considered more suitable.

Plastic recycling is not considered a feasible option due to the continuing presence of an incompatible mixture, as the majority of the plastics contain a substantial portion of additives such as flame retardants [23]. Therefore, energy recovery from plastics by means of combustion should represent one of the most cost-effective options.

For the present case study shredding followed by thermal treatment of plastic parts in a municipal incineration plant and recycling of the copper was chosen. Recycling is considered to take place in Germany.

2.5.3.2. Converters. The end-of-life of electronic equipment is described in detail in Section 2.4.3.2.

2.6. Environmental impact and discussion of results

Based on the above information the two scenarios have been modelled. In Figs. 4 and 5 the main life stages of the cable and converters are shown in a simplified sketch.

With regard to the optic fibre cable incineration has been chosen as it is a likely form of end-of-life treatment. The energy recovery from the plastic coating is assumed. The copper cable is assumed to be recycled, where secondary copper is gained and the plastic coating is incinerated with energy recovery. For the converters it is assumed that these are handled by a company at the end-of-life and thus are more likely to be introduced into the separate collection system and not be disposed of as household waste. In the scenarios the steel from the housing is recycled while other parts are incinerated with energy recovery.

Since the life spans of the components of the scenarios differ, a period of 1 year was taken as the time frame for assessment. All data have been adjusted to this 1 year period. Electric power during the use phase was calculated as supplied by the Irish electricity grid, while during production either German or average energy values were considered. The end-of-life treatment is assumed as having taken place in Germany.

In both scenarios the transport was neglected due to a lack of available data. Furthermore Salhofer and colleagues [24] found that transports in waste management are of low relevance for environmental impact.

For assessment of the environmental impact the CML impact categories were applied. Both scenarios showed similar figures in all categories. In Table 4 the selected results for both scenarios are summarised and Fig. 6 shows the GWP in detail. In both cases electricity consumption in the use stage has a high impact on the results. The following chapters examine the Global Warming Potential (GWP) in more detail. The other impact categories show the same pattern.

2.6.1. Production

With regard to both scenarios the production stage reveals the second highest GWP. Indeed, the values obtained for

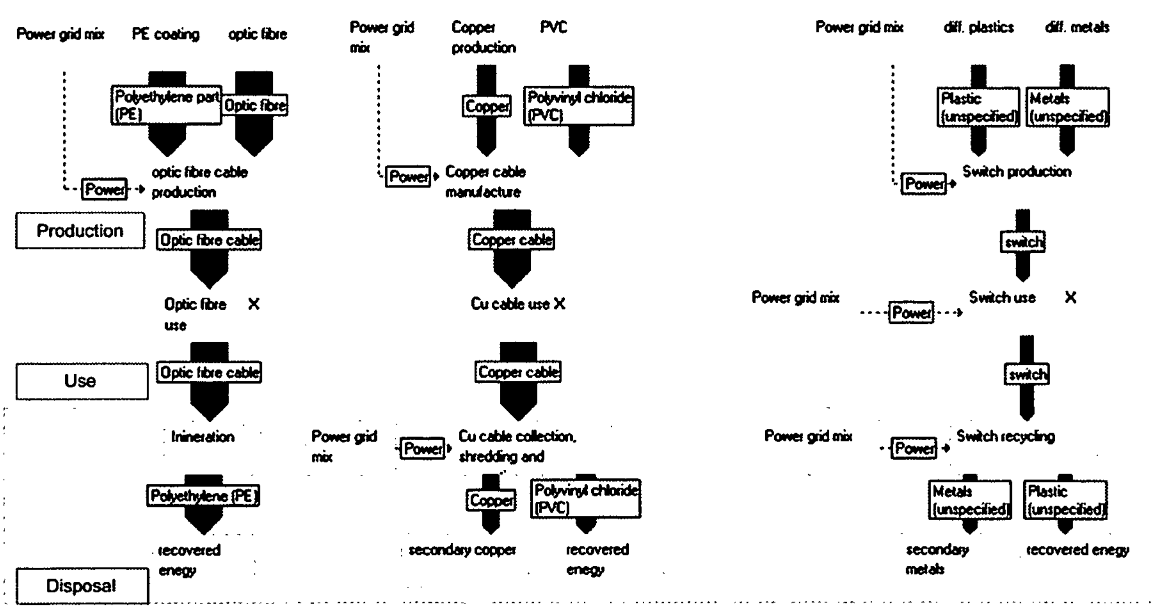

Fig. 4. Simplified schematic sketch of the optic fibre scenario life cycle.

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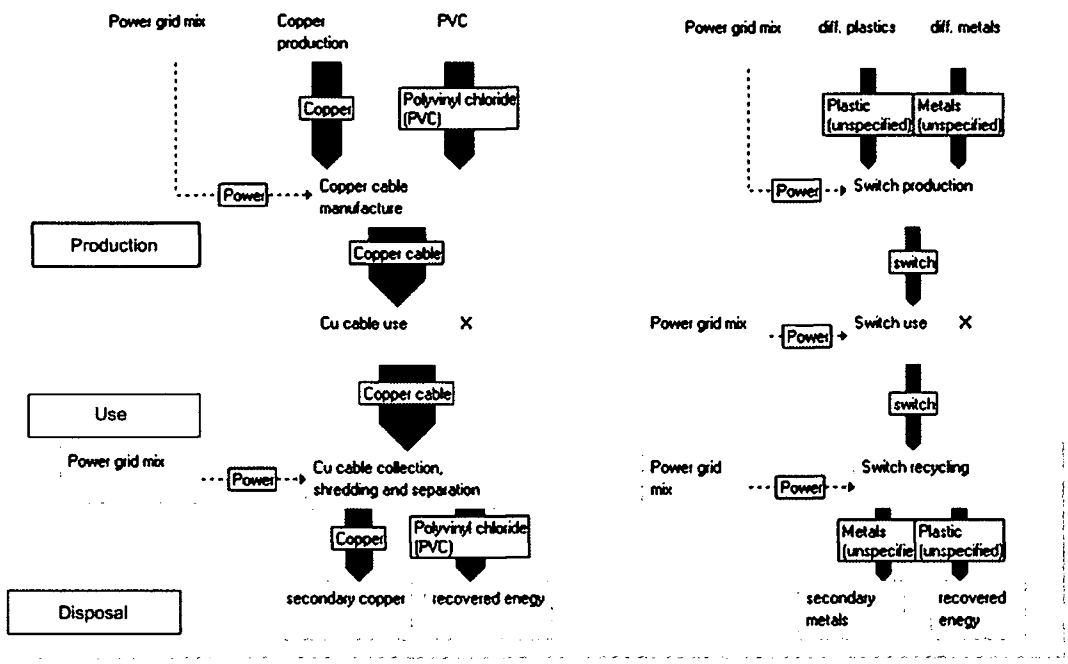

Fig. 5. Simplified schematic sketch of the copper scenario life cycle.

copper cable production are exceptionally high due to the long distance covered by copper cable (about 30 km) in comparison to optic fibre cable (only 1.3 km), as shown in Table 1. Although copper cable was only used for connection from the apartments to the block hall the huge number of accesses implies the use of a considerably longer total distance of copper cable than optic fibre cable.

2.6.2. Use

The use phase is characterised by the highest impact in terms of GWP during the life cycle, although converters alone have an impact in the use phase. It was estimated that the latter operate 24/7 at maximum capacity, as a worst case scenario. Additional switches used in the copper scenario for distances exceeding 100 m (7 pieces) have a relatively low impact, as consumption (7.5 W) is considerably less than that of the converters in each of the 13 blocks (90 W). Furthermore, the composition of the Irish electricity mix, containing approximately 95% of fossil fuels is responsible for the high GWP in both scenarios.

Table 4
Selected CML impact categories for optic fibre and copper scenario

	Optic fibre scenario [kg]	Copper scenario [kg]
Global warming potential (GWP)	939.99	1010.84
Abiotic depletion	5.47	5.81
Freshwater aquatic ecotoxicity potential	13.78	14.94
Eutrophication potential (EP)	0.29	0.31
Human toxicity potential	95.09	102.17
Photochemical ozone creation potential (POCP)	0.57	0.59
Terrestric ecotoxicity potential (TETP inf.)	0.68	0.74
Acidification potential (AP)	4.97	5.32

2.6.3. End-of-life and credits

The disposal routes chosen represent the most likely rather than the 'best case scenarios'. All parts of the two scenarios (optic cable, copper cable and converters) show a lower GWP in the end-of-life stage than during production, although a considerable amount of thermal treatment occurs in both scenarios. Energy credits have been given for that. Only for the copper in the cable and the steel housing credits are given, while metals from PWBs will end up in scrap and slag and are not recovered. In the copper scenario energy and copper

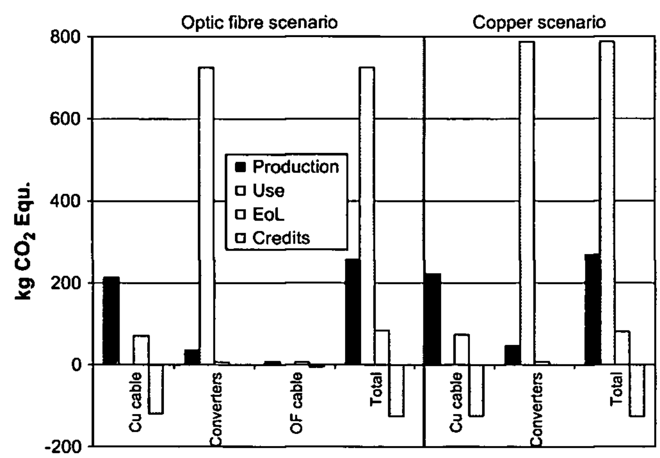

Fig. 6. Global Warming Potential in kg CO_2 equivalents for different life stages of the optic fibre and copper scenario.

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contribute to approximately the same degree towards the totalling of credits.

2.6.4. Direct comparison of optic fibre cable and copper cable

To enable a better comparison between the two types of cable used in the case study 1 km of copper cable was compared with 1 km of optic fibre cable. The same production and end-of-life options (copper recovery and incineration of plastic parts, and incineration of the optic fibre cable, respectively) were assumed for the two scenarios. On considering the outcome of the comparison an environmental advantage of copper cable was observed. In both cases, thermal treatment for optic fibre cable and a combination of thermal treatment and copper recycling for copper cable, a considerable number of credits were accounted for. In view of the fact that no material recovery is envisaged for the optic fibre cable, no energy is needed for pre-treatment before incineration.

All impact categories show similar results. The results obtained for Global Warming Potential (GWP) are again illustrated as an example. In Fig. 7 the share of the life stages implicated in the total GWP is shown. For the copper cable a total of 107.77 kg and for the optic fibre cable 129.28 kg CO_2 equivalents were calculated (including credits). During the production stage the optic fibre cable displayed higher GWP values. The copper cable was characterised by lower GWP values in the end-of-life stage as only part (approx. 52%) of the cable was incinerated, while the remaining portion (copper) was recovered. With regard to the optic fibre cable no material was recovered and a higher percentage of material was incinerated (the entire cable with the exception of optic fibres, i.e. 99.1%). In both scenarios carbon dioxide resulted as being the main emission contributing towards GWP.

The recovery and recycling of copper has been assumed as taking place in the present study. However, if copper cable is not recycled but thermally treated the overall impact will be higher than that produced by optic fibre cable due to the fact that no credits are assigned for secondary copper. The credits will be reduced to half the amount assigned for recycling, thus rendering optic fibre cable the material of choice.

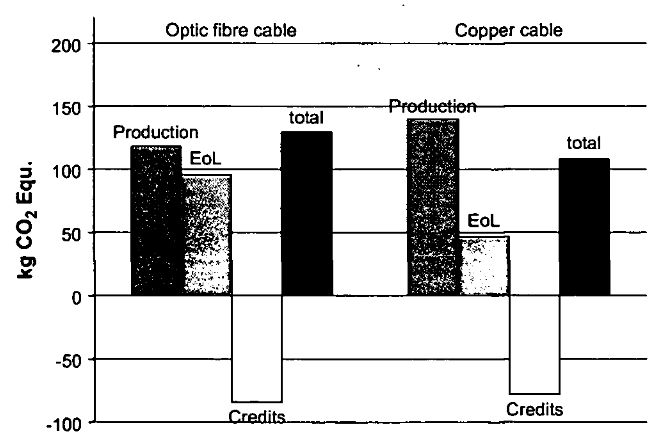

Fig. 7. Global Warming Potential for 1 km of optic fibre cable and 1 km of copper cable.

3. Conclusion

Although the importance of optic fibre in the field of modern information and communication technologies is undeniable, its environmental implications are still largely unknown. In this case study the environmental impact of optic fibre cable systems in comparison with the older technology of copper cable was tested.

The case study showed no environmental advantage of using the newer technology afforded by optic fibre cable rather than the older technology with copper cable. The finding cited in Section 2, reporting an enhanced preference for using optic fibre cable due to a higher information capacity could not be confirmed. The technical advantages, mainly fewer losses and thus longer distances without repeating and amplifying of the signal produce a positive effect on longer distances. However, in this case study an accommodation complex where short distances prevail was analysed. Accordingly, the technical advantages were of a lesser effect. Thus for such short distances optic fibre cable presents no advantages from an environmental point of view. On the contrary, considerably relevant advantages can be obtained using optic fibre cable if in the case of copper cables these are incinerated and no copper recovered.

In systems involving longer distances, such as connecting villages and towns with each other, the technical advantages of optic fibre cable will become more obvious. A comparison of copper cable and optic fibre cable over longer distances has not been carried out due to the difficulty in reaching adequate data transfer capacities by means of copper cable.

Environmental impact assessment emphasised how the main impact in the two scenarios was due to electricity consumption in the use phase. Effective improvements could be made in this situation, although these would vary on the basis of the electricity composition. For calculations the maximum power consumption was taken, therefore the actual values are expected to be lower. Further the use spans for the cable (20 years) and the converters (6 years) are rather on the lower side. Longer use spans would reduce the impact from this equipment.

Moreover, the impact of the life cycle of the two types of cable alone reveals few differences. One explanation for this is that both types of cable consist to a large extent of fossil based materials. When verifying availability of materials 'sand' based optic fibre is considerably preferable over copper which has only a limited availability. A high percentage of the component in both types of cable is plastic. The use of materials from renewable sources could represent a feasible option for the future.

In the present case study no additional appliances such as PC and laptops were taken into consideration. Surely the providing of an ICT infrastructure is an incentive to use such items. Furthermore, due to the increasing importance of the internet it is easy to envisage how the availability of internet access in each room will not only increase the amount of time computers are actually used but also encourage leaving them switched on to a high degree and thus will lead to a higher

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demand for electricity. This demand will exceed the amount required for providing internet infrastructure by far. Making a large number of internet access points easily available may even affect the number of students owning their own computer.

To conclude, the latter gives rise to the question as to whether the use and widespread distribution of the internet and the devices used in its implementation may be the more important question to investigate than the medium used for data transfer — copper wire or optic fibre?

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