Available online at www.sciencedirect.com
SCIENCE DIRECT®

Environment International 32 (2006) 656–675

ENVIRONMENT INTERNATIONAL

www.elsevier.com/locate/envint

# Life cycle assessment of second generation (2G) and third generation (3G) mobile phone networks

Wolfram Scharnhorst [a,b,*], Lorenz M. Hilty [b], Olivier Jolliet [a,c]

[a] Life Cycle Systems Group (ENAC-GECOS)/Swiss Federal Institute of Technology, CH-1015 Lausanne, Switzerland
[b] Technology and Society Laboratory/Swiss Federal Laboratories for Materials Testing and Research, CH-8600 Dübendorf, Switzerland
[c] Center for Risk Science and Communication, Department of Environmental Health Sciences, School of Public Health, University of Michigan, Ann Arbor, Michigan 48109, USA

Received 28 October 2005; accepted 1 March 2006
Available online 19 April 2006

## Abstract

The environmental performance of presently operated GSM and UMTS networks was analysed concentrating on the environmental effects of the End-of-Life (EOL) phase using the Life Cycle Assessment (LCA) method. The study was performed based on comprehensive life cycle inventory and life cycle modelling. The environmental effects were quantified using the IMPACT2002+ method. Based on technological forecasts, the environmental effects of forthcoming mobile telephone networks were approximated.

The results indicate that a parallel operation of GSM and UMTS networks is environmentally detrimental and the transition phase should be kept as short as possible. The use phase (i.e. the operation) of the radio network components account for a large fraction of the total environmental impact. In particular, there is a need to lower the energy consumption of those network components. Seen in relation to each other, UMTS networks provide an environmentally more efficient mobile communication technology than GSM networks. In assessing the EOL phase, recycling the electronic scrap of mobile phone networks was shown to have clear environmental benefits. Under the present conditions, material recycling could help lower the environmental impact of the production phase by up to 50%.

*Keywords:* Mobile phone networks; Mobile telephony; UMTS; GSM; Life cycle assessment; End-of-Life phase; Environmental impact; Data transfer rate

## 1. Introduction

The presented study aims at providing in-depth knowledge on the environmental consequences related to the life cycles of GSM[1] and UMTS[2] mobile phone networks, concentrating on the EOL phase.[3] Based on representative forecasts, prognoses of the environmental consequences related to forthcoming mobile phone network infrastructure are made and recommendations to the concerned stakeholders are formulated.

Mobile telephony, presently superseding wired telephony, has become one of the most convenient information exchange tools since the implementation of the GSM standard in the early 1990ies. The subscriber numbers rising by hundreds per second (GSMworld, 2005) and the new mobile phone networks launched weekly (GSMAssociation, 2004) may help to illustrate this trend. Today GSM technology, modified and improved by high-speed data transmission techniques (GPRS[4], EDGE[5]), has arrived at a nearly fully developed state. In order to provide real universal mobile phone access and enabling still faster data transfer rates, the UMTS standard has been under development since 1987 (Hillebrand, 2002) and the first standard package was adopted in 1999 (ETSI, 1999b). In 2004, the first commercial UMTS networks were rolled out in

---

* Corresponding author. Technology and Society Laboratory/Swiss Federal Laboratories for Materials Testing and Research, CH-8600 Dübendorf, Switzerland. Tel.: +41 44 823 48 30; fax: +41 44 823 40 42.
*E-mail address:* Wolfram.Scharnhorst@empa.ch (W. Scharnhorst).

[1] *G*lobal *S*ystem for *M*obile communication. GSM belongs to the so-called *second generation* (2G) of mobile phone networks.

[2] *U*niversal *M*obile *T*elecommunication *S*ystem. UMTS networks belong to the so-called *third generation* (3G) of mobile phone network.

[3] *E*nd-*o*f-*L*ife phase.

[4] *G*eneral *P*acked *R*adio *S*ervice. GSM-GPRS networks belong to the so-called *second and a half generation* (2.5G) of mobile phone networks.

[5] *E*nhanced *D*ata rates for *G*lobal *E*volution. GSM-EDGE networks belong to the so-called *second and a half generation* (2.5G) of mobile phone networks.

0160-4120/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.envint.2006.03.001

Western Europe. For the future, consultants expect worldwide success of the UMTS technology similar to the success of the GSM technology (Delpho, 2005; Schullitz, 2001).

Although mobile telephony provides undeniably useful services, it can cause relevant environmental impacts, e.g. through the dramatically growing amount of electronic scrap, inefficient energy management during its operation and service times of, in particular, mobile phones that are still too short. The change-over and the associated competition between the GSM and the UMTS technology will further exacerbate these problems. In order to reduce the environmental impacts of electric and electronic equipment and of electronic scrap, the European Union has adopted regulations to ban hazardous substances from electronics (CEC, 2003a), and to increase the recycling rate of electronic scrap (CEC, 2003b). Likewise substantial efforts have been undertaken by the telecommunication industry. For example, today the subscriber contracts last longer, typically about two years. Correspondingly, the service time of a mobile phone has been expanded to 1.5–2 years compared with 0.5–1 year in 2001 (Swisscom, 2005b).

In the context of the qualitative and quantitative analysis of the environmental consequences of large technical systems, such as mobile telephone equipment, LCA[6] has been recognised as a powerful tool. This method provides a framework with which to localise potentials to improve the environmental performance of mobile phone networks and components.

Recent LCA studies as well as experimental analyses have investigated the environmental effects related to

- electronic *elements* contained in network components (Uryu et al., 2003),
- separate mobile phone network *components* (Fishbein, 2002; Grunewald and Gustavsson, 1999; RANDA-GROUP, 2000; Scharnhorst et al., 2005b; Tanskanen and Takala, 2001), and
- entire mobile phone *networks* (Faist-Emmenegger et al., 2004; Malmodin et al., 2001; Pehrsson and Hedblom, 2005; Scharnhorst et al., 2005a; Weidman and Lundberg, 2001).

Most of the LCA studies arrive at the conclusion that the use phase dominates the overall environmental impact of the networks and/or the components. The other phases mostly seem to have a minor (production phase) or negligible (EOL phase) environmental impact. The contributions of the separate network components to the total network impact are controversially debated and study results are differing. Only a very few studies have considered the upcoming UMTS standard based on data that thus far have been deficient.

Thus, although, LCA studies in general provide substantial environmental know-how, for assessment of large technical systems, such as mobile phone networks, they are often subject to weaknesses resulting in possibly biased results:

- the analysed systems are highly complex, and
- the analysed systems are modelled in an oversimplified way, e.g. the EOL phase is not modelled in a comprehensive way.

Bearing these issues in mind, an LCA study was performed concentrating on:

i.) the comparison of the environmental performance of a *GSM network* (corresponding to the ETSI[7] standard package — Release 1997 (ETSI, 1996)) and a *UMTS network* (corresponding to the 3GPP[8] standard package — (R'99)[9] (ETSI, 2002c)) as presently operated in Switzerland,
ii.) a realistic analysis of the environmental consequences of the EOL phase of both network types,
iii.) a prognosis on the environmental performance of GSM networks technically modified for accelerated data transfer (using GPRS and EDGE) and of UMTS networks likewise modified (corresponding to the 3GPP standard packages — (R'04)[10] (ETSI, 2003c) and (R'06)[11] (ETSI, 2005), and
iv.) a sensitivity analysis of the key influencing parameters: number of subscribers and total data download volume.

This paper compiles the results representative for GSM and UMTS (R'99) technology in Switzerland in 2004. It also documents prospective results for UMTS networks complying with the upcoming standard packages (R'04) and (R'06). In particular, it aims to address the following issues:

a) When comparing GSM and UMTS, which type of network performs better environmentally?
b) When the EOL phase of networks is properly modelled, which life cycle phase dominates the total environmental impact of the networks?
c) When the networks are modelled according to the relevant standards and including all of the major network components, which component of the networks dominates the total environmental impact?
d) Is processing of electronic scrap and the production of secondary raw materials in the EOL phase more environmentally relevant than the production of primary raw materials in the production phase?
e) When high-speed data transfer techniques for GSM (GRPS and EDGE) are included, do these techniques help to lower the environmental impact of the GSM network?
f) When UMTS network alterations complying with the future standard packages (R'04 and R'06) are considered, what will be the environmental impact of such UMTS networks?

The presented LCA study was performed and the paper is structured in compliance with the ISO 14040 series (ISO 1998a, b) into the following sections: goal and scope definition, life cycle inventory, life cycle impact assessment and results interpretation. The paper is complemented by a sensitivity

---

[6] *L*ife *C*ycle *A*ssessment.

[7] *E*uropean *T*elecommunications *S*tandards *I*nstitute.

[8] *3rd G*eneration *P*artnership *P*roject.

[9] *R*elease 19*99*.

[10] *R*elease 20*04*.

[11] *R*elease 20*06*.

analysis and is completed by a discussion and recommendations to the stakeholders concerned.

## 2. Method, goal and scope

### 2.1. Methodological background

The continuously increasing exploitation of natural resources and the growing amount of emissions associated with, in particular, industrial activities necessitated the implementation of measures to monitor and manage the effects on the environment. The Life Cycle Assessment (LCA) methodology provides a consistent framework aiming at the assessment of environmental aspects and potential impacts associated with a product/service[12] (ISO, 1997). In practice, LCA can assist to identify environmental aspects of products at different life cycle stages and thus can be used for decision-making in industry or government (ISO, 1997). An LCA typically consists of four phases: goal and scope definition, life cycle inventory (LCI[13]), life cycle impact assessment (LCIA[14]) and result interpretation (ISO, 1997; Rebitzer et al., 2004). Following the standards defined for LCA, in the goal and scope section of the presented study the studied system was defined, the data representativity was specified, and the impact assessment method was determined (ISO, 1997). Subsequently the life cycle inventory part was performed for the various processes of the production, use and EOL phases. The environmental data of the separate network components (i.e. the resource consumptions and the emission releases) were inventoried in compliance with the earlier defined scope of the study. Processes that did not fit into the previously defined study scope were not inventoried. The inventory step also included the assembly of the network model (life cycle modelling) and the allocation of material and energy flows (ISO, 1997, 1998a). In compliance with the ISO standards for LCA, which require a broad coverage of impact categories (Pennington et al., 2004), in the impact assessment section of the presented study the environmental impacts of the network and/or its components were calculated by assigning impact scores to the various resource consumptions and emissions which had been compiled in the life cycle inventory part (ISO, 1997, 1998b). In the final section the results of the impact assessment were interpreted, a sensitivity analysis was performed for the obtained results, conclusions were drawn and recommendations were formulated for the attention of the concerned stakeholders.

### 2.2. System description

#### 2.2.1. Functional unit and reference flow

The environmental impact of a product or service is related to the functionality it provides. In order to cover the key functionalities of GSM and UMTS mobile phone networks (voice and data transmission) the transmission of data (i.e. speech and non-voice applications) in bit from a mobile phone via the mobile phone network was selected as functional unit and 1 bit of traffic data transmitted was selected as the reference flow (ISO, 1998a). The selected functional unit enables a common analysis of environmental effects associated with *i.)* voice transmission (typically measured in tax minutes) and *ii.)* non-voice, i.e. data transmission (typically measured in bits transmitted). This basic functional unit has the advantage that other — more application-oriented — functional units can be derived from it. For example, one tax minute of phone conversation requires the transmission of about 576 kbit in the case of GSM and 732 kbit in the case of UMTS.

#### 2.2.2. Data requirements

The following requirements were set and the data should be representative for:

- Western Europe with respect to services, frequencies, data transfer rates, etc., and for Switzerland with respect to network load,
- the year 2005 with respect to GSM (including GPRS and EDGE) and UMTS (R'99) networks and for 2006/07 with respect to UMTS (R'04, R'06) networks, and
- Western Europe and 2005 with respect to EOL treatment.

#### 2.2.3. System boundaries

The system under study encompasses all life cycle phases of a representative GSM, GSM-GPRS and -EDGE and UMTS (R'99) networks as well as of UMTS networks complying with the forthcoming standard packages (R'04 and R'06).

The production phase of any network or its components begins with the extraction of ores and energy carriers, it includes the fabrication of base materials such as metal alloys and plastics, and ends as the network component assembly is finalised, i.e. as the electronic components and the supporting structural elements (e.g. PWBA[15], frames, casings, etc.) are assembled (Scharnhorst et al., 2005a). The final assembly of network components was not included in the studied system as other studies have proven that this stage is of minor environmental relevance (Faist-Emmenegger et al., 2003; RANDA-GROUP, 2000; Weidman and Lundberg, 2001). No environmental data were inventoried for these processes.

The use phase follows the production phase. In the case of mobile phone networks, it includes the network installation and continues with the operation of the network components. In principle, this phase also includes maintenance and repair services as well as periodical software updates (Scharnhorst et al., 2005a). However, the latter two stages (i.e. maintenance and repair services) were not included in the presented study due to their proven low environmental relevance (Faist-Emmenegger et al., 2003).

---

[12] According to ISO-terminology the term "product" does also "services" ISO: ISO 14040: Ökobilanz — Prinzipien und allgemeine Anforderungen, International Organisation for Standardisation Brussels. 1997.

[13] *L*ife *C*ycle *I*nventory.

[14] *L*ife *C*ycle *I*mpact *A*ssessment.

[15] *P*rinted *W*iring *B*oard *A*ssembly.

The life cycle of the mobile phone networks ends with the EOL phase. This phase begins with the dismounting of the device to be replaced. Thereafter a more or less sophisticated pre-processing of the electronic scrap follows. Subsequently, thermal EOL treatment is applied in order to recover energy and precious metals. The recovered materials are recycled and energy is reused. For the studied system, it was assumed that all secondary materials and all energy are reused for manufacturing of new network components (closed-loop). It was not assumed that any secondary raw materials or energy is used in other life cycle systems. The residuals of the EOL phase are finally stabilised and landfilled. In the case of the presented study, the environmentally most favourable EOL scenario, determined earlier (Scharnhorst et al., 2005a), was selected to represent state-of-the-art processing of electronic scrap in the EOL phase (Fig. 1).

### 2.2.4. Allocation

The foreground system was modelled based on physical property allocation when there was a physical causality (Ekvall and Finnveden, 2001). For example, the usage of a shredder is allocated to the mass of the treated scrap.

For the background system, the allocation rules as applied in the ecoinvent-database were adopted (Frischknecht et al., 2004). According to these guidelines, multi-output unit processes are inventoried in the database prior to allocation. Thereafter the mass and energy flows are allocated to each co-product generated by a multi-output process by application of allocation factors (Frischknecht et al., 2004). The unit process data sets obtained by this procedure were then used to model the background system.

With respect to precious metals, such as gold, silver, tungsten, etc., no appropriate production data sets were available. These processes were approximated as single-output processes, i.e. no co-products were taken into account, based on publicly available information (ISO, 2005). The approximation as single-output processes makes an allocation superfluous.

The EOL phase was modelled including system expansion (Scharnhorst et al., 2005b). Credits, i.e. numerically negative environmental impacts, were considered in the EOL phase with respect to the production of secondary raw materials and the energy recovery, substituting primary materials and energy from primary sources respectively (BDSV, 2001; HELCOM, 2002; Lehner, 2001; VSSV, 2005).

### 2.2.5. Impact assessment

The IMPACT2002+ method (Jolliet et al., 2003) was used in order to determine the environmental impacts related to resources consumed and emissions released during the life cycle of the mobile phone networks. This method, based on the IMPACT2002 model (Pennington et al., 2005), comprises 14 midpoint categories and four damage categories: human health, ecosystem quality, climate change and resource consumption. The method links the input and output flows inventoried for a certain object to derive effect scores of specific reference substances. The scores are finally linked to the damage categories to yield a measure of the environmental impact of a product or service. The CML2001 method (Guinée et al., 2001) was used in order to evaluate the results obtained with the IMAPCT2002+ method.

### 2.2.6. Interpretation and weighting

The results of the impact assessment were interpreted for each damage category. No additional normalisation and weighting and thus no additional aggregation were applied.

### 2.2.7. Review process

The entire study in all its subsequent sections was subject to internal review (performed by members of the participating institutions).

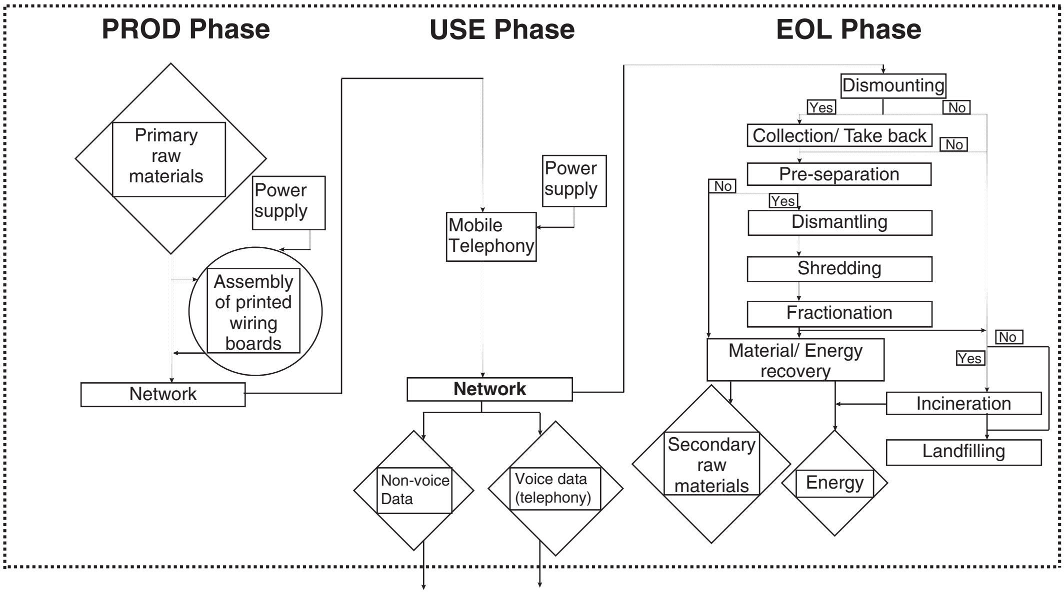

Fig. 1. System boundaries of the life cycle phase of the investigated mobile phone networks investigated.

### 2.3. Description of mobile telephone technologies and techniques considered

#### 2.3.1. GSM

The GSM network analysed reflects GSM technology as currently operated in Switzerland. It complies with the GSM standard packages defined and adopted in 1996 for the basic network architecture (ETSI, 1996), in 1999 for the interface principles (ETSI, 1999a), and in 2000 for the radio transmission principles (ETSI, 2000a,c).[16] In GSM a combination of the FDMA[17]/TDMA[18] techniques is applied to bridge the air interface between the MS[19] and the BTS[20]. Independent of the frequency band deployed (900 or 1800 MHz), 124 traffic channels are provided for the uplink and downlink direction (Duque-Antón, 2002). Each of these channels can be shared simultaneously by eight subscribers. Typically, voice transmission is performed at 9.6 kbit/s (details are compiled in Appendix B). Voice transmission is performed in the circuit switched mode, i.e. during a phone call a subscriber is permanently physically connected to the mobile phone network. Data transmission is performed at 9.6 kbit/s in the uplink and the downlink direction. The same channels are used as for voice transmission. As in the case with voice, data are processed in circuit switched mode. An analysis of the principle architecture of the GSM network and its modifications (GPRS and EDGE) can be found in Appendix B. A description of the separate network components is available in Scharnhorst et al. (2005a) and in Scharnhorst (2005).

#### 2.3.2. GPRS

This technique was introduced in 1995 (Sanders et al., 2003) in order to boost the remote data transfer rates of GSM networks. Using this service, data (e.g. e-mail, web-documents, etc.) are transmitted at a maximum data rate of 31.2 kbit/s (uplink) and 62.4 kbit/s (downlink) (ETSI, 2001a). Theoretically 171.2 kbit/s are possible but not practiced (Rudolf, 2003). The data are processed in packet switched mode, which allows for the faster transfer rates. Information on the modification of the physically underlying GSM network (e.g. additional network components) are compiled in Appendix B and in the relevant literature (ETSI, 2000b, 2003b; Halonen et al., 2003; Sanders et al., 2003).

#### 2.3.3. EDGE

This data transmission technique represents the final step in the evolution of mobile telephony from GSM towards UMTS, i.e. from 2G to 3G (Halonen et al., 2003). The application of a different signal modulation scheme allows for another increase in data transfer rates per traffic channel (ETSI, 2000d, 2003a). Maximal available data rates up to 192 kbit/s (uplink) and 384 kbit/s (downlink) are theoretically possible (Schnabel, 2004). Again, this service applies to data transmission and data are processed in the packet switched mode (details are compiled in Appendix B).

#### 2.3.4. UMTS (R'99)

The UMTS network investigated complies with the UMTS technology currently practiced in Switzerland. It meets the UMTS standard packages as defined and adopted in 2002 for the basic network architecture (ETSI, 2002c,e), in 2000 for data transfer service (ETSI, 2000b), and in 2002 for the interface principles (ETSI, 2002a,b).[16] Radio transmission in UMTS, i.e. the signal exchange between Ue[21] and NodeB, is performed using CDMA[22] (in Europe W-CDMA[23]). The CDMA technique does not foresee any discrete channel separation. Instead, all subscribers use the same frequency spectrum (FDD[24]: 5 MHz in the 1900/2100 MHz band; TDD[25]: 5 MHz in the 1900/2000 MHz band). For the transmission of voice, the so-called voice service (Banet, 2005b; Banet et al., 2004) at 12.2 kbit/s is deployed (details are given in Appendix B). According to the 3GPP standard package (R’99), voice transmission is performed in the circuit switched mode (Banet et al., 2004). In contrast to the GSM standard, data transmission in UMTS is packet switched (Banet et al., 2004), i.e. a subscriber is physically connected with the network only as long as data is transferred. The 3GPP standard package (R’99) foresees the operation of UMTS networks in the FDD and in the TDD mode (ETSI, 2002d). Presently however, most UMTS networks are operated in the FDD mode (Gärtner, 2005). This mode limits the theoretical maximum data transfer rates to 64 kbit/s (uplink) and 384 kbit/s (downlink) (Banet et al., 2004; Schnabel, 2003, 2004). Further details on data processing are presented in the cited literature compiled in Appendix B and outlined in Scharnhorst (2005). The composition of the UMTS network analysed and its modifications (R’04 and R’06) can be found in Appendix B. A description of the separate components is available in Scharnhorst (2005).

#### 2.3.5. UMTS (R'04/R'05)

This first substantial modification of the original UMTS standard represents an evolution towards: *i.)* packet switched voice transmission and *ii.)* the implementation of the TDD mode for high-speed data transfer (Banet, 2005a; ETSI, 2003c; Holma and Toskala, 2004). Using TDD, maximal download data transfer rates of 1920 kbit/s and upload rates of 960 kbit/s are possible (Banet et al., 2004). Although packet switched voice transmission is optionally available, it is assumed that networks complying with these standard packages still perform voice transmission in the circuit switched mode (Banet, 2005a).

---

[16] Mobile phone standards are subject to permanent updates. To take the present conditions into account, the latest standard versions were adopted.

[17] *F*requency *D*ivision *M*ultiple *A*ccess.

[18] *T*ime *D*ivision *M*ultiple *A*ccess.

[19] *M*obile *S*tation (GSM mobile phone). For convenience throughout the paper, except in the diagrams, MS will be termed *mobile phone*.

[20] *B*ase *T*ransceiver *S*tation.

[21] *U*ser *e*quipment (UMTS mobile phone). For convenience throughout the paper, except in the diagrams, Ue will be termed *mobile phone*.

[22] *C*ode *D*ivision *M*ultiple *A*ccess.

[23] *W*ideband-CDMA.

[24] *F*requency *D*ivision *D*uplex.

[25] *T*ime *D*ivision *D*uplex.

### 2.3.6. UMTS (R'06)

This most recently adopted standardisation package (ETSI, 2005) in particular aims at a further increase in data transfer rates using HSDPA[26] and HSUPA[27] (ETSI, 2003d, 2004). Uplink data transfer rates up to 5800 kbit/s (Ihlenfeld, 2005) and downlink rates up to 14400 kbit/s are envisaged (Anonymous, 2005a; Holma and Toskala, 2004; ETSI, 2001b). This standard package concentrates on the simultaneous packed switched processing of voice and data (All-IP) (Holma and Toskala, 2004).

## 3. Life cycle inventory — system modelling

### 3.1. Network modelling

A basic GSM network was modelled in compliance with the above addressed standards and for Swiss conditions based on the most recent statistics (BAKOM, 2004a; Orange, 2004; Sunrise, 2005; Swisscom, 2005a). Likewise, the UMTS (R’99) network was modelled based on current statistics (Scholz, 2005). Future UMTS networks complying with the forthcoming standards (R’04 and R’06) were modelled based on recent forecasts (PhoneContent.com, 2004; Schullitz, 2001). For each of the networks studied, the technically feasible maximum data transfer rates were adopted. In order to provide higher data transfer rates, GPRS and EDGE require the bundling of traffic channels. It was assumed that four traffic channels are combined to get one GPRS data channel, and eight traffic channels to get one EDGE data channel. Also, it was assumed that a BTS covers three sectors. In UMTS different modulation and access schemes provide higher data transfer rates. In order to alter the capacity of a NodeB, the number of covered sectors and cells and the amount of power amplifiers installed at the NodeB sites can be varied. In the presented study, it was assumed that a NodeB of a UMTS (R’99) network covered three sectors and three cells. In the case of UMTS (R’04) and (R’06) networks three sectors and six cells (two cells per sector) were assumed to be covered. Further details are compiled in Appendix B.

The technical specifications of the separate network components were compiled from original manufacturer data sheets (sources are given in Appendix C). Information on the basic network component materials were adopted from Goosey and Kellner (2002), Ludwig et al. (2003), Motorola (2005), Scharnhorst et al. (2005a) and from the network component manufacturers listed in Appendix C. Supplementary information on the network architecture was compiled from relevant books (Banet et al., 2004; Bekkers and Smits, 1997; Benkner and Stepping, 2002; Duque-Antón, 2002; Eberspächer et al., 2001; Halonen et al., 2003; Rudolf, 2003; Sanders et al., 2003; Schnabel, 2003; Steele et al., 2001). Information on the operation modes of the networks was obtained from component manufacturers (Gärtner, 2005).

The data used to model the basic and the modified GSM networks (GPRS and EDGE) as well as the basic UMTS (R’99) network refer to Western European conditions in 2005. The data used to model the evolved UMTS networks (R’04) and (R’06) refer to tentative forecasts of European network operators and are valid for Western European conditions (ERICSSON, 2005; Janssen, 2005; Nokia, 2003). All network component data comply with the respective standards mentioned above.

In order to simulate the different operating conditions, the following parameters were introduced:

| | |
|---|---|
| • Seasonal parameter (SP1) | Varies the seasonal conditions; the energy consumption of the network components is altered accordingly. |
| • Traffic parameter (TP) | Adjusts the energy consumption of the radio and core network components according to the subscriber load. |
| • Data transfer parameter (DTP) | Adjusts the data transfer rates according to the technically feasible maximum data rates. |
| • Subscriber parameter (SP2) | Modifies the number of subscribers according to subscriber forecasts. |
| • Download volume parameter (DVP) | Varies the total data download volume per subscriber according to hypothetical estimates. |

Table 1 documents selected present average conditions adopted for the mobile phone networks and the parameters that were used. The detailed operating conditions for the networks are compiled in Appendix B.

### 3.2. Life cycle modelling

The life cycles of the mobile phone networks were divided into the three phases: *production*, *use* and *End of Life treatment*.

The *production* phase was modelled as defined in the system boundaries paragraph (see Section 2.1) and information on the energy consumption in the PWBA manufacturing were adopted

Table 1
Selected average operating network conditions representing present conditions and parameters

| Technical network parameters | Networks | GSM | UMTS (R’99) |
|---|---|---|---|
| | Model parameters | | |
| Data rate [kbit/s] | DTP | 9600 | 384,000 |
| MS (Mobile station)/Ue (User equipment) [–] | SP2 | 6,188,793 | 70,000 |
| Phone call [s/MS·year] | – | 87 600 | 87,600 |
| Total data download volume [Mbit/MS·year] | DVP | 0.7 | 564.0 |
| BTS (Base Transceiver Station)/NodeB [–] | SP1, TP, DTP, DVP | 6800 | 3465 |
| BSC (Base Station Controller)/RNC (Radio Network Controller) [–] | ” | 50 | 23 |
| MSC (Mobile Switching Centre) [–] | ” | 34 | 15 |
| SGSN (Serving GPRS Support Node) [–] | ” | - | 23 |
| GGSN (Gateway GPRS Support Node) [–] | ” | - | 23 |
| BBC (Back Bone Cable network) [km] | ” | 95,000 | 66,000 |

---

[26] *H*igh *S*peed *D*ownlink *P*acket *A*ccess.

[27] *H*igh *S*peed *U*plink *P*acket *A*ccess.

from Kincaid and Geibig (1998). The production phase was modelled adopting process data compiled in the ecoinvent-database (ecoinventCentre, 2003). Transport process data were adopted from the GaBi4-software (IKP and PE, 2003). Little information was available on the production of metals, in particular precious metals, thus necessitating an explicit approximation of the production processes for: antimony, arsenic, beryllium, bismuth, brome, cadmium, europium, gallium, germanium, gold, indium, indium-tin-oxide, lithium, ruthenium, silver, thallium and tungsten.

In the *use* phase, only the energy consumed to operate and to aerate the network components was included. Seasonal weather conditions that influence the energy consumption of the network components were included by varying the energy consumption for the HVAC[28] of the network components. Peak energy consumptions of the network components were addressed by using a traffic parameter (TP). The parameter was derived from the total annual mobile phone traffic (BAKOM, 2004a). Energy consumption data of the network components considered were adopted from the manufacturers listed in Appendix C, from service personnel (Hausammann, 2005) and from one network operator (Swisscom, 2004). Mobile phone power consumption data were estimated from reports (AFU, 2004; Stromtip.de, 2000) and the manufacturers listed in Appendix C. The energy supply processes were modelled adopting data sets compiled in the ecoinvent-database (ecoinventCentre, 2003).

The EOL phase was modelled in detail according to a scenario identified earlier representing the environmentally preferable EOL option (Scharnhorst et al., 2005a). This EOL alternative includes the dismounting and collection of the network components as well as a rough dismantling. These steps are followed by state-of-the-art thermal processing in order to recover metals and energy. The EOL treatment is completed by the incineration (stabilisation) of the residuals and by dumping the stabilised residuals in landfill sites. For all mobile phones it was assumed that 20% of the discarded phones are not processed in recycling facilities, but are directly processed in MSWI[29] plants. Net recycling rates of 75% (aluminium and steel) and of 95% (precious metals such as gold, palladium, silver) were assumed for metal recycling (BDSV, 2001; HELCOM, 2002; Lehner, 2001; VSSV, 2005).[30] For the MSWI plant, it was assumed that the efficiency of the filter units located downstream from the incineration facilities was 90% (Farrell, 2000). For the *EOL* treatment, transfer coefficients[31] and fractions for the incineration stage were directly estimated based on experimental measurements (Scharnhorst et al., 2005c). Coefficients and fractions for the landfilling stage were estimated based on physio-chemical properties (Scharnhorst et al., 2005b). Information on the mechanical and thermal EOL treatment was partly obtained from recyclers (BOLIDEN, 2002; Stengele, 2004) and partly from literature (Ludwig et al., 2003; Scharnhorst et al., 2005b). Technical specifications were adopted from relevant data sheets (Berzelius, 1993; BückmannGmbH, 2001a,b,c; Weyhe, 2004). All foreground EOL processes, e.g. the infrastructure, were specifically modelled. All background EOL processes (e.g. fabrication of most of the base materials of which, for instance, the EOL infrastructure consists) were modelled adopting data sets from the ecoinvent-database (ecoinventCentre, 2003). Transport process data were adopted from the GaBi4-software (IKP and PE, 2003). Administration processes are not considered in any of the life cycle phases.

All data adopted are applicable under the data requirements set out above.

## 4. Life cycle impact assessment results (IMPACT2002+)

In this section, the environmental performance is presented of the GSM and UMTS networks investigated with respect to the functionality of the networks (i.e. related to the data transmission). All results presented represent relative environmental impacts per functional unit. The absolute environmental impacts are addressed in the discussion section.

### *4.1. Resource depletion*

This damage category is dominated by the total environmental impact score of the UMTS (R'99) network (71%[32]). Comparing the resource depletion effects of the two network standards reveals that GSM networks (basic configuration[33]) under present conditions perform better than UMTS (R'99) networks (factor 8). Upgrading from UMTS (R'99) to (R'04 and R'06)[34] will lead to lower environmental profiles per bit compared with UMTS (R'99) (factors 8[35] and 21[35]). The upgrade of UMTS network technology results in environmental profiles close to that of GSM networks equipped with the EDGE-technique (factor 0.3[35] and 0.8[35] in the case of UMTS (R'04) and (R'06) respectively). However, the installation of additional network infrastructure (NodeB, RNC, etc.) as well as the increased energy consumption in the use phase moderately increases the absolute total annual consumption of the network (see Section 5) and limits the environmental benefit per functional unit.

The total environmental impacts of the basic standard networks (i.e. GMS and UMTS (R'99)) are dominated by the use phase (80%[36] and 56%[36]) (Fig. 2). Key processes are the

---

[28] *H*eating, *V*entilation, *A*ir *C*onditioning.

[29] *M*unicipal *S*olid *W*aste *I*ncineration plant.

[30] These net recycling rates are representative for the pure recycling process and take no losses during scrap sorting and collection into account. In case of large network components this loss was assumed to be not relevant. In case of small network components, such as mobile phones, this loss was taken into account by assuming that 20% of the mobile phones are discarded without any recycling.

[31] These coefficients are used to quantify the volatilisation of e.g. metals.

[32] Total impact of all networks.

[33] i.e. no GPRS and no EDGE.

[34] Forecasted subscriber numbers and increased total data download volumes per subscriber are taken into account.

[35] Additional environmental impacts due to the expansion of network infrastructure and due to the increased power consumption of the network components are taken into account.

[36] Share of total impact of the respective network.

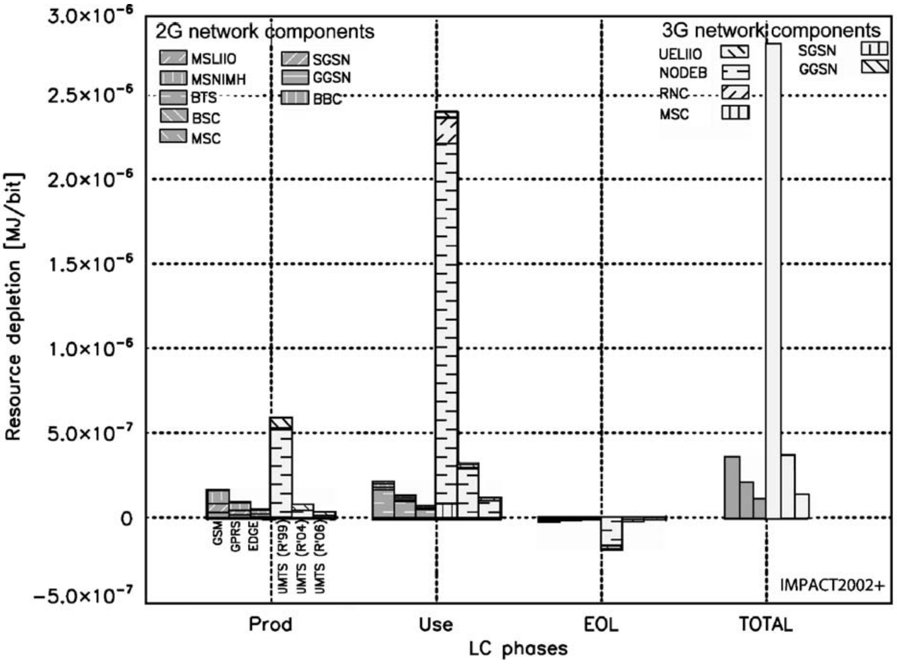

Fig. 2. Resource depletion damage category: Life cycle phase specific and total impact scores of the GSM network (basic, GPRS and EDGE-technique) the UMTS networks (R'99, R'04, R'06). The abbreviations of the network components displayed in this diagram and all following diagrams are explained as follows. MS LIIO: mobile phones with rechargeable lithium ion batteries (GSM). MS NIMH: mobile phones with rechargeable nickel-metal-hydride batteries (GSM). BTS: Base Transceiver Station (GSM). BSC: Base Station Controller (GSM). MSC: Mobile Switching Centre (GSM/UMTS). SGSN: Serving GPRS Support Node (GSM/UMTS). GGSN: Gateway GPRS Support Node (GSM/UMTS). BBC: Back Bone Cable network of the mobile phone network (GSM/UMTS). Ue LIIO: mobile phones with rechargeable lithium ion batteries (UMTS). RNC: Radio Network Controller (UMTS).

energy consumption by the NodeB (89%[37]) and the BTS (79%[37]). The uranium depletion related to the Swiss electricity generation contributes to the impact score of the use phase (64%[36] in the case of the GSM network and 72%[36] in the case of the UMTS (R'99) network). The production phase contributes only to a limited extent to the total environmental impact of a UMTS (R'99) network (20%[36]), which is mainly due to the generation of electricity for the production of primary aluminium (54%[37]), and contributes dominantly to the impact score. The production phase of the GSM network accounts for 44%[36] of the total impact score and is dominated by the energy intensive manufacturing of PWBA for mobile phones and BTS racks (71%[37]). The environmental benefit related to the recycling and manufacturing of secondary raw materials in the EOL-phase is restricted in terms of resources both for the GSM and the UMTS networks (−5%[36] and −6.0%[36] respectively).

### 4.2. Climate change

The total environmental impact of the UMTS (R'99) network is the highest for this damage category and results are very similar to the resource depletion category (70.5%[38]) (Fig. 3). Comparing the climate effects of the two network standards shows that GSM networks (basic configuration[39]) under the given initial conditions perform better than UMTS (R'99) networks (factor 8). Upgrading from UMTS (R'99) to (R'04 and R'06)[40] will lead to lower environmental profiles compared with UMTS (R'99) (factor 8[41] and 22[41]). The UMTS network upgrade again results in environmental profiles close to GSM networks deploying the advanced EDGE-technique (factor 0.3[41] and 0.9[41] in the case of UMTS (R'04) and (R'06) respectively).

As before, the use phase dominates the total climate change score in each of the UMTS networks (68%[42] for a UMTS (R'99) network, 72%[42] and 69%[42] in the case of a UMTS (R'04) and (R'06) network respectively). The impact scores in each network configuration are attributable to the $CO_2$ emissions associated with the generation of electrical energy supplied to operate the NodeB (88%[43] in the case of a UMTS (R'99) network). $CO_2$ emissions related to the energy intensive production of primary aluminium for NodeB racks (27%[43]) and the manufacturing of the PWBA used in NodeB racks and mobile phones (32%[43]) account for the impact score in the production phase. The recycling of electronic scrap in the EOL phase can account for a reduction of the total environmental

---

[37] Share of total phase impact of the respective network.

[38] Total impact of all networks.

[39] i.e. no GPRS and no EDGE.

[40] Forecasted subscriber numbers and increased total data download volumes per subscriber are taken into account.

[41] Additional environmental impacts due to the expansion of network infrastructure and due to the increased power consumption of the network components are taken into account.

[42] Share of total impact of the respective network.

[43] Share of total phase impact of the respective network.

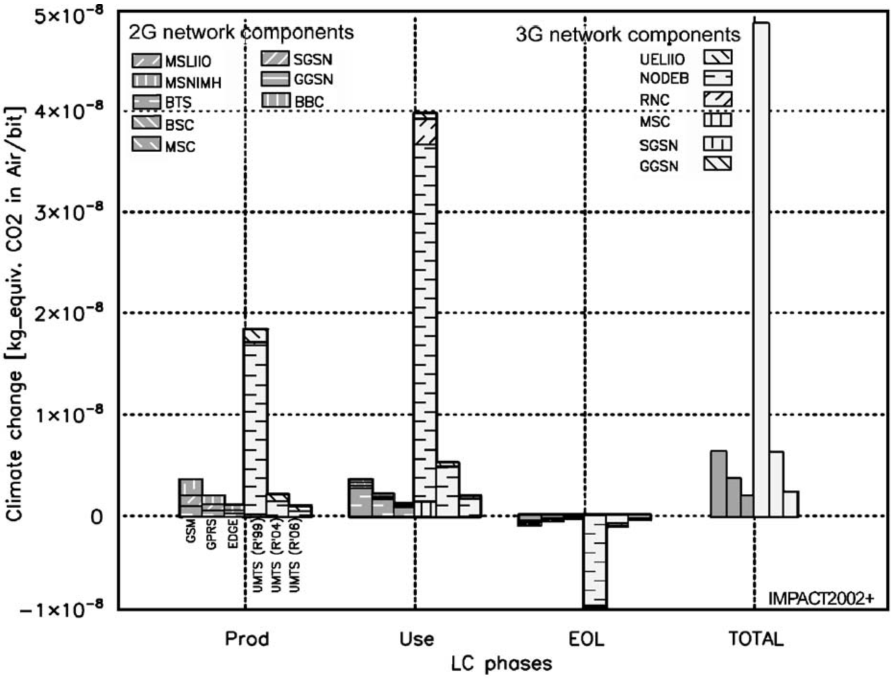

Fig. 3. Climate change damage category: Life cycle phase specific and total impact scores of the GSM network (basic, GPRS and EDGE-technique) the UMTS networks (R'99, R'04, R'06).

impact score of −16%[44] and it can halve the environmental impact score of the production phase. In particular energy savings due to the recovery of aluminium (61%[45]) and silver (18%[45]) contribute to this reduction.

In contrast to the UMTS networks, under the given conditions, the total environmental impact score of the GSM networks is dominated by the production phase (52%[44]). The impact score of this phase is dominated by $CO_2$ emissions associated with the energy intensive PWBA manufacturing of mobile phones and BTS racks (65%[45]). The use phase is dominated by $CO_2$ emissions associated with the energy supplied to operate the BTS (78%[45]). The EOL phase can reduce the climate change score by −11.6%[44] — a quarter of the impact score of the production phase. Again, the energy savings due to recycling of silver (54%[45]) and aluminium (36%[45]>) account for this reduction.

### 4.3. Human health

Under the defined conditions, the UMTS (R'99) network dominates this damage category and accounts for 70%[46] of the total environmental impact of all networks (Fig. 4). Networks complying with the GSM standard perform better compared with the basic UMTS (R'99) network (factor 7[47] in the case of a basic GSM network, factor 13[47] in the case of a GSM-GPRS network, and factor 25[47] in the case of a GSM-EDGE network). Future UMTS networks (R'04 and R'06) will have an environmental performance close to that of GSM networks deploying the most recent EDGE-technique (factor 0.3[47] in the case of UMTS (R'04), and factor 0.9[47] in the case of UMTS (R'06)).

Under the given initial conditions, the use phase of a UMTS (R'99) network accounts for a majority of the network's total environmental impact score (52%[44]), in particular due to the energy supplied to operate the NodeB. Primary and secondary particles are the main impacting sources, due to $SO_2$, $NO_x$ and particle emissions to air (25%[45], 19%[45], 29%[45]). The impact score of the production phase is dominated by the production of primary aluminium for the NodeB racks (22%[45]) and the production of primary lead for the NodeB back-up batteries (20%[45]). The energy intensive PWBA manufacturing (12%[45]), and the primary steel production for the NodeB racks and the primary palladium production for the PWBA (each 7%[45]) are also significant. Again, primary and secondary particles are the main sources for the impact score of this phase. The EOL phase can account for a reduction of the total environmental impact by −29%[48] and it can lower the environmental impact of the production phase by a factor of 1.6. In particular the recycling of aluminium (35%[49]), steel (18%[49]) and palladium (11%[49]) of the NodeB racks can account for the reduction of environmental impact score.

In contrast to the UMTS networks, the production phase dominates the human health impact score of GSM networks (63%[48]). This is due to primary and secondary particle generation linked with the energy intensive manufacturing of

---

[44] Share of total impact of the respective network.

[45] Share of total phase impact of the respective network.

[46] Total impact of all networks.

[47] Additional environmental impacts due to the expansion of network infrastructure and due to the increased power consumption of the network components are taken into account.

[48] Share of total impact of the respective network.

[49] Share of total phase impact of the respective network.

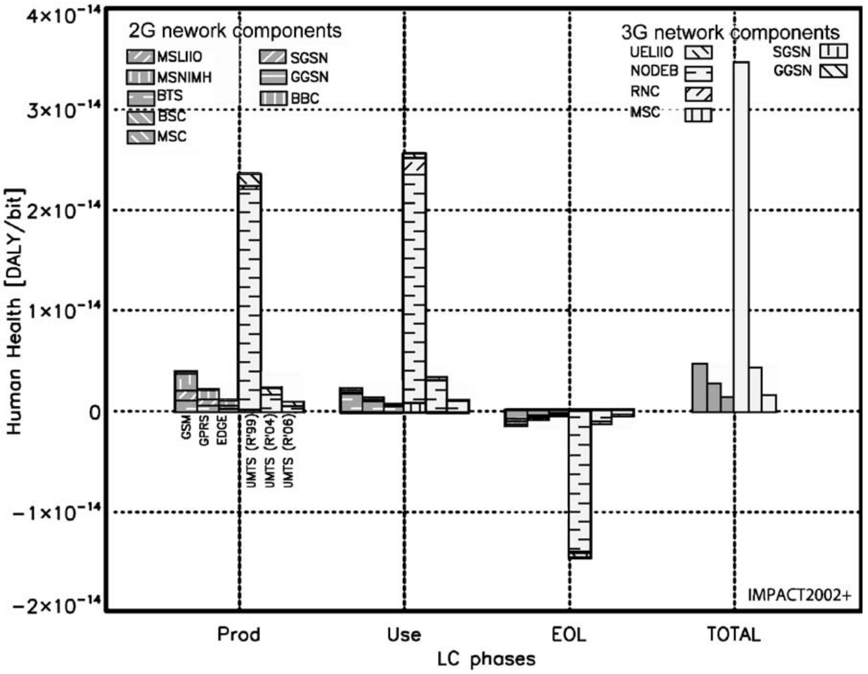

Fig. 4. Human health damage category: Life cycle phase specific and total impact scores of the GSM network (basic, GPRS and EDGE-technique) the UMTS networks (R'99, R'04, R'06).

PWBA for mobile phones and BTS racks, as well as the production of primary palladium, silver[50] and aluminium for the BTS racks (26%[49], 15%[49], 10%[49] and 7%[49]). Additional effects are attributable to the manufacturing of rechargeable nickel-metal-hydride batteries (15.9%[49]). $SO_2$, $NO_x$ and particle emissions to air contribute to the impact of this phase (48.2%[49], 16.6%[49], 24.0%[49]). The use phase of a basic GSM network accounts for 37%[48] of the human health impact score mainly due to the operation of the BTS (79%[48]) and the mobile phones (17%[48]). The recycling of network scrap in the EOL phase can account for a reduction of the network's total environmental impact (−23%[48]) and it can nearly halve the environmental impact score of the production phase due to recovery of secondary palladium (39%[49]), aluminium (19%[49]), and steel (13%[49]).

### 4.4. Ecosystem quality

Under the given conditions, the UMTS (R'99) network shows the highest total environmental impact score on ecosystem of all networks analysed (57.9%[51]) (Fig. 5), although assessment uncertainty is higher for this impact category. Again, GSM networks of any configuration perform better than a UMTS (R'99) network (factor 4[52] in the case of a basic GSM network, factor 7[52] in the case GPRS is deployed and factor 13[52] if EDGE is used). Under future conditions (increased total data download volumes per subscriber and increased subscriber numbers) UMTS networks will have an environmental performance close to or better than that of GSM networks using the EDGE-technique (factor 0.5[52] and 1.2[52] in the case of (R'04) and (R'06) respectively).

The total impact on ecosystems of a UMTS (R'99) network operated under the defined initial conditions is dominated by the use phase (70%[48]), mainly due to the energy consumed by the NodeB. The main emissions are, in decreasing order, copper to soil, zinc to water and copper to air (generated in the electricity generation by means of hard and brown coal (Frischknecht and Faist-Emmenegger, 2003; Röder et al., 2004)). The impact of the production phase is dominated by the fabrication of primary aluminium for the NodeB racks (46%[53]). Particularly, emissions of aluminium to water (released from landfilled redmud of the aluminium oxide production (Althaus et al., 2004)), zinc to air (released as zinc dust in the production of primary lead for the back-up batteries (Althaus et al., 2004)) and zinc to soil (released from landfilled by-products of the lead production (Althaus et al., 2004)) contribute to the impact score of this phase.

Under the given conditions, the environmental profiles of the GSM networks are completely different from those of the UMTS networks and from previous impact categories. Dominating life cycle phase is the EOL phase (68%[54]) with high impact scores attributable to long-term emission of copper and nickel to soil from dumped incineration ashes of mobile phones.[55] Environmental benefits account for less than 8%[54]

---

[50] Both metals are important materials in PWB.

[51] Total impact of all networks.

[52] Additional environmental impacts due to the expansion of network infrastructure and due to the increased power consumption of the network components are taken into account.

[53] Share of total phase impact of the respective network.

[54] Share of total impact of the respective network.

[55] 20% of the mobile phones were assumed to be directly incinerated in a MSWI and then referred to a landfill.

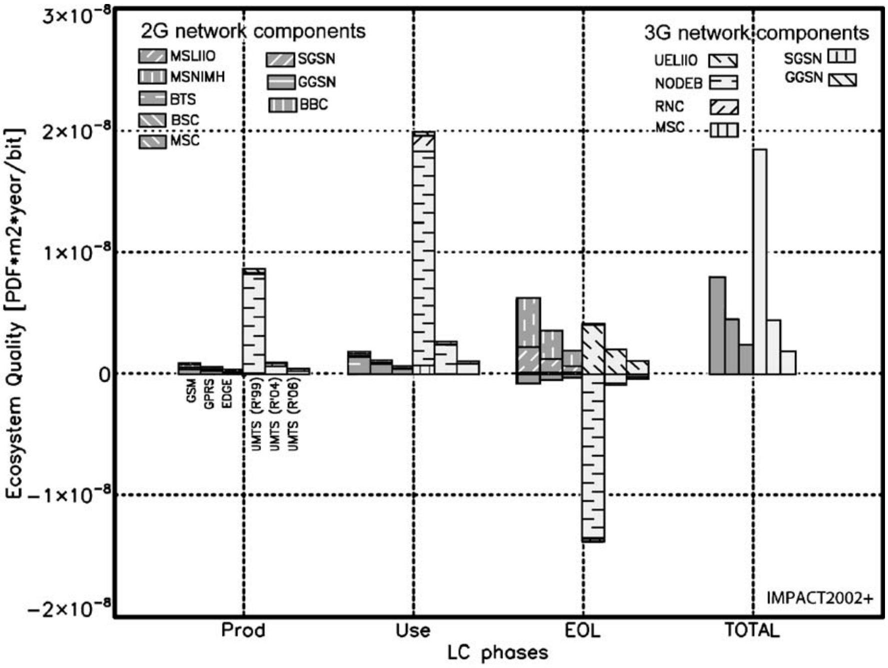

Fig. 5. Ecosystem quality damage category: Life cycle phase specific and total impact scores of the GSM network (basic, GPRS and EDGE-technique) the UMTS networks (R'99, R'04, R'06).

and are attributable to the recycling of aluminium from BTS racks and of lead from BTS back-up batteries. The use phase accounts for only 22%[54], mainly linked to the operation of the BTS. The impact of the production phase on ecosystems is low compared with the other phases (<10%[54]) and is dominated by emissions of dissolved aluminium to water (emitted from landfilled red mud generated in the aluminium oxide production (Althaus et al., 2004)) and copper to air (generated in the electricity generation by means of hard and brown coal (Frischknecht and Faist-Emmenegger, 2003; Röder et al., 2004)) in the production of BTS racks and mobile phones as well as of copper to air (released as copper dust in the production of primary lead for the back-up batteries (Althaus et al., 2004)) during the production of primary lead for the BTS back-up batteries.

The robustness of the results obtained with the IMPACT2002+ method was tested using the CML2001 method. For global warming and ionising radiation, both methods arrive to similar results. For human health and ecotoxicity impacts, the ranking between the networks is similar for CML2001 and IMPACT2002+, but the contribution of the individual substances can differ. The present accuracy of LCIA methods in these categories and the uncertainty of long-term emission only enable a preliminary screening and the identification of the main substances potentially contributing to more than 1% or 1 per thousand of the impact.

In the case of the photochemical oxidation potential, the results of the methods are similar with the exception that the IMPACT2002+ method assigns a higher environmental impact to methane emissions associated with the energy supply for the mobile phone networks in the use phase. In the case of terrestrial ecotoxicity, the methods reveal comparable results with respect to use and production (the former phase dominates the latter one). However, there is a difference in the order of magnitude. The CML method assesses higher environmental effects of chromium +VI releases to soil whereas IMPACT2002+ does not include a characterisation of the chromium +VI emissions. These chromium +VI emissions are related to the energy supply for the mobile phone networks in the use phase: thus the use phase dominates that impact category when assessed with CML2001. According to the mass inventory analysis, chromium +VI emissions represent the sixth largest emission and as it is known to be highly toxic, it is recommended to calculate an appropriate characterisation factor for this emission. For human toxicity the CML2001 method does not fully consider particle impacts and assigns the highest impact scores to thallium emissions to water from landfilled electronic scrap. The impact scores of the production and the use phase are comparatively low. The findings of the evaluation are in agreement with an earlier performed method evaluation (Scharnhorst et al., 2005b).

## 5. Sensitivity analysis and discussion

Presently, UMTS networks are overdimensioned, particularly due to the requirements set out in association with the allocation of radio frequency capacity by the governmental authorities.[56] A comparative sensitivity analysis,

---

[56] In Switzerland the allocation of frequencies to the operators was associated with the commitment by the operators to provide 50% population coverage by the end of 2004 (BAKOM, 2004b).

Table 2
Parameters varied in the sensitivity analysis

| Networks | Parameters | Scenarios | | | | |
|---|---|---|---|---|---|---|
| | | 0 | 01 | 01a | 02 | 02a |
| GSM-EDGE | Subscriber [–] | 6,189,000 | 4,087,473 | 4,087,473 | 1,986,153 | 1,986,153 |
| UMTS R'04 | Subscriber [–] | 1,051,000 | 2,101,320 | 2,101,320 | 4,202,640 | 4,202,640 |
| | Total download volume per subscriber [Mbit/a] | 2256 | 2256 | 4512 | 2256 | 9024 |

complementing the above LCA analysis, was performed for a GSM-EDGE network and a UMTS (R'04) network[57] in order to demonstrate the improvement capabilities of the environmental performance of UMTS networks and the following parameters were varied (Table 2).

Both the absolute overall yearly network performances and the performances per bit transferred are analysed. The environmental performance of a GSM-EDGE network under the conditions as adopted for the LCA study (scenario 0) was selected as the reference and set to 100%.

For both networks, an increase in subscribers leads on the one hand to a moderate increase in the absolute overall yearly impact of the network of about 10% to 20% when doubling the number of subscribers (R04_0 to R04_1 in Fig. 6). This is due to the additional number of mobile phone produced and the increased energy consumption of phones and network infrastructure during use phase. On the other hand, the impact per bit strongly decreases when subscribers increase (R04_0 to R04_1 in Fig. 7: about 40% when the number of subscriber doubles). Similarly, an increasing download volume per subscriber leads to a slight increase of 5% to 10% in the overall yearly network consumption when doubling the transferred volume ((R04_1 to R04_1a) in Fig. 6) and to a further strong reduction in consumption per bit (Fig. 7).

The results show that under the initial conditions (scenario 0) a UMTS (R'04) network has a slightly lower overall environmental impact per year than a GSM-EDGE network (Fig. 6), due to the low number of subscribers. This inefficient network load of UMTS (R'04) networks results in a higher environmental impact per bit (Fig. 7). As discussed above the environmental impact per bit strongly decreases with the increase in subscribers of UMTS (R'04) that also causes a decrease in GSM-EDGE subscribers (scenario 1). Therefore, the relative environmental performance of the GSM-EDGE network per bit worsens compared to the reference situation (Fig. 7). The annual environmental impact however, is reduced (Fig. 6). When increasing the total download volume per subscriber additionally to the increase in subscribers (scenario 1(a)), or when doubling once more the number of subscribers for UMTS (R'04) (scenario 2), then the relative environmental impact of UMTS (R'04) networks is reduced to that of the reference GSM-EDGE network (Fig. 7). A further increase in the total download volume per subscriber (scenario 2(a)), leads to another dramatic reduction in the relative environmental impact at about half of the reference GSM-EDGE network (Fig. 7). It leads again to a moderate increase in the total annual impact score of the UMTS network (Fig. 6). This increase is partly compensated by the further decrease in the GSM-EDGE yearly network consumption.

As obvious from the above results from an absolute point of view, UMTS networks per se perform environmentally worse than GSM networks when it comes to GSM-like full geographic coverage (Fig. 6). This is in particular attributable to the significantly higher energy demand of the NodeB racks (when operated under full load a NodeB rack can consume up to 6 kWh (Hausammann, 2005) compared with up to 1.3 kWh of a BTS rack (SiemensAG, 2000)). Secondly, in order to cover a geographical area equal to that which a GSM network can cover, up to 30% more NodeB will be required[58] (Hugentobler, 2000). It is obvious that, when comparing GSM and UMTS simply based on mobile telephony (i.e. the transmission of speech), UMTS again will perform environmentally worse due to the above mentioned technological aspects and due to the fact that this additional standard is not required, as the service of mobile telephony is already sufficiently covered by GSM. However, an absolute environmental consideration of two products, such as GSM and UMTS networks, providing similar functions but using different techniques, does not take into account the added functional value UMTS networks can provide. Looking for example at the data transfer (i.e. non-voice data transfer); UMTS enables a larger number of subscribers (simultaneous) access to high-speed data transfer services. Additionally, UMTS provides a multifunctionality of services (e.g. mobile telephony, sms, mms, video telephony, television, fax,

---

[57] UMTS (R'99) networks were not considered as this standard will soon become phased out. UMTS (R'06) networks were not presented here as even slight increases in the network load lead to a reduced environmental impact as compared with GSM-EDGE.

[58] This figure has to be considered carefully as the number of NodeB highly depends on the transmission technique an operator selects.

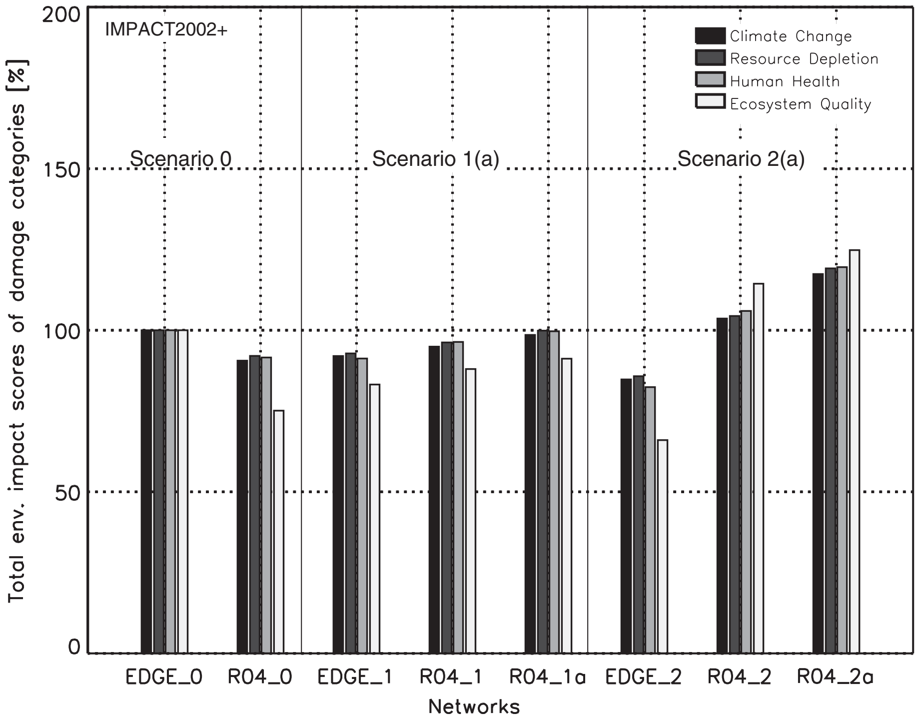

Fig. 6. Total impact scores per year relative to the total impact scores of the GSM-EDGE reference network for all four damage categories. For the GSM-EDGE reference network: 7.9413E9 MJ/year non-renewable energy, 1.3776E8 kg $CO_2$-equivalents/year, 93.729 DALY/year and 1.245E8 PDF·$m^2$·year/year.

web-browsing, ftp-services, etc.[59]) that is difficult or impossible to provide with GSM. Therefore, and in order to get comprehensive information, the consideration of the absolute impact and the environmental impact per functional unit is necessary.

## 6. Conclusions and outlook

Based on the study results, the following conclusions are drawn and recommendations are made:

a.) A parallel operation of GSM and UMTS networks is environmentally adverse (Figs. 6 and 7) and thus the transition phase between GSM and UMTS technology should be kept as short as possible.

b.) It is of urgent importance to lower the operational energy consumption (HVAC) of the radio network components, i.e. of the RNS[60] (in particular the NodeB) and of the BSS[61] (in particular the BTS). For instance, in comparison with public railway transport, the energy demand of mobile phone networks accounts for almost half of the energy consumed by railway: the annual operation of one GSM mobile phone[62] (GPRS-compliant) accounts for an energy consumption of about 530 MJ/(mobile phone · year), resulting in a total energy consumption of 916 GWh/year. The *Schweizerische Bundesbahnen (Swiss Federal Railways)* consume in total about 2000 GWh/year (P.S., 2005).

The reduction of the energy demand of the UMTS radio network components is also of particular importance in consideration of the fact that UMTS networks will be implemented in a GSM-like extent and that NodeB consumes up to six times more energy than BTS.

c.) In order to lower the environmental impact of the production phase there is a particular need to thoroughly analyse the energy intensive PWBA manufacturing for potentials to save energy. This could be beneficial in particular with respect to mobile phones as they contain large amounts of PWBA (Table 3).

Also, a similar simple upgradeability of the UMTS networks (3G networks) to next generation network standards (e.g. Super 3G, 4G) as it is presently the case for GSM networks when upgraded with EDGE-technique (ERICSSON, 2003) could help to lower the total environmental impact of the networks.

d.) The particular environmental benefit of the EOL phase lies in the fabrication of secondary raw materials, which can help to significantly lower the environmental impact of the production phase, in particular with respect to the depletion of resources. But recycling also has an economic aspect. The increasing shortage of, e.g.,

---

[59] Of course, the usefulness of the services is debatable.

[60] *R*adio *N*etwork *S*ubsystem (in a UMTS network, see Fig. 2).

[61] *B*ase *S*tation *S*ubsystem (in a GSM network, see Fig. 2).

[62] Including the energy consumption of the phone and the network.

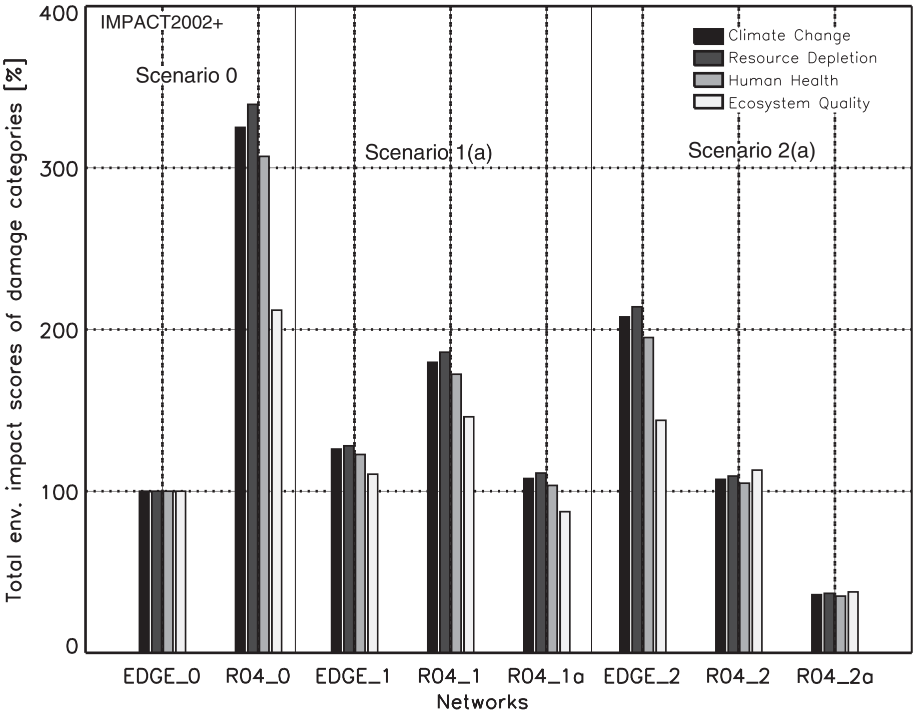

Fig. 7. Relative impact scores for all four damage categories relative to the impact scores of the GSM-EDGE reference network.

> precious and rare metals, such as gold, silver, palladium and indium results in impressively rising costs making the production of for example mobile phones ever more expansive. Therefore, the treatment of electronic scrap and the recovery of precious and rare metals as well as energy represent a preferable ecological and economic alternative.

From a methodological point of view the results obtained for the environmental effects associated with the EOL phase have to be interpreted carefully. First of all, present LCA methodology considers overall integrated emissions accumulated assuming a linear model at low doses. It does not take into account possible changes in dose–responses at low exposures and natural background concentrations, for example of metals, are not accounted for. Secondly, the databases and the impact assessment method (IMPACT2002+) applied distinguish only between a very few metal speciations. That can possibly lead to a biased and blanket characterisation of the environmental impact of several metals/metal speciations. In order to improve the LCA methodology the following future research activities are recommended:

i.) A differentiation of the characterisation factors for metals in the life cycle impact assessment and speciation of the metals in the life cycle inventory.
ii.) An integration of characterisation factors for flame retardants.
iii.) A realistic approximation of long-term effects of emissions from landfill sites.
iv.) The implementation of such study results into the daily business of telecommunications industry.

With respect to the modelling of large technological systems, such as mobile phone networks, it has been proven that the modelling of an entire network can be focussed to the modelling of the mobile stations (i.e. mobile phones), the antenna stations (BTS/NodeB) and the antenna station controllers (BSC/RNC). The core network components (i.e. MSC, SGSN, GGSN) do not need to be modelled in great detail as their impact share is comparatively low.

Table 3
Comparing PWBA masses contained in GSM network components with components of other ICT[a] (all figure in the table taken from (Scharnhorst, 2005)

| | MS | BTS | BSC | MSC | TV-set | PC |
|---|---|---|---|---|---|---|
| Number of units in Western Europe (estimated for the end of 2005) | 3.75E+08 | 4.17E+05 | 5210 | 2605 | 1.00E+08 | 2.00E+08 |
| Average use time [years] | 1.5 | 7 | 8 | 10 | 10.5 | 3–5 |
| PWBA [g/unit] | 30 | 31,350 | 128,000 | 74,750 | 500 | 400 |
| PWBA total [t] | 11,250 | 13,060 | 666 | 195 | 50,000 | 80,000 |
| PWBA total [t/year] | 7500 | 1866 | 83 | 20 | 4762 | 26,667–16,000 |

[a] *I*nformation and *C*ommunication *T*echnologies.

## Appendix A. Typical architecture of mobile phone networks

| Network generation | | 2G | 2.5G | 2.5G | 3G | 3G | 3G |
|---|---|---|---|---|---|---|---|
| Network standards | | GSM (Phase 2) | (Phase 2+) | (Phase 2+) | UMTS (3GPP R'99) | UMTS (3GPP R'04) | UMTS (3GPP R'06) |
| Data transmission mode(s) | | CS[1] | CS/PS[2] | CS/PS | CS/PS | CS/PS | PS[3] |
| Data transmission services | | | GPRS | EDGE | | | |
| Data transfer rates [kbit/s] | Voice transmission | 9.6–14.4 | 9.6–14.4 | 9.6–14.4 | 12.2 | 12.2 | 12.2 |
| | Data (uplink) | 9.6 | 31.2 | 192.0 | 64.0 | 960.0 | <5800.0 |
| | Data (downlink) | 9.6 | 62.4 | 384.0 | 384.0 | 1920.0 | <14400.0 |
| Access methods | | FDD/TDD | | | FDD | FDD/TDD | |
| Modulation | | FDMA/TDMA | | | W-CDMA | | |
| Network configuration/ Network elements | Mobile system/ User system | *M*obile *S*tation (MS) incl.<br>*S*ubscriber *I*dentity *M*odule card (SIM-card) | | | *U*ser *e*quipment (Ue) incl.<br>*U*ser *S*pecific *I*dentity *M*odule card (USIM-card) | | |
| | Base station subsystem/Radio network subsystem | *B*ase *T*ransceiver *S*tation (BTS)<br>BTS racks (2–3)<br>Back-up batteries (<17)<br>Air conditioner<br>Cabling (indoor, outdoor)<br>Mast (site depending)<br>Antennae (~6)<br>*B*ase *S*tation *C*ontroller (BSC)<br>BSC racks (3–4)<br>Air conditioner<br>Cabling (indoor, outdoor) | | | NodeB<br>NodeB racks (1–2)<br>Back-up batteries (<17)<br>Air conditioner<br>Cabling (indoor, outdoor)<br>Mast (site depending)<br>Antennae (~6)<br>*R*adio *N*etwork *C*ontroller (RNC)<br>RNC racks (3–4)<br>Air conditioner<br>Cabling (indoor, outdoor) | | |
| | Switching system — Circuit Switched Domain (CSD) | *M*obile *S*witching *C*entre (MSC)<br>MSC racks (4–6)<br>Air conditioner<br>Cabling | | | | | –<br>–<br>–<br>– |
| | Packet Switched Domain (PSD) | –<br>–<br>–<br>–<br>–<br>– | *S*erving *G*PRS *S*upport *N*ode (SGSN)<br>SGSN racks (1–2)<br>Cabling<br>*G*ateway *G*PRS *S*upport *N*ode (GGSN)<br>GGSN racks (1–2)<br>Cabling | | | | |

[1] *C*ircuit *S*witched.

[2] *P*acked *S*witched.

[3] The data transfer rates represent theoretical values (in case of UMTS R'06 USDPA- and HSDPA technology is anticipated).

## Appendix B. Configuration of the modelled networks

| Network generation | | 2G | 2.5G | 2.5G | 3G | 3G | 3G |
|---|---|---|---|---|---|---|---|
| Network standards | | GSM | | | UMTS (R'99) | UMTS (R'04) | UMTS (R'06) |
| Data transmission services/Access methods | | | GPRS | EDGE | FDD | FDD/TDD | FDD/TDD (incl. HSDPA, USDPA) |
| Data transfer rates [kbit/s] | Voice transmission | 9.6 | 9.6 | 9.6 | 12.2 | – | – |
| | Data transmission | 9.6 | 62.4 | 384.0 | 384.0 | 1920.0 | 14,400.0 |
| Network configurations | *M*obile *S*tation (MS)/*U*ser *e*quipment (Ue) | | 6,188,793 | | 70,000 | 1,050,660 | |
| | *B*ase *T*ransceiver *S*tation (BTS)/NodeB | | 6800[1] | | | 3465[2] | |
| | BTS racks/NodeB racks[3] | | 2 | | 1 | 2 | |
| | Back-up batteries[3] | | 17 | | | 15 | |
| | Subscriber capacity[3] | 192 | 192 | 192 | 198 | 396 | 324[4] |
| | Air conditioner[3] | | 1 | | | 1 | |
| | Cabling ([m], outdoor)[3] | | 40 | | | 40 | |
| | Mast (site depending)[3] | | 1 | | | 1 | |
| | Antennae[3] | | 6 | | | 3 | |
| | *B*ase *S*tation *C*ontroller (BSC)/*R*adio *N*etwork *C*ontroller (RNC) | 50 | 53 | | 23 | 33 | |
| | BSC racks/RNC racks[5] | | 4 | | | 4 | |
| | Air conditioner[5] | | 2 | | | 2 | |
| | Cabling ([m], outdoor)[5] | | 20 | | | 40 | |
| | *M*obile *S*witching *C*entre (MSC) | 34 | 35 | | 15 | 22 | – |
| | MSC racks (4–6)[6] | | | 4 | | | – |

Appendix B (*continued*)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Air conditioner[6] | | | 8 | | | – |
| | Cabling[6] | | | 40 | | | – |
| | *S*erving *G*PRS *S*upport *N*ode (SGSN) | – | 53 | | 23 | 33 | |
| | SGSN racks[7] | – | 1 | | | 1 | |
| | Cabling ([m], outdoor)[7] | – | 35 | | | 35 | |
| Network generation | | 2G | 2.5G | 2.5G | 3G | 3G | 3G |
| Network standards | | GSM | | | UMTS | UMTS | UMTS |
| Data transmission services/Access methods | | | GPRS | EDGE | FDD | FDD/TDD | Fdd/TDD (incl. HSDPA, USDPA) |
| Network configurations | *G*ateway *G*PRS *S*upport *N*ode (GGSN) | – | 53 | | 23 | | |
| | GGSN racks[8] | – | 1 | | | 1 | |
| | Cabling ([m], outdoor)[8] | – | 35 | | | 35 | |

[1] The BTS were assumed to cover three sectors.

[2] In case of UMTS (R'99) the NodeB were assumed to cover three sectors, each comprising one cell (i.e. 1+1+1). In case of UMTS (R'04) and (R'06) the NodeB were assumed to cover three sectors, each comprising two cells (i.e. 2+2+2) Holma, H. and Toskala, A.: WCDMA for UMTS: Radio Access for Third Generation Mobile Communications, John Wiley and Sons Ltd. Chichester. 2004.

[3] Per BTS.

[4] The number of voice channels decreases from 66 per cell to 54 due to information overhead related to *V*oice *o*ver *IP* (VoIP).

[5] Per BSC/RNC.

[6] Per MSC.

[7] Per SGSN.

[8] Per GGSN.

## Appendix C. Data sources of network components

| Network | Component | Subcomponent | Sources |
|---|---|---|---|
| GSM 900 (basic) | MS | | (ERICSSON, 1999, Nokia, 2005a,b) |
| | BTS | Antenna | (Conquadrat, 2003, Doradus, 2003a,b) |
| | | Mast | (ITF, 2005) |
| | | Cable (outdoor) | (SuperiorCables, 2003) |
| | | Rack | (LucentTechnologies, 2000; SiemensAG, 2000) |
| | | Backup battery | |
| | BSC | Rack | (Enderin et al., 2001; ERICSSON, 2002, 2004) |
| | MSC | Rack | (LucentTechnologies, 2001a, 2003a,b,c, 2005, NSI, 2005, SUNmicrosystems, 1999) |
| GSM 900 (GPRS/EDGE) | SGSN | Rack | (Lucent, 2004a) |
| | GGSN | Rack | (CiscoSystems, 2004, Lucent, 2004b) |
| UMTS | Ue | | (Anonymous, 2005b, UMTSlink.at, 2004, Xonio, 2004, ZDNet, 2005) |
| | NodeB | Antenna | See in GSM 900 (basic): antenna |
| | | Mast | See in GSM 900 (basic): mast |
| | | Cable (outdoor) | See in GSM 900 (basic): cable (outdoor) |
| | | Rack | (LucentTechnologies, 2001b, 2004) |
| | | Back-up battery | See in GSM 900 (basic): back-up battery |
| | RNC | Rack | (Gestner and Persson, 2002) |
| | MSC | Rack | See in GSM 900 (basic): MSC |
| | SGSN | Rack | See in GSM 900 (GPRS/EDGE): SGSN |
| | GGSN | Rack | See in GSM 900 (GPRS/EDGE): GGSN |

## Appendix D

### D.1. Transfer coefficients and fractions for incineration processes

| Element | Transfer coefficient | Emission path | Transfer fraction [%] | Element | Transfer coefficient | Emission path | Transfer fraction [%] |
|---|---|---|---|---|---|---|---|
| Ag_tot | 0.01 | Ag_air | 0.9 | Ge_tot | 0.01 | Ge_air | 0.1 |
| | | Ag_soil | 0.05 | | | Ge_soil | 0.7 |
| | | Ag_wat | 0.05 | | | Ge_wat | 0.2 |
| Al_tot | 0.144 | Al_air | 0.95 | Hg_tot | 0.75 | Hg_air | 0.99 |
| | | Al_soil | 0.025 | | | Hg_soil | 0.005 |
| | | Al_wat | 0.025 | | | Hg_wat | 0.005 |

(*continued on next page*)

Appendix D.1 (*continued*)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| As_tot | 1 | As_air | 0.99 | In_tot | 0.01 | In_air | 0.1 |
| | | As_soil | 0.005 | | | In_soil | 0.6 |
| | | As_wat | 0.005 | | | In_wat | 0.3 |
| Au_tot | 0.01 | Au_air | 0.4 | Mn_tot | 0.1 | Mn_air | 0.1 |
| | | Au_soil | 0.4 | | | Mn_soil | 0.6 |
| | | Au_wat | 0.2 | | | Mn_wat | 0.3 |
| Be_tot | 0.01 | Be_air | 0.9 | Na_tot | 0.5 | Na_air | 0.4 |
| | | Be_soil | 0.05 | | | Na_soil | 0.1 |
| | | Be_wat | 0.05 | | | Na_wat | 0.5 |
| Bi_tot | 0.01 | Bi_air | 0.1 | Ni_tot | 0.01 | Ni_air | 0.1 |
| | | Bi_soil | 0.8 | | | Ni_soil | 0.6 |
| | | Bi_wat | 0.1 | | | Ni_wat | 0.3 |
| Br_tot | 1 | Br_air | 0.9 | Pb_tot | 0.271 | Pb_air | 0.1 |
| | | Br_soil | 0.05 | | | Pb_soil | 0.6 |
| | | Br_wat | 0.05 | | | Pb_wat | 0.3 |
| Cd_tot | 1 | Cd_air | 0.8 | Pd_tot | 0.01 | Pd_air | 0.1 |
| | | Cd_soil | 0.15 | | | Pd_soil | 0.6 |
| | | Cd_wat | 0.05 | | | Pd_wat | 0.3 |
| Cl_tot | 0.75 | Cl_air | 0.5 | Pt_tot | 0.01 | Pt_air | 0.1 |
| | | Cl_soil | 0.1 | | | Pt_soil | 0.7 |
| | | Cl_wat | 0.4 | | | Pt_wat | 0.2 |
| Co_tot | 0.2 | Co_air | 0.1 | Ru_tot | 0.01 | Ru_air | 0.1 |
| | | Co_soil | 0.6 | | | Ru_soil | 0.6 |
| | | Co_wat | 0.3 | | | Ru_wat | 0.3 |
| Cr_tot | 0.01 | Cr_air | 0.2 | Sb_tot | 0.361 | Sb_air | 0.2 |
| | | Cr_soil | 0.7 | | | Sb_soil | 0.6 |
| | | Cr_wat | 0.1 | | | Sb_wat | 0.2 |
| Cr_VI_tot | 0.1 | Cr_VI_air | 0.3 | Se_tot | 0.01 | Se_air | 0.1 |
| | | Cr_VI_soil | 0.25 | | | Se_soil | 0.7 |
| | | Cr_VI_wat | 0.1 | | | Se_wat | 0.2 |
| Cu_tot | 0.01 | Cu_air | 0.1 | Si_tot | 0.2 | Si_air | 0.05 |
| | | Cu_soil | 0.8 | | | Si_soil | 0.4 |
| | | Cu_wat | 0.1 | | | Si_wat | 0.3 |
| Eu_tot | 0.01 | Eu_air | 0.1 | Sn_tot | 0.01 | Sn_air | 0.1 |
| | | Eu_soil | 0.7 | | | Sn_soil | 0.6 |
| | | Eu_wat | 0.2 | | | Sn_wat | 0.3 |
| Fe_tot | 0.041 | Fe_air | 0.1 | Th_tot | 0.01 | Th_air | 0.1 |
| | | Fe_soil | 0.6 | | | Th_soil | 0.6 |
| | | Fe_wat | 0.3 | | | Th_wat | 0.3 |
| Ga_tot | 0.01 | Ga_air | 0.2 | Zn_tot | 0.356 | Zn_air | 0.1 |
| | | Ga_soil | 0.4 | | | Zn_soil | 0.7 |
| | | Ga_wat | 0.4 | | | Zn_wat | 0.2 |

## *D.2. Transfer coefficients and fractions for landfill processes*

| Element | Transfer coefficient | Emission path | Transfer fraction [%] | Element | Transfer coefficient | Emission path | Transfer fraction [%] |
|---|---|---|---|---|---|---|---|
| Ag_tot | 1 | Ag_air | 0.05 | Hg_tot | 1 | Hg_air | 0.22 |
| | | Ag_soil | 0.3 | | | Hg_soil | 0.55 |
| | | Ag_wat | 0.65 | | | Hg_wat | 0.33 |
| Al_tot | 1 | Al_air | 0.05 | In_tot | 1 | In_air | 0.01 |
| | | Al_soil | 0.3 | | | In_soil | 0.65 |
| | | Al_wat | 0.25 | | | In_wat | 0.34 |
| As_tot | 1 | As_air | 0.1 | Mn_tot | 1 | Mn_air | 0.05 |
| | | As_soil | 0.3 | | | Mn_soil | 0.35 |
| | | As_wat | 0.6 | | | Mn_wat | 0.6 |
| Au_tot | 1 | Au_air | 0.01 | Na_tot | 1 | Na_air | 0.3 |
| | | Au_soil | 0.24 | | | Na_soil | 0.1 |
| | | Au_wat | 0.75 | | | Na_wat | 0.6 |
| Be_tot | 1 | Be_air | 0.05 | Ni_tot | 1 | Ni_air | 0.01 |
| | | Be_soil | 0.4 | | | Ni_soil | 0.55 |
| | | Be_wat | 0.55 | | | Ni_wat | 0.14 |
| Bi_tot | 1 | Bi_air | 0.01 | Pb_tot | 1 | Pb_air | 0.05 |
| | | Bi_soil | 0.44 | | | Pb_soil | 0.34 |
| | | Bi_wat | 0.55 | | | Pb_wat | 0.2 |

Appendix D.2 (*continued*)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Br_tot | 1 | Br_air | 0.1 | Pd_tot | 1 | Pd_air | 0.04 |
| | | Br_soil | 0.2 | | | Pd_soil | 0.36 |
| | | Br_wat | 0.7 | | | Pd_wat | 0.6 |
| Cd_tot | 1 | Cd_air | 0.05 | Pt_tot | 1 | Pt_air | 0.01 |
| | | Cd_soil | 0.45 | | | Pt_soil | 0.34 |
| | | Cd_wat | 0.35 | | | Pt_wat | 0.65 |
| Cl_tot | 1 | Cl_air | 0.24 | Ru_tot | 1 | Ru_air | 0.05 |
| | | Cl_soil | 0.3 | | | Ru_soil | 0.35 |
| | | Cl_wat | 0.46 | | | Ru_wat | 0.6 |
| Co_tot | 1 | Co_air | 0.01 | Sb_tot | 1 | Sb_air | 0.05 |
| | | Co_soil | 0.24 | | | Sb_soil | 0.75 |
| | | Co_wat | 0.75 | | | Sb_wat | 0.2 |
| Cr_tot | 0.25 | Cr_air | 0.05 | Se_tot | 1 | Se_air | 0.05 |
| | | Cr_soil | 0.35 | | | Se_soil | 0.65 |
| | | Cr_wat | 0.25 | | | Se_wat | 0.3 |
| Cr_VI_tot | 0.25 | Cr_VI_air | 0.05 | Si_tot | 1 | Si_air | 0.05 |
| | | Cr_VI_soil | 0.25 | | | Si_soil | 0.85 |
| | | Cr_VI_wat | 0.7 | | | Si_wat | 0.1 |
| Cu_tot | 1 | Cu_air | 0.05 | Sn_tot | 1 | Sn_air | 0.01 |
| | | Cu_soil | 0.45 | | | Sn_soil | 0.34 |
| | | Cu_wat | 0.35 | | | Sn_wat | 0.65 |
| Eu_tot | 1 | Eu_air | 0.1 | Th_tot | 1 | Th_air | 0.01 |
| | | Eu_soil | 0.3 | | | Th_soil | 0.29 |
| | | Eu_wat | 0.6 | | | Th_wat | 0.7 |
| Fe_tot | 1 | Fe_air | 0.01 | Zn_tot | 1 | Zn_air | 0.01 |
| | | Fe_soil | 0.14 | | | Zn_soil | 0.65 |
| | | Fe_wat | 0.85 | | | Zn_wat | 0.24 |
| Ga_tot | 1 | Ga_air | 0.05 | | | | |
| | | Ga_soil | 0.25 | | | | |
| | | Ga_wat | 0.7 | | | | |
| Ge_tot | 1 | Ge_air | 0.01 | | | | |
| | | Ge_soil | 0.65 | | | | |
| | | Ge_wat | 0.34 | | | | |

## References

AFU (Amt für Umwelt und Energie). Stromverbrauch Schweizer Handies, Basel; 2004.

Althaus H-J, Classen M, Blaser S, Jungbluth N. Ecoinvent — life cycle inventories for metals. Dübendorf: Swiss Centre for Life Cycle Inventories; 2004.

Anonymous: High-Speed Downlink Packet Access, http://en.wikipedia.org/wiki/High-Speed_Downlink_Packet_Access; 2005a.

Anonymous: Sharp V902 UMTS, http://www.factory-2-you.de/shop/datasheet.php?products_id=112648; 2005b.

BAKOM. Amtliche Fernmeldestatistik 2003. Biel: Bundesamt für Kommunikation; 2004a.

BAKOM. Faktenblatt UMTS v2.20. Bern: Bundesamt für Kommunikation; 2004b.

Banet F-J. Anfrage zu UMTS (R'05), Scharnhorst, W. personal communication (e-mail correspondence (2005-05-23)); 2005a.

Banet F-J. Fragen zu UMTS, Scharnhorst, W. personal communication (e-mail correspondence (2005-04-25)); 2005b.

Banet F-J, Gärtner A, Tessmar G. UMTS — Netztechnik, Dienstarchitektur, Evolution. Bonn: Hüthig Telekommunikation; 2004.

BDSV: Stahlschrott—ein "grüner" Rohstoff, Bundesvereinigung Deutscher Stahlrecycling-und Entsorgungsunternehmen Düsseldorf; 2001.

Bekkers R, Smits J. Mobile telecommunications: standards, regulation, and applications. London: Artech House Boston; 1997.

Benkner T, Stepping C. UMTS — Universal Mobile Telecommunications System, J. Schlembach Fachverlag Weil der Stadt; 2002.

Berzelius. QSL — Die umweltfreundliche Bleigewinnung. Stolberg: Berzelius Stolberg GmbH; 1993.

BOLIDEN. Boliden — world class recycler. Skelleftehamn: BOLIDEN Mineral AB; 2002.

BückmannGmbH: Setztisch — Technisches Datenblatt, Mönchengladbach. 2001a.

BückmannGmbH: Standardkegelsichter (Saugbetrieb) — Technisches Datenblatt, Mönchengladbach; 2001b.

BückmannGmbH: Zick-Zack Windsichteranlagen — Technisches Datenblatt, Mönchengladbach; 2001c.

CEC (Comission of the European Parliament). On the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS). Brussels; 2003a.

CEC (Comission of the European Parliament). On waste electrical and electronic equipment (WEEE). Brussels; 2003b.

CiscoSystems. Cisco 7609 router — enhanced 9-slot chassis. San Jose: Cisco Systems; 2004.

Conquadrat (Conquadrat). Produktkatalog 2003 mit Preisliste, Schwanstetten; 2003.

Delpho H. Mobilkommunikation 2009. Basel: Prognos AG; 2005.

Doradus. 6015 V patch 2.4 Ghz base station antenna. Stella Doradus Ireland Ltd.; 2003a.

Doradus. 12008 V patch 2.4 Ghz base station antenna. Stella Doradus Ireland Ltd.; 2003b.

Duque-Antón, M.: Mobilfunknetze—Grundlagen, Dienste und Protokolle, Vieweg Braunschweig/Wiesbaden; 2002.

Eberspächer J, Vogel H-J, Bettstetter C. GSM Global System for Mobile Communication—Vermittlung, Dienste und Protokolle in digitalen Mobilfunknetzen, B.G. Teubner GmbH Stuttgart, Leipzig, Wiesbaden; 2001.

ecoinventCentre: ecoinvent data v1.01, Dübendorf, CH; 2003.

Ekvall T, Finnveden G. Allocation in ISO 14041—a critical review. J Clean Prod 2001;9:197–208.

Enderin M, LeCorney D, Lindberg M, Lindqvist T. Axe 810 — the evolution continues. Ericsson Review, vol. 1; 2001.

ERICSSON. Manual Ericsson A1018s. Stockholm: Ericsson Mobile Communication AB; 1999.

ERICSSON (Ericsson Radio Systems AB). BSC/TRC, BSC and TRC 9.1 — product overview, Stockholm; 2002.

ERICSSON (ERICSSON AB). EDGE — introduction of high-speed data in GSM/GPRS networks, Stockholm; 2003.

ERICSSON. Axe system description. Stockholm: Ericsson Telecom AB; 2004.

ERICSSON. Ericsson demonstrates WCDMA, HSDPA phase 2 during CTIA Wireless; 2005.

ETSI (European Telecommunications Standards Institute). Digital cellular telecommunications system (phase 2): network architecture (GSM 03.02); 1996.

ETSI (European Telecommunications Standards Institute). Digital cellular telecommunications system (phase 2+): Base Station System-Mobile-services Switching Centre (BSS-MSC) interface — interface principles (GSM 08.02 version 6.0.0 release 1997), Sophia Antipolis; 1999a.

ETSI (European Telecommunications Standards Institute). Universal Mobile Telecommunication System (UMTS): general UMTS architecture, Sophia Antipolis; 1999b.

ETSI (European Telecommunications Standards Institute). Digital cellular telecommunications system (phase 2+): Base Station Controller-Base Transceiver Station (BSC-BTS) interface—layer 3 specifications (GSM 08.58 version 8.4.0 release 1999), Sophia Antipolis; 2000a.

ETSI (European Telecommunications Standards Institute). Digital cellular telecommunications system (phase 2+): GSM/Univeral Mobile Telecommunication System UMTS/General Packed Radio Service GPRS: serivce description — stage 1 (3GPP TS 22.060 version 3.5.0 release 1999), Sophia Antipolis; 2000b.

ETSI (European Telecommunications Standards Institute). Digital cellular telecommunications system (phase 2+): radio transmission and reception (3GPP TS 05.05 version 6.8.0 release 1997), Sophia Antipolis; 2000c.

ETSI (European Telecommunications Standards Institute). Digital cellular telecommunications system (phase 2+): rate adaption on the Mobile Station-Base Station System (MS-BSS) interface (3GPP TS 04.21 version 8.3.0 release 1999), Sophia Antipolis; 2000d.

ETSI (European Telecommunications Standards Institute). Digital cellular telecommunications system (phase 2+): General Packet Radio Service (GPRS) — overall description of the GPRS radio interface — Stage 2 (GSM 03.64 version 6.4.0 release 1997), Sophia Antipolis; 2001a.

ETSI (European Telecommunications Standards Institute). Universal Mobile Telecommunication System (UMTS): UTRA high speed downlink packet access (3GPP TR 25.950 version 4.0.0 release 4), Sophia Antipolis; 2001b.

ETSI (European Telecommunications Standards Institute). Digital cellular telecommunications system (phase 2+): Base Station System-Mobile Services Switching Centre (BSS-MSC) interface — interface principles (3GPP TS 08.02 version 8.0.1 release 1999), Sophia Antipolis; 2002a.

ETSI (European Telecommunications Standards Institute). Digital cellular telecommunications system (phase 2+): general aspects on the BSS-MSC interface (3GPP TS 08.01 version 8.0.1 release 1999), Sophia Antipolis; 2002b.

ETSI (European Telecommunications Standards Institute). Universal Mobile Telecommunication System (UMTS): network architecture (3GPP TS 23.002 version 3.6.0 release 1999), Sophia Antipolis; 2002c.

ETSI (European Telecommunications Standards Institute). Universal Mobile Telecommunication System (UMTS): physical layer — general description (3GPP TS 25.201 version 3.4.0 release 1999), Sophia Antipolis; 2002d.

ETSI (European Telecommunications Standards Institute). Universal Mobile Telecommunication System (UMTS): UTRAN Iu interface: general aspects and principles (3GPP TS 25.410 version 3.8.0 release 1999), Sophia Antipolis; 2002e.

ETSI (European Telecommunications Standards Institute): digital cellular telecommunications system (phase 2+): GSM/EDGE Radio Access Network (GERAN) — overall description stage 2 (3GPP TS 43.051 version 5.10.0 release 5), Sophia Antipolis; 2003a.

ETSI (European Telecommunications Standards Institute). Digital cellular telecommunications system (phase 2+): Univeral Mobile Telecommunication System (UMTS)/General Packet Radio Service (GPRS): serivce description — stage 2 (3GPP TS 23.060 version 3.16.0 release 1999), Sophia Antipolis; 2003b.

ETSI (European Telecommunications Standards Institute). Universal Mobile Telecommunication System (UMTS): network architecture (3GPP TS 23.002 version 4.8.0 release 4), Sophia Antipolis; 2003c.

ETSI (European Telecommunications Standards Institute). Universal Mobile Telecommunication System (UMTS): spacial channel model for Multiple Input Multiple Output (MIMO) simulations (3GPP TR 25.996 version 6.1.0 release 6), Sophia Antipolis; 2003d.

ETSI (European Telecommunications Standards Institute). Universal Mobile Telecommunication System (UMTS) UTRA High Speed Downlink Packet Access (HSDPA): overall description — stage 2 (3GPP TS 25.308 version 6.3.0 release 6), Sophia Antipolis; 2004.

ETSI (European Telecommunications Standards Institute). Digital cellular telecommunications system (Phase 2+): Universal Mobile Telecommunication System (UMTS) — network architecture (3GPP TS 23.002 version 6.7.0 release 6), Sophia Antipolis; 2005.

Faist-Emmenegger M, Frischknecht R, Jungblut N. LCA des Mobilfunksystems UMTS. Uster: ESU Services; 2003.

Faist-Emmenegger M, Frischknecht R, Stutz M, Guggisberg M, Witschi R, Otto T. Life cycle assessment of the mobile communication system UMTS. Int J LCA Online First 2004:1–12.

Farrell F. Integrated Pollution Prevention and Control (IPCC) — reference document on best available techniques in the non ferrous metals industries. Sevilla: Insitute of Prospective Technological Studies; 2000.

Fishbein BK. (INFROM Inc): Waste in the Wireless World: The Challange of Cell Phones, New York; 2002.

Frischknecht R, Faist-Emmenegger M. Ecoinvent — Strommix und Stromnetz. Dübendorf: Swiss Centre for Life Cycle Inventories; 2003.

Frischknecht R, Jungbluth N, Althaus H-J, Doka G, Dones R, Heck T, et al. Ecoinvent — overview and methodology. Dübendorf: Swiss Centre for Life Cycle Inventories; 2004.

Gärtner A. Datentransferraten in UMTS, Scharnhorst, W. personal communication (e-mail correspondence (2005-05-17)).

Gestner B, Persson B. RNC3810 — Ericsson's first WCDMA radio network controller. Ericsson Rev 2002;2.

Goosey M, Kellner R. A scoping study — end-of-life printed circuit boards. Yorkshire: Department of Trade and Industry; 2002.

Grunewald A, Gustavsson J. End-of-life Treatment of Radio Base Station Transceivers in Europe, Japan and the USA — a Life Cycle Assessment Study. Stockholm: Industrial Ecology Royal Institute of Technology/ Chemical Engineering Linköping Institute of Technology; 1999.

GSMAssociation: GSMA statistics Q2/04, http://www.gsmworld.com/news/statistics/pdf/gsma_stats_q2_04.pdf; 2004.

GSMworld: GSM subscribers connected, http://www.gsmworld.com/index.shtml; 2005.

Guinée JB, Gorrée M, Heijungs R, Huppes G, Kleijn R, de Koning A, et al. Life Cycle Assessment; An Operational Guide to the ISO Standards; Final Report, May 2001, Ministry of Housing, Spatial Planning and Environment (VROM) and Centrum voor Milieukunde (CML), Rijksuniversiteit Den Haag and Leiden; 2001.

Halonen T, Romero J, Melero J. GSM, GPRS and EDGE performance. Chichester: John Wiley & Sons Ltd.; 2003.

Hausammann E. Power consumption BTS and NodeB, Scharnhorst, W. personal communication (e-mail correspondence (2005-02-04)).

HELCOM (HELCOM). Land-based pollution group—6h meeting, Vilnius; 2002.

Hillebrand F. GSM and UMTS: the creation of global mobile communication. Chichester: John Wiley & Sons, Ltd.; 2002.

Holma H, Toskala A. WCDMA for UMTS: radio access for third generation mobile communications. Chichester: John Wiley & Sons Ltd; 2004.

Hugentobler S. Beschwerlicher Weg beim Bau von Mobilefunkanlagen. Neue Züricher Zeitung; 2000. 2000-12-12.

Ihlenfeld J. NOKIA zeigt HSUPA — mehr Upstream-Bandbreite für UMTS, http://www.golem.de; 2005.

IKP and PE (IKP Universität Stuttgart und PE Europe GmbH). GaBi4: Software und Datenbank zur Ganzheitlichen Bilanzierung, Stuttgart; 2003.

ISO. ISO 14040: Ökobilanz — Prinzipien und allgemeine Anforderungen. Brussels: International Organisation for Standardisation; 1997.

ISO. ISO 14041: environmental management—life cycle assessment — goal and scope definition and inventory analysis. Brussels: International Organisation for Standardisation; 1998a.

ISO. ISO 14042: environmental management—life cycle assessment — life cycle impact assessment. Brussels: International Organisation for Standardisation; 1998b.

ISO. ISO 14044: environmental management—life cycle assessment — requirements and guidelines. Brussels: International Organisation for Standardisation; 2005.

ITF: Selbsttragender Antennenmast der Höhe von 36 m des Durchmessers von 1016 mm mit zwei Plattformen—schwere Konstruktion, http://www.itf.co.yu/stubovi/stub_teski_ger.html; 2005.

Janssen W. UMTS- T-Mobile beschleunigt HSDPA-Technik auf 7.2 MBit/s, http://www.at-mix.de/news/996.html; 2005.

Jolliet O, Margni M, Charles R, Humbert S, Payet J, Rebitzer G, et al. IMPACT2002+: a new life cycle impact assessment methodology. Int J LCA 2003;8(6):324–30.

Kincaid LE, Geibig JR. Printed wiring board cleaner technologies substitutes assessment: making holes conductive. Washington: University of Tennessee; 1998.

Lehner T. Recovery of precious metals using plastics as reducing agent. Brussels; 2001.

Lucent. Flexent Serving GPRS Support Node (SGSN) for UMTS. Wiltshire: Bell Labs; 2004a.

Lucent. Lucent Gateway GPRS Support Node (GGSN). Wiltshire: Bell Labs; 2004b.

LucentTechnologies. FLEXENT™ GSM macrocell. Wiltshire: Bell Labs; 2000.

LucentTechnologies. Flexent mobile switching centre for UMTS. Wiltshire: Bell Labs; 2001a.

LucentTechnologies. Flexent™ OneBTS™ NodeB. Wiltshire: Bell Labs; 2001b.

LucentTechnologies. APX 1000 universal gateway. Wiltshire: Bell Labs; 2003a.

LucentTechnologies. APX 8000 universal gateway. Wiltshire: Bell Labs; 2003b.

LucentTechnologies. MAX TNT universal gateway. Wiltshire: Bell Labs; 2003c.

LucentTechnologies. The FLEXENT UMTS macrocell base station family. Wiltshire: Bell Labs; 2004.

LucentTechnologies. PacketStar PSAX 4500 multiservice media gateway. Wiltshire: Bell Labs; 2005.

Ludwig CD, Hellweg S, Stucki S. Municipal solid waste management. Berlin: Springer Verlag; 2003.

Malmodin J, Oliv L, Bergmark P. Life cycle assessment of third generation (3G) wireless telecommunication systems at Ericsson, Stockholm; 2001.

Motorola. Material assay of the GSM 900 handy PWB and GSM 900 BTS rack PWB. Taunusstein: Rapid Environmental Assessment Lab; 2005.

Nokia. Nokia HSDPA solution; 2003.

Nokia: Nokia 3210, http://www.nokia.ch/german/phones/phone_models/3210/features.html; 2005a.

Nokia: Nokia 6150, http://www.nokia.ch/german/phones/phone_models/6150/features.html; 2005b.

NSI. Line interface modules for the stinger DSL access concentrator. Simi Valley: Network Systems Integration; 2005.

Orange: Schlüsselzahlen, http://www.orange.ch/aboutus/corporateaffairs/keyFigures?ts=1113985534112; 2004.

P.S. Wie die SBB am Strom hängen. Neue Züricher Zeitung; 2005. 23.06.2005.

Pehrsson U, Hedblom M-O. Sustainability. Stockholm: Ericsson; 2005.

Pennington DW, Potting J, Finnveden G, Lindeijer E, Jolliet O, Rydberg T, et al. Life cycle assessment part 2: current impact assessment practice. Environ Int 2004;30:721–39.

Pennington DW, Margni M, Ammann C, Jolliet O. Multimedia fate and human intake modeling: spatial versus nonspatial insights for chemical emissions in Western Europe. Environ Sci Technol 2005;39:1119–28.

PhoneContent.com: IDC finds mobile phone market in need of new growth catalyts, http://www.phonecontent.com/bm/news/se/663.shtml; 2004.

RANDA-GROUP. Life cycle assessment of a mobile phone. Telefónica Servicios Móviles S.A.; 2000.

Rebitzer G, Ekvall T, Frischknecht R, Hunkeler D, Norris G, Rydberg T, et al. Life cycle assessment part 1: framework, goal and scope definition, inventory analysis, and applications. Environ Int 2004; 30:701–20.

Röder A, Bauer C, Dones R. Ecoinvent — Kohle. Dübendorf: Swiss Centre for Life Cycle Inventories; 2004.

Rudolf R. GPRS basics — Die Grundkonzepte des General Packet Radio Service. Nürnberg: T.O.P BusinessInteractive; 2003.

Sanders G, Thorens L, Reisky M, Rulik O, Deylitz S. GPRS networks. Chichester: John Wiley & Sons Ltd.; 2003.

Scharnhorst W. Life-Cycle Assessment of Mobile Telephone Networks, with Focus on the Environmental Relevance of the End-of-Life Phase. PhD thesis, EPFL-ENAC-ISTE Lausanne; 2005.

Scharnhorst W, Althaus H-J, Classen M, Jolliet O, Hilty LM. End of life treatment of second generation mobile phone networks: strategies to reduce the environmental impact. Env Imp Ass Rev 2005a;25(5):540–66.

Scharnhorst W, Althaus H-J, Hilty L, Jolliet O. Environmental assessment of End-of-Life treatment options for an GSM 900 antenna rack. Int J LCA Online first 2005b:1–18.

Scharnhorst W, Ludwig C, Wochele J, Schuler A, Hilty LM, Jolliet O. Heavy metal partitioning from electronic scrap during thermal End-of-Life treatment. Environ Sci Technol 2005c.

Schnabel P. Kommunikationstechnik-Fibel. Ludwigsburg; 2003.

Schnabel P. Datenübertragung im Mobilfunknetz, http://www.elektronik-kompendium.de, Ludwigsburg; 2004.

Scholz J. Swisscom Mobile: 30000 bis 40000 UMTS-Kunden, http://www.teltarif.ch/arch/2005/kw22/s4059.html, Berlin; 2005.

Schullitz M. (Arthur D. Little Int. GmbH): Key success factors for M-commerce, Vienna; 2001.

SiemensAG (Siemens AG). BS-240/BS-241 base transceiver stations, München; 2000.

Steele R, Lee C-C, Gould P. GSM, cdmaONE and 3G systems. Chichester: John Wiley & Sons Ltd; 2001.

Stengele M. Telephone Call: EOL treatment processes at IMMARK, Scharnhorst, W. personal communication (Telephone call 2004-05-11).

Stromtip.de: Stromverbrauch durch Handy-Ladegeräte, http://www.stromtip.de/news/2959/archiv/Kaum-Stromverbrauch-durch-Handy-Ladegeraete.htm; 2000.

SUNmicrosystems. Sun's Netra t1400 and Netra t1405 servers. Palo Alto: Sun Microsystems, Inc.; 1999.

Sunrise: sunrise Facts and Figures 2004, http://www.sunrise.net/facts_figures_04.pdf; 2005.

SuperiorCables (Superior Cables GmbH). Glasfaserkabel, Markt Schwaben; 2003.

Swisscom (Swisscom). Infrastructure UMTS; 2004.

Swisscom: Fakten und Zahlen, http://www.swisscom-mobile.ch/scm/wir_fakten_und_zahlen-de.aspx; 2005a.

Swisscom: Information on mobile phone subscriptions, Scharnhorst, W. personal communication (Telephone conference (2005-04-18)); 2005b.

Tanskanen P, Takala R. Concept of a mobile terminal with active disassembly mechanism. Helsinki: NOKIA Research Centre; 2001.

UMTSlink.at: Motorola V980, http://umtslink.at/cgi-bin/reframer.cgi?/telefone/3g/motorola_v980.php; 2004.

Uryu T, Yoshinaga J, Yanagisawa Y. Environmental fate of gallium arsenide semiconductor disposal. J Ind Ecol 2003;7(2):103–12.

VSSV: Information über Stahlrecycling in der Schweiz, Scharnhorst, W. personal communication (telephone call); 2005.

Weidman E, Lundberg S. Life cycle assessment of ERICSSON third generation systems. Stockholm: ERICSSON A.B.; 2001.

Weyhe, R.: ACCUREC- Recycling GmbH, Scharnhorst, W. personal communication (internal information (2004-02-16)).

Xonio: Panasonic Z800: UMTS-Handy mit Megapixel-Kamera, http://www.xonio.com/news_12628607.html?tid1=7469 and tid2=0; 2004.

ZDNet: Sony Ericsson V800 UMTS, http://www.zdnet.de/mobile/handy/0,39024717,39130524,00.htm; 2005.