LIFE CYCLE ASSESSMENT OF MOBILE TELEPHONE NETWORKS, WITH FOCUS ON THE END-OF-LIFE PHASE

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To the man with the iron hand

“Communication is the cement that makes organisations. Communication alone enables a group to think together, to see together, and to act together.”

(Norbert Wiener)

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Abstract

Mobile communication, in particular mobile telephony, is a service whose nonexistence nowadays is unimaginable. The ongoing, ever increasing penetration of mobile communication equipment, presently intensified by the transition from second generation**[1]** to third generation**[2]** mobile telephone technology, raises the necessity for environmentally sound production, operation and End-of-Life**[3]** treatment.

In order to determine potentials to improve the overall environmental performance of large technical systems, such as mobile phone networks, Life Cycle Assessment**[4]** is increasingly accepted as the state-of-the art tool. Up to now, this tool has been primarily used to determine the environmental effects of the production and the use phase. The environmental consequences related to the EOL treatment of mobile telephone electronic scrap has been addressed only marginally. A reliable assessment of the overall environmental consequences however, requires a comprehensive analysis of all life cycle phases.

The focus of the present thesis is directed towards the environmental assessment of the EOL treatment of scrap of mobile phone networks that comply with present and forthcoming mobile phone standards in order to provide in-depth knowledge on the related environmental effects. Additionally, reliable environmental data for future studies shall be generated.

After a brief introduction in Chapter 1, the application of LCA for the environmental analysis of mobile phone networks is outlined in general in Chapter 2 (***LCA method applied to mobile phone technology***). A decomposition[5] of the mobile telephone network infrastructure is proposed in order to investigate the network components separately (hierarchical classification of the network components into classes A-D). Technical background knowledge, compiled in parallel, is used in order to assemble a mobile phone network model used for network recomposition later on. Similar to the network decomposition, a dissection of the End-of-Life[6] phase is proposed in order to explore and model the processing of the electronic scrap in the EOL phase appropriately.

Subsequently, the infrastructure and communication techniques of the presently applied 2G and 3G mobile telephone networks are described in detail in Chapter 3 (***Technical characterisation of mobile phone technology***). Using the decomposition approach the mobile phone network infrastructure is characterised in detail. Technique related effects are explained. Applying the subdivision approach, the various EOL stages are presented.

Chapters 4 and 5 compile the results of LCA studies performed for a separate network component and an entire network. The objects of the studies both comply with the modern Global System for Mobile communication standard**[7]**. The ***Screening LCA of an antenna station rack*** (Chapter 4) is based on comprehensive inventories of an antenna station rack[8] and currently applied EOL treatment. The environmental impacts related to the End-of-Life treatment of the rack are investigated. Six different EOL treatment scenarios are developed to find an environmentally acceptable treatment alternative. System expansion, i.e. inclusion of the production phase, is applied to all scenarios in order to consider different amounts of recycled materials.

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[1] 2G.

[2] 3G.

[3] EOL treatment.

[4] LCA.

[5] In the context of network modelling the term „decomposition“ is used to denote the disaggregation of the entire network into the separate network components and their sub-components.

[6] EOL phase.

[7] GSM.

[8] Technologically this rack complies with the Global System for Mobile communication standard (GSM).

The production of primary rack materials to substitute lost materials, especially that of palladium (which accounts for almost 40 % of the ecotoxicity impact category), dominates the overall environmental impact. Emissions of heavy metals from landfilled rack components/materials and of by-products to the environment greatly influence the overall impacts on human health and ecosystem quality. The final disposal of rack components contributes to about 70% of the non-carcinogenic effects. Landfilled dust from steel production contributes to nearly 11% of this impact category.

The results suggest that all precious metals containing electronic scrap should be treated in specially equipped metal recovery plants. A complete rack disassembly before processing in high-standard metal recovery plants is not necessary. An elaborated pre-treatment and fractionation of the scrap prior to precious material recovery does not lower the environmental impacts and is not mandatory and would only become environmentally interesting if high recovery of heavy metals is achieved. To avoid the formation and release of volatile and toxic heavy metals, incineration of electronic scrap and of by-products prior to landfilling should be avoided. To reduce the overall environmental load, standardisation of the sizes of rack components is recommended in order to facilitate their re-use. The ***LCA of a GSM Network*** (Chapter 5) comprises a life cycle assessment based on a detailed life cycle inventory for a typical GSM mobile phone network and related EOL treatment infrastructure. The environmental relevance of the three life cycle phases: production, use and EOL treatment has been analysed using IMPACT2002+. The environmentally preferable EOL treatment alternative was identified adopting the six earlier developed EOL treatment scenarios.

Results indicate that environmental impacts attributable to the use phase dominate the environmental impacts during the entire life cycle of the network. The impacts of the production phase are primarily attributable to the energy intensive manufacturing of Printed Wiring Board Assemblies[1]. The EOL phase dominates impacts on ecosystem quality. In particular long-term emissions of heavy metals cause critical effects.

Detailed analysis of the EOL phase shows that recycling of network materials in general leads to a two fold reduction of environmental impacts: in the EOL phase itself as well as by means of the avoided primary production of materials that are recovered in the EOL phase. An increase in the material quality of the secondary precious and rare materials leads to a significant reduction of impacts on human health.

The EOL phase is assessed in-depth by developing different EOL treatment scenarios. Comprehensive experimental results on the volatilisation of heavy metals from PWBA during thermal EOL treatment are presented in Chapter 6 (***Heavy metal partitioning from electronic scrap during thermal End-of-Life treatment***). Samples of identical PWBA have been incinerated in a Quartz Tube Reactor[2] in order to detect the volatility of selected key heavy metals in electronic scrap. In preparation, evaporation experiments were performed using a Thermo-Gravimeter[3] in connection with an Inductively Coupled Plasma Optical Emissions Spectrometer[4]. The QTR-experiments were performed under reducing and under oxidising conditions at 550 and 880°C. The volatilisation has been determined for *As*, *Cd*, *Ni*, *Ga*, *Pb*, *Sb* and *Zn* using ICP-OES. The results were evaluated by thermodynamic equilibrium calculations and in comparison with similar studies.

Neither *As* nor *Cd* nor *Ga* could be detected in the incineration ash residuals, expressing a high volatility. *Ni* remains as stable compound in the ash. *Zn* shows an increasing volatility with increasing temperature and depending on the supply of oxygen. *Sb* shows a high volatility nearly independent on temperature and oxygen supply.

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[1] PWBA (Printed Wiring Board Assemblies are boards populated with Integrated Circuit (IC) components such as micro controllers, memory elements, diodes, etc.)..

[2] QTR.

[3] TG.

[4] ICP-OES.

The results imply that, if electronic scrap is incinerated, attention has to be paid in particular to *Sb*, *As* and *Ga*. These metals are increasingly used in new electronic equipment such as mobile phone network equipment of the third generation.
The series of the core chapters is finalised by presenting results of a comparative LCA study performed for mobile phone networks complying with the GSM and Universal Mobile Telecommunication System standard[1] (Chapter 7: ***LCA of of Second Generation (2G) and Third Generation (3G) Mobile Phone Networks***). The environmental performance of presently operated GSM and UMTS networks was analysed, concentrating on the environmental effects of the EOL phase using the 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 and the robustness of the results was tested with other LCIA methods. 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 per bit transferred than GSM networks and a slightly higher absolute impact. In assessing the EOL phase, recycling the electronic scrap of mobile phone networks has clear environmental benefits. Under the present conditions, material recycling could help to lower the environmental impact of the production phase by up to 50%.
Based on the recapitulation of the achievements of the thesis and an outline of the thematic limitations, challenges for future studies are formulated in Chapter 8.

The results documented in the thesis are supported by the complementing appendices (A-D).

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[1] UMTS.

Riassunto

La comunicazione mobile, in particolare la telefonia mobile, è cresciuta in maniera impressionante nell'ultima decade e fa oramai parte della vita quotidiana di una grande porzione della società odierna. La crescente diffusione di apparecchiature di comunicazione mobile, attualmente rinforzata dal passaggio dalla tecnologia di seconda generazione[1] a quella di terza generazione[2], fa sorgere questioni riguardanti la produzione, l'utilizzo, e il trattamento o lo smaltimento rispettosi dell'ambiente.

Per poter determinare le possibili ottimizzazioni dal lato ecologico di grandi sistemi tecnici, viene vieppiù utilizzato il metodo dei bilanci ecologici[3]. Finora questo metodo è stato impiegato soprattutto per studiare le ripercussioni sull'ambiente delle fasi di produzione e di utilizzo dei sistemi di telefonia mobile. LCA e' stato utilizzato solo marginalmente per studiare le conseguenze ambientali del trattamento di rifiuti elettronici prodotti dalla telefonia mobile. Pertanto una valutazione affidabile e completa delle conseguenze sull'ambiente richiede un'analisi di tutti i tre cicli di vita.

Oggetto di questa tesi di dottorato è l'analisi delle ripercussioni sull'ambiente dovute al trattamento di rifiuti elettronici della telefonia mobile, sia dell'attuale generazione (2G) che della futura (3G). Lo scopo e' quello di ricavare conoscenze profonde riguardo alle conseguenze ambientali del trattamento, e di paragonarle con quelle delle fasi di produzione e di utilizzo. Inoltre si vogliono mettere a disposizione di studi futuri dati ambientali affidabili.

Mentre il Capitolo 1 contiene una breve introduzione, il Capitolo 2 (***LCA method applied to mobile phone technology***) si dedica al metodo sviluppato per applicare LCA all'analisi ecologica di reti di telefonia mobile. Per poter studiare separatamente le ripercussioni sull'ambiente delle singole componenti delle reti di telefonia mobile durante le fasi di produzione, di utilizzo e di smaltimento, viene proposta una suddivisione dell'infrastruttura della rete nella quale le componenti vengono ordinate gerarchicamente nelle classi A-D. Contemporaneamente conoscenze tecniche di base servono a modellare una rete di telefonia mobile. Per ottenere un modello e un'analisi degli aspetti ecologici del trattamento di rifiuti elettronici il più possibilmente vicini alla realtà, pure la fase di trattamento viene suddivisa.

In seguito, nel Capitolo 3 (***Technical characterisation of mobile phone technology***) vengono descritti in dettaglio l'infrastruttura e le tecniche di comunicazione della telefonia mobile 2G e 3G. Basandosi sull'approccio presentato nel Capitolo 2, le singole componenti di una rete di telefonia mobile vengono presentate in dettaglio. Aspetti tecnici vengono brevemente descritti. Utilizzando il medesimo approccio vengono spiegate le fasi di trattamento di rifiuti e le sue subfasi.

Nei Capitoli 4 e 5 vengono presentati i risultati di studi LCA applicati a una singola componente di rete rispettivamente a una rete intera, entrambi facenti parte dello standard Global System for Mobile communication[4]. Lo studio (***Screening LCA of an antenna station rack***) si basa su un'inventarizzazione completa dei consumi di materia prima e delle emissioni di un armadio di distribuzione. Pure in maniera estesa viene inventarizzata l'infrastruttura utilizzata nella fase di trattamento dei rifiuti. Sei scenari differenti di trattamento di rifiuti vengono sviluppati per poter determinare le ripercussioni sull'ambiente di diverse strategie di

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[1] 2G.
[2] 3G.
[3] Life Cycle Assessment (LCA).
[4] GSM.

trattamento dei rifiuti e per poter definire l'alternativa ottimale. Un allargamento del sistema tramite inclusione della fase di produzione viene elaborato per ciascun scenario. La produzione di materia prima per sostituire materiale deposto o non riciclato, in particolare la produzione di palladio (che contribuisce per il 40% al carico ambientale qualitativo del sistema ambientale), domina il carico totale sull'ambiente di un armadio di distribuzione. Emissione di metalli pesanti provenienti da componenti deposti di armadi di distribuzione e di altri prodotti di smaltimento influiscono in particolare sulla salute dell'uomo e sulla qualità del sistema ecologico. Il deposito di parti di armadi di distribuzione contribuisce per il 70% a effetti non cancerogeni e i rifiuti sottoforma di polveri depositati provenienti dalla produzione di acciaio contribuiscono per il 11%.

I risultati mettono in risalto il fatto che possibilmente tutti i rifiuti elettronici dovrebbero essere trattati adeguatamente in impianti di riciclaggio di metallo. Non è necessario disfare completamente un armadio di distribuzione prima che venga riciclato. Con una separazione completa delle materie prime durante la fase di trattamento dei rifiuti, per esempio in materiali ferrosi, non ferrosi e plastici, non si ottiene un'ulteriore riduzione del carico ambientale. Per evitare che si sprigionino metalli pesanti volatili, si dovrebbe evitare di incenerire rifiuti elettronici durante il loro smaltimento. Una standardizzazione di componenti elettroniche potrebbe contribuire al riutilizzo di queste componenti o di interi armadi di distribuzione.

Lo studio (***LCA of a GSM Network***) comprende il bilancio ecologico di una rete di telefonia mobile GSM, basandosi su una completa inventarizzazione dei consumi di materia prima, delle emissioni e delle fasi di trattamento delle singole componenti di una rete di telefonia mobile GSM. L'importanza ecologica delle tre fasi: produzione, utilizzo e trattamento, è stata studiata con IMPACT2002+. I sei scenari di trattamento dei rifiuti, menzionati sopra, sono stati nuovamente analizzati per determinare la strategia di trattamento ottimale.

I risultati mostrano che la fase di utilizzo di una rete è la predominante tra le tre fasi di vita di una rete di telefonia mobile in quanto a carico ambientale. Nella fase di produzione il carico proviene dalla produzione di schede madri, che richiede molta energia. La fase di trattamento domina negli effetti sulla qualità del sistema ecologico, in particolare le emissioni a lungo termine di metalli pesanti.

Un'analisi dettagliata della fase di trattamento mostra che il riciclaggio di materiali porta a una riduzione del carico ambientale totale di una rete di telefonia mobile: nella fase di trattamento (minore e nessuna emissione a lungo termine da deponie) e tramite diminuzione della produzione di materia prima nella fase di produzione.

I risultati sperimentali del trattamento termico di schede madri[1] vengono presentati nel Capitolo 6 (***Heavy metal partitioning from electronic scrap during thermal End-of-Life treatment***), in particolare concentrandosi sulla volatilità dei metalli pesanti *As*, *Cd*, *Ni*, *Ga*, *Pb*, *Sb* e *Zn*. Campioni di schede madri identiche furono bruciati in un forno a quarzo per analizzare la volatilità di alcuni metalli pesanti. In preparazione sono stati eseguiti esperimenti di evaporazione con un termogravimetro, unito a un TG-ICP. Gli esperimenti nel forno a quarzo sono stati realizzati in condizioni riducenti e ossidanti a 550 e 880 °C. Le misurazioni ottenute sono state paragonate con i risultati di calcolo dell'equilibrio termodinamico.

Né *As*, né *Cd* e neppure *Ga* sono stati trovati nei residui. *Ni* rimane quasi stabile sotto qualsiasi condizione. *Zn* tende a una volatilità maggiore a temperature più elevate e a dipendenza del contenuto di ossigeno. Per contro *Sb* è volatile quasi indipendentemente dalla temperatura e dal contenuto in ossigeno. I risultati mostrano che nell'incenerimento di rifiuti elettronici bisogna porre particolare attenzione su *Sb*, *As* e *Ga*. Questi metalli vengono utilizzati sempre più nelle componenti più recenti, in particolare nelle componenti di reti della telefonia mobile di terza generazione.

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[1] Printed Wired Board Assembly (PWBA).

I risultati di uno studio comparativo sulle ripercussioni ambientali di una rete GSM paragonata a una rete Universal Mobile Telecommunication System[1] sono contenuti nel Capitolo 7 (***LCA of of Second Generation (2G) and Third Generation (3G) Mobile Phone Networks***). Inoltre vengono riportate possibili ripercussioni ambientali di reti UMTS future. Lo studio si basa su un'inventarizzazione completa dei consumi di materia prima e delle emissioni di ogni singola componente di rete di telefonia mobile UMTS. Per ottenere risultati vicini alla realtà vien dato peso a un modello fedele agli standard di telefonia mobile. Le ripercussioni sull'ambiente sono state nuovamente analizzate con IMPACT2002+. La credibiltà dei risultati è stata confortata da risultati ottenuti con altri metodi.
I risultati mostrano che un'operazione parallela di reti GSM e UMTS è sfavorevole all'ambiente. La fase di transizione tra i due standard dovrebbe essere la più breve possibile. La fase di utilizzo delle componenti di rete contribuiscono maggiormente al carico totale della rete. In particolare dovrebbe essere ridotto il consumo di energia delle stazioni di antenne. Se paragonate tra di loro, la tecnologia UMTS (utilizzata in maniera sensata) è più ecologica per unità di dati trasmessa. Gli studi mostrano che il riciclaggio di rifiuti elettronici è ecologicamente sensato. Nelle condizioni attuali il riciclaggio può compensare il carico ambientale della fase di produzione fino al 50%.

Il Capitolo 8 infine ricapitola i risultati ottenuti, basandosi sui quali vengono mostrati i limiti tematici e le possibili sfide future nell'ambito della telefonia mobile.

I risultati documentati nella presente tesi di dottorato vengono completati nelle appendici (A-D).

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[1] UMTS.

Zusammenfassung

Mobilkommunikation, insbesondere Mobiltelephonie, stellt eine Dienstleistung dar, deren Inexistenz heutzutage undenkbar ist. Die beständig zunehmende Anzahl an Mobiltelephonen und Netzwerkinfrastruktur, derzeit noch verstärkt bedingt durch den Übergang zwischen Mobiltelephontechnologien der zweiten Generation[1] und der dritten Generation[2], wirft zunehmend die Frage nach umweltschonender Produktion, Verwendung und Verwertung auf.

Um die ökologischen Optimierungspotentiale großer technischer Systeme, wie Mobiltelephonnetzwerke, zu bestimmen, wird zunehmend die Ökobilanzierungsmethode, als dem Stand der Technik entsprechend, eingesetzt. Bis heute wurde diese Methode hauptsächlich verwendet um die Umweltauswirkungen der Produktions- und der Verwendungsphase zu bestimmen. Nur marginal hingegen, wurde die Bedeutung der Verwertungsphase von Elektronikschrott aus Mobiltelephonnetzwerken untersucht. Eine verlässliche und umfassende Bewertung des ökologischen Aspektes der Mobiltelephonie bedarf jedoch einer tiefgreifenden Untersuchung aller drei Lebensphasen eines entsprechenden Netzwerkes.

Der Schwerpunkt der vorliegenden Dissertation liegt auf der Bewertung der Umweltauswirkungen hervorgerufen durch der Verwertung von Elektronikschrott aus Mobiltelephonnetzwerken, die sowohl den derzeit aktuellen (2G) als auch den zukünftigen (3G) Mobiltelephoniestandards entsprechen. Ziel ist es, profunde Kenntnisse über die Effekte auf die Umwelt zu erlangen und verlässliche Daten für nachfolgende Studien zur Verfügung zu stellen.

Nach einer kurzen Einführung in Kapitel 1, wird in Kapitel 2 die Verwendung der Ökobilanzmethode zur Bestimmung der Umweltauswirkungen von Mobiltelephonnetzwerken vorgestellt (***LCA method applied to mobile phone technology***). Um die ökologischen Auswirkungen der einzelnen Netzwerkkomponenten während der Herstellungs-, der Benutzungs- und während der Verwertungsphase getrennt darstellen zu können, wird eine Untergliederung der Netzwerkinfrastruktur vorgeschlagen. Dabei sollen die einzelnen Komponenten hierarchisch in Klassen A bis D eingeteilt werden. Gleichzeitig angeeignetes technisches Grundlagenwissen wird verwendet um Mobiltelephonnetzwerke modellhaft zusammenzustellen. Um eine möglichst realitätsnahe Modellierung und Analyse der ökologischen Aspekte der Verwertung von Elektronikschrott zuzulassen wird, ähnlich der Untergliederung der Netzwerkinfrastruktur, eine Unterteilung der Verwertungsphase in aufeinanderfolgende Schritte vorgeschlagen.
Nachfolgend werden die technischen Details der untersuchten aktuellen 2G und 3G Mobiltelephonnetzwerke in Kapitel 3 zusammenfassend erläutert (***Technical characterisation of mobile phone technology***). Unter Verwendung des in Kapitel 2 erläuterten Untergliederungsansatzes werden die einzelnen Komponenten eines Mobiltelephonnetzwerkes im Detail vorgestellt. Technische Aspekte, z.B. Übertragungsmodi, werden kurz beschrieben. Ebenfalls unter Verwendung des Unterteilungsansatzes werden die Verwertungsphase und die darin enthaltenen einzelnen Schritte im Wesentlichen erläutert.
Kapitel 4 und 5 fassen die Resultate je einer Ökobilanzstudie für eine einzelne Netzwerkkomponente und eines ganzen Netzwerkes, beide dem Global System for Mobile communication standard[3] entsprechend, zusammen. Die Studie ***Screening LCA of an antenna station rack*** (Kapitel 4) basiert auf einer umfassenden Inventarisierung der Resourcenverbräuche und Emissionen eines Antennenracks. Ebenso umfassend ist die in der Verwertungsphase ver-

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[1] 2G.
[2] 3G.
[3] GSM.

wendete Infrastruktur inventarisiert. Sechs unterschiedliche Verwertungsszenarien wurden erstellt, um die ökologischen Auswirkungen von verschiedenen Strategien zu untersuchen und eine optimale Alternative zu bestimmen. Eine Systemerweiterung durch Einbeziehung der Produktionsphase wird in allen Szenarien durchgeführt. Die Produktion von Primärmaterialien um nicht zurückgewonnene oder deponierte Materialien zu ersetzen, besonders die Produktion von Palladium (trägt zu ca. 40% der Ökosystemqualitätsbelastung bei), dominiert die Gesamtumweltbelastung eines Racks. Schwermetallemissionen aus deponierten Rackbestandteilen/materialien und von anderen Abfallprodukten beeinflussen insbesondere die Auswirkungen auf die menschliche Gesundheit und die Ökosystemqualität. Die Deponierung von Rackbestandteilen trägt zu 70% und deponierte Staubabfälle aus der Stahlproduktion tragen zu 11% der nichtkarzinogenen Effekte bei.

Die Resultate unterstreichen, dass möglichst jeglicher Elektronikschrott in angemessen ausgestatten Metallrückgewinnungsanlagen behandelt werden sollte. Ein vollständiges Auseinandernehmen eines Racks vor der Metallrückgewinnung ist nicht zwingend notwendig. Eine umfassende Materialfraktionierung, z.B. in Eisen- und Nichteisenmetalle und Kunststoffe, ist nicht erforderlich, da dadurch keine zusätzliche Senkung der Umweltbelastung in der Verwertungsphase erreicht wird. Um eine unerwünschte Freisetzung flüchtiger Schwermetalle zu vermeiden sollten Elektronikschrott, oder während der Verwertung anfallende Abfallprodukte, nicht verbrannt werden. Eine konsequente Normung von z.B. Rackgrössen und Leitungsverbindungen könnte dazu beitragen, dass einzelne Rackkomponenten oder das Rack als Ganzes andernorts weiterverwendet werden können. Dadurch könnte eine tatsächliche Reduzierung der Umweltbelastungen eines Racks erzielt werden. Die Studie ***LCA of a GSM Network*** (Kapitel 5) umfasst die Ökobilanzierung eines kompletten Mobiltelephonnetzwerkes basierend auf einer umfassenden Inventarisierung der Resourcenverbräuche und Emissionen der einzelnen Netzwerkkomponenten. Gleichermassen detailliert sind die einzelnen Verfahrensschritte der Verwertungsphase inventarisiert. Die ökologische Bedeutung der drei Lebensphasen: Produktion, Nutzung und Verwertung wurde mit Hilfe der IMPACT2002+ Methode untersucht. Die sechs vorher zusammengestellten Verwertungsszenarien wurden wieder angewandt, um die optimale Verwertungsstrategie zu bestimmen.

Die Resultate zeigen, dass die Nutzungsphase eines Netzwerkes die ökologischen Auswirkungen während des ganzen Lebenszyklusses dominiert. Die Belastungen in der Produktionsphase werden besonders durch die energieintensive Herstellung der Leiterplatten verursacht. Die Verwertungsphase dominiert wiederum die Auswirkungen auf die Ökosystemqualität. Besonders Langzeitemissionen von Schwermetallen verursachen nachteilige Auswirkungen.

Die detaillierte Untersuchung der Verwertungsphase zeigt, dass Rückgewinnung von Netzwerkmaterialien in zweifacher Hinsicht zu einer Reduzierung der Gesamtumweltbelastung durch ein Netzwerk führt: in der Verwertungsphase selber (verringerte oder keine Langzeitemissionen aus Deponien) und durch Vermeidung/Verringerung der Produktion von Primärmaterialien in der Produktionsphase. Eine Steigerung der Qualität der rückgewonnenen Materialien kann zu einer Verringerung nachteiligen Auswirkungen auf die menschliche Gesundheit führen.

In beiden besprochenen Studien liegt der Schwerpunkt auf der Verwertungsphase, wobei diese durch die Entwicklung und Analyse verschiedener Szenarien im Detail untersucht wird. Kapitel 6 (***Heavy metal partitioning from electronic srap during thermal End-of-Life treatment***) faßt die Resultate umfangreicher Experimente zur thermischen Verwertung von Leiterplatten zusammen. Proben von identischen Leiterplatten wurden in einem Quarzrohrofen verbrannt, um die Flüchtigkeit ausgewählter Schwermetalle zu analysieren. Zur Vorbereitung wurden Verdampfungsexperimente mit einem Thermogravimeter, verbunden mit einem induktiv gekoppelten Plasma Emissionsspektrometer, durchgeführt. Die Experimente im Quarzrohrofen wurden unter reduzierenden und unter oxidierenden Bedingungen bei 550 und 880°C durchgeführt. Ausführlich wurde die Verflüchtigung der Schwermetalle *As*, *Cd*, *Ni*, *Ga*, *Pb*, *Sb* und *Zn* analysiert. Die Resultate wurden mit Resulaten aus thermodynamischen Gleichgewichtsberechnungen verglichen.

Weder *As* noch *Cd* noch *Ga* wurden in den Rückständen unter oxididierenden oder reduzierenden Bedingungen gefunden. *Ni* bleibt nahezu stabil unter jeglichen Bedingungen. *Zn* tendiert zu einer höheren Flüchtigkeit bei steigender Temperatur und in Abhängigkeit vom Sauerstoffgehalt. *Sb* ist flüchtig nahezu unabhängig von Temperatur und Sauerstoffgehalt. Die Resultate zeigen, dass bei der Verbrennung von Elektronikschrott besondere Aufmerksamkeit auf *Sb*, *As* und *Ga* gelegt werden sollte. Diese Metalle werden zunehmend in neueren elektronischen Bauteilen, insbesondere Mobiltelephonnetzwerkkomponenten der 3. Generation, eingesetzt.

Abgeschlossen wird die Reihe der Kernkapitel der Dissertation durch die Zusammenfassung der Resultate einer Vergleichsstudie über die Umweltauswirkungen eines GSM-Netzwerkes verglichen mit denen eines Univeral Mobile Telecommunication System[1] Netzwerkes (Kapitel 7: ***LCA of Second Generation (2G) and Third Generation (3G) Mobile Phone Networks***). Dieses Kapitel beinhaltet außerdem prospektive Resultate über mögliche Umweltauswirkungen zukünftiger UMTS-Netzwerke. Die Studie basiert auf einer umfassenden Inventarisierung der Resourcenverbräuche und Emissionen der einzelnen Netzwerkkomponenten. Um realitätsnahe Resultate zu erzielen, wurde Gewicht auf eine standardgetreue Modellierung der jeweiligen Netzwerke und ihrer technischen Modifikationen gelegt. Die Umweltauswirkungen wurden wieder mit der IMPACT2002+ Methode analysiert. Die Robustheit der Ergebnisse wurde durch Vergleich mit Resultaten anderer Methoden ermittelt. Basierend auf Vorhersagen wurden die zu erwartenden Umweltauswirkungen zukünftiger Mobiltelephonnetzwerktechnoligien abgeschätzt.

Die Resultate verdeutlichen, dass ein gleichzeitger Betrieb von GSM- und UMTS-Netzwerken ökologisch nachteilig ist. Die Übergangsphase zwischen beiden Standards sollte so kurz wie möglich gehalten werden. Die Nutzungsphase (d.h. der Betrieb) der Radionetzwerkkomponenten trägt am meisten zur Gesamtnetzwerkbelastung bei. Insbesondere sollten die Energieverbräuche der Antennenstationen reduziert werden, um eine Reduzierung der Gesamtbelastung zu erzielen. Im Vergleich miteinander stellt die UMTS-Technologie (sobald sinnvoll ausgelastet) die ökologisch effizientere Technologie pro übertragene Datenmenge dar. Die absolute Gesamtbelastung liegt geringfügig über der der GSM-Technologie. Die Studien zeigten, dass Verwertung von Elektronikschrott zum Zweck der Rückgewinnung von Materialien ökologisch vorteilhaft ist. Unter derzeitigen Bedingungen kann eine Materialrückgewinnung die ökologischen Belastungen der Produktionsphase bis zu 50% kompensieren.

Kapitel 8 schließlich, rekapituliert die erzielten Resultate und zeigt die thematischen Grenzen der Dissertation auf. Basierend darauf wird ein Ausblick auf noch ausstehende wissenschaftliche Fragen gegeben.

In den Anhängen A-D sind ausgewählte Daten und Informationen über die Netzwerkkomponenten sowie Transferkoeffizienten und –fraktionen enthalten.

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[1] UMTS.

Units

-	…	Piece or Unit
%	…	Percent
°C	…	Degrees Celsius
a	…	Year
DALY	…	Disability Adjusted Life Years
g	…	Gram
K	…	Kelvin
kbit/s	…	Kilobit per Second
kg	…	Kilogram
kHz	…	Kilohertz
kW	…	Kilowatt
m	…	Metre
mm	…	Millimetre
m^2	…	Square Metre
Mbit/s	…	Megabit per Second
MHz	…	Megahertz
MJ	…	Megajoule
Nl/h	…	Norm Litre per Hour
PDF	…	Potentially Damage Fraction of species

Abbreviations

1G	…	First Generation
2G	…	Second Generation
3G	…	Third Generation
8PSK	…	8Level Phase Shift Keying
16QAM	…	16Quadrature Amplitude Modulation
AuC	…	Authentification Centre
BBC	…	Backbone Cable network
BTS	…	Base Transceiver Station
BSC	…	Base Station Controller
BSS	…	Base Station Subsystem
CDMA	…	Code Division Multiple Access
CI	…	Condensation Interface
CN	…	Core Network
CSD	…	Circuit Switched Domain
d	…	Depth
DALY	…	Disability Adjusted Life Years
EDGE	…	Enhanced Data rates for Global Evolution
EIR	…	Equipment Identity Register
EOL	…	End of Life
ETSI	…	European Telecommunications Standards Institute
FDD	…	Frequency Division Duplex
FDMA	…	Frequency Division Multiple Access
GGSN	…	Gateway GPRS Support Node
GMSC	…	Gateway MSC

GMSK	…	Gaussian Minimum Shift Keying
GPRS	…	General Packed Radio Service
GSM	…	Global System for Mobile communication
h	…	Height
HLR	…	Home Location Register
HSCSD	…	High Speed Circuit Switched Data
HSDPA	…	High Speed Downlink Packet Access
HSUPA	…	High Speed Uplink Packet Access
ISO	…	International Organisation for Standardisation
kbit	…	Kilobit
kg	…	Kilogram
$kg_{equiv.}$	…	Kilogram equivalents
kHz	…	Kilohertz
LCA	…	Life Cycle Assessment
LCI	…	Life Cycle Inventory
LCIA	…	Life Cycle Impact Assessment
LiIo	…	Lithium Ion
m^2	…	Square metre
Mbit	…	Megabit
ME	…	Mobile Equipment
mg	…	Milligram
MHz	…	Megahertz
min	…	Minute(s)
MJ	…	Megajoule
mm	…	Millimetre
MS	…	Mobile Station

MSC	…	Mobile Switching Centre
MSS	…	Mobile Subsystem
MSWI	…	Municipal Solid Waste Incineration
NiCd	…	Nickel Cadmium
NiMh	…	Nickel Metalhydride
Nl	…	Norm litre
NMT	…	Northern Mobile Telecommunication systems
NSS	…	Network Switching Subsystem
PDF	…	Potentially Damage Fraction of species
PSD	…	Packed Switched Domain
PWBA	…	Printed Wiring Board Assembly
QPSK	…	Quadrature Phase Shift Keying
QTR	…	Quart Tube Reactor
RNC	…	Radio Network Controller
RNS	…	Radio Network Subsystem
SGSN	…	Serving GPRS Support Node
SIM	…	Subscriber Identity Module
TC	…	Transfer Coefficient
TDD	…	Time Division Duplex
TDMA	…	Time Division Multiple Access
TG-ICP-OES	…	Thermo-Gravimeter/Inductively Coupled Plasma Optical Emission Spectrometer
UMTS	…	Universal Mobile Telecommunication System
VLR	…	Visitor Location Register
w	…	Width
W-CDMA	…	Wideband-CDMA

1. Introduction to the Thesis

1.1. *Mobile Communication: Background, Perspectives and Challenges*

Any kind of artificial entity can be seen as a model-like transformation and application of naturally existing archetypes in order to provide functionality to individuals as well as organisations[1] (Avery, 2003, Bonabeau *et al.*, 1999, Shannon and Weaver, 1976, Zemanek, 1959).
One of the key functionalities that organisations[2] intimately depend on is the provision of information (Fleming, 1967, Mirow, 1969, Wiener, 1992). As in a control circuit, the flow of information helps to organise and enables adaptation to environmental influences (Bonabeau *et al.*, 1999). In evolutionary terms, the exchange of information between individuals[3], i.e. the ability to communicate, is one of the key success factors (Avery, 2003). In the course of the continuously progressive evolution of mankind, however, the development of regionally distributed cultures hampered direct communication without technical means and necessitated the development of communication facilities, i.e. of communication networks, in order to convey information also to distant individuals (Aschoff, 1995, Thomas, 1995).
From a **social perspective**, modern and prospering cultures (organisations) are characterised by well-functioning communication networks (Mayntz and Hughes, 1988). Today, mobile telephone networks increasingly bear this task and represent an integrating part of modern societies (Graham *et al.*, 1996, Minges, 1999, Roos, 1993).
From a more abstract **economic point of view**, communication networks, and , in the context of this thesis, mobile phone networks, represent a tool that can contribute to successful company management[4] (Haselhoff, 1967, Mirow, 1969). A flourishing economy in turn characterises a prospering and progressive society (Dasgupta *et al.*, 2001, van-der-Vlies, 1996). In economic competition, an expeditious exchange of information between employees of a company is of fundamental importance for a company's flexibility and economic survival (Mirow, 1969). For instance, since the years of rapid industrial expansion in Germany, the economic environment has changed drastically. Primarily the growth of companies with ever more and ever more distant employees gave the incentive for the implementation of (initially national) mobile phone networks (Haug, 2001). The recent increasing international integration of consolidated companies necessitated the development and implementation of truly international mobile telephone standards which has been realised with the implementation of the second[5] and the third generation[6] of mobile phone standards.
So far it has been shown that mobile phone networks are important from a social and an economic point of view. That mobile phone networks also have an **environmental aspect** is a rather new realisation. This vital aspect of mobile phone networks did not become evident until the first reports on harmful effects related to the processing of electronic scrap were published around the turn of the millennium (Fishbein, 2002, Socolof *et al.*, 2001). This aspect is of even more importance when it comes to significant technology transitions, as is presently the case with the transition from 2G to 3G mobile phone networks. Such a transition is always associated with a parallel operation of different technologies and an increased amount of scrap due to the replacement of the outdated technology. Presently more than 1.6 billion people

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[1] In this context groups of individuals are considered as organisations.

[2] Organisations are seen as equivalent to organisms.

[3] For example human beings.

[4] Similar to the above mentioned control circuits, mobile phone networks connect the individual elements (fellows) of a company with each other, in turn allowing for fast information flow and rapid adaptation to new economic situations.

[5] 2G.

[6] 3G.

worldwide use GSM technology to make mobile phone calls (GSMworld, 2005)[1]. More than 2 billion people have access to mobile telephone technology (GSMAssociation, 2005). Similar to the Western European average, a mobile phone presently has a use time of about 1.5 years in Switzerland (e.g. Swisscom, 2005, Sunrise, 2005). That means that 250 million of the 375.7 million mobile phones operated in Western Europe at the end of 2005[2] will be discarded by the end of 2006. Alone the mass of Printed Wiring Board Assembly[3] discarded with the mobile phones[4], results in 7500 t/year of electronic scrap. This is little in comparison with the total annual amount of waste generated in Western Europe (only 0.00025% of 3000 million t/year (Kazmierczyk, 2004)). However, this amount of electronic scrap[5] corresponds to 0.0017% of the total annual municipal waste generated in Western Europe. Though these values may suggest that electronic scrap is only of minor relevance compared with the overall waste stream(s), it should not be forgotten that *i.)* potentially hazardous substances can be released in large fractions from electronic scrap if the scrap is improperly or not treated and *ii.)* electronic scrap can represent a significant sink of increasingly rare resources if no appropriate End-of-Life treatment is performed in order to recover materials and energy (Christen, 2005).

The early environmental reports on electronics in general, and the ongoing investigations since on the environmental consequences of mobile telephony, indicate that today, as resources decrease and increasingly become rare goods, a more sustainable organisation[6] is characterised by a resource efficient and emissions preventing usage of technical facilities such as mobile phone networks (Berkhout and Hertin, 2001, WCED, 1987). In this context it is necessary that only those mobile phone and related communication techniques survive that are of social benefit, that are of economic advantage and that are environmentally preferable.

The first studies directly addressing the environmental aspects of mobile telephony (and essentially of the network infrastructure) concentrated on effects due to exposure to radio frequency fields (Léonard *et al.*, 1983, Szmigielski *et al.*, 1982). They, as well as later studies, arrived at the conclusion that there is no evidence that exposure to non-ionising radiation causes detrimental effects for human health (Hermann and Hossmann, 1997, Hyland, 2000, Stewart *et al.*, 2000, Verschaeve and Maes, 1998). Other studies concentrated on the production of electronics and stressed the environmental effects related to lead contained in the solder mass when manufacturing PWBA (Kindesjö, 2002, Shapiro *et al.*, 2003, Wilfing and Száva, 2005). Recently adopted EU regulations prohibit the usage of lead in solders (CEC, 2003a) and alternative compositions, such as tin-silver compounds have been identified to be of environmental benefit in manufacturing electronics (Suganuma, 2001). Only recently published studies and reports addressed the environmental aspect of the End-of-Life phase[7] of electronics, in particular of thermal EOL treatment (Antonetti *et al.*, 2004, Blazsó *et al.*, 2002, Fishbein, 2002, Hardy, 2002). In general, the analyses arrived at the conclusion that electronic scrap contains elements (mostly metals) which can become volatilised and which may pose an environmental risk if released. In order to reduce harmful environmental impacts related to electronic scrap, the EU has adopted regulations (CEC, 2003a, 2003b).

Common to most environmental studies performed for electronics in general, and mobile phone networks in particular, is a lacking comprehensiveness. This aspect complicates the interpretation of the results when it comes to comparative environmental analyses, i.e. when the environmental performance of similar products shall be analysed. In order to provide a framework for consistent analysis of environmental aspects of products, Life Cycle Assess-

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[1] Value taken from the referenced website onDec 28th, 2005.

[2] It is assumed that each subscriber has only one mobile phone (which is of course a fairly conservative assumption).

[3] PWBA.

[4] Assuming that a PWBA mounted in a mobile phone weighs about 30 g.

[5] Again it is only the mass of PWBA discarded with mobile phones that is discussed here, rechargeable batteries and battery recharger are not included.

[6] Be it a company a town or a nation, etc.

[7] EOL phase.

ment[1] has been under development since the late 1960ies (Fava *et al.*, 1991, Hunt and Franklin, 1996). Characteristic for this method is the holistic consideration of the environmental performance of products (ISO, 1997, ISO, 1998). Initially simple but essential products, such as paper or cardboard, were analysed using LCA (Villanueva *et al.*, 2004). Today, LCA is increasingly perceived as an essential and supporting tool for any kind of product, also of large technical facilities such as mobile telephone networks.

There have been several LCA studies performed to model the environmental effects of separate elements of network components (Grunewald and Gustavsson, 1999), entire networks (Faist-Emmenegger *et al.*, 2004, Malmodin *et al.*, 2001) and individual life cycle phases (Tanskanen and Takala, 2001). It has been found that the use phase dominates the overall environmental impact of mobile phone networks and that mobile phones as well as antenna stations play a key role (Faist-Emmenegger *et al.*, 2004, Pehrsson and Hedblom, 2005). Although various reports on the EOL processing of electronic scrap (as contained in mobile telephone networks) document that hazardous environmental impacts can be attributed to the materials (e.g. metals, organic substances) contained in the scrap (Fishbein, 2002, Goosey and Kellner, 2002), in most LCA studies the systems under study, i.e. the networks, were modelled in an oversimplified way and focus was directed only on the production and the use phase. Very few LCA studies have addressed the EOL phase of mobile telephone networks, respective their components and elements and have proven that processing of electronic scrap in the EOL phase aiming at the recovery of materials and energy can contribute to lowering the overall environmental impact of e.g. mobile telephone networks (Leskinen *et al.*, 2002, Tanskanen and Takala, 2001). There is no in-depth analysis on the environmental effects associated with the transition from 2G to 3G mobile telephone networks based on current data. However, several factors make necessary a comprehensive investigation of the environmental consequences related to the overall life cycle of a mobile phone network in general and a detailed consideration of the EOL phase of electronic scrap in particular:

(a) The number of mobile telephony subscribers as well as of network infrastructure is on the rise (BAKOM, 2004, GSMAssociation, 2004).
(b) The subscriber and infrastructure growth rates will continue to increase (Delpho, 2005, Schullitz, 2001, Wallace, 2005).
(c) Governmental regulations require the increase in recycling rates and the ban of substances assessed to be hazardous (CEC, 2003a, 2003b).

Based on a comprehensive modelling and experimental measurements, for the first time the environmental effects associated with the EOL treatment of mobile phone networks has been put in relation to the environmental effects of the production and the use phase. The extensive collection of network infrastructure and operation data of 2G and 3G mobile phone networks enabled the in-depth analysis of the environmental effects associated with the technological transition between these two standards. The adoption of forecasted subscriber data allowed the calculation of prospective environmental consequences.

1.2. *Thesis Goal, Scope and Constraints*

The goal of this thesis is to discover the critical environmental effects of mobile telephony and, in turn, to identify potential to lower and or eliminate the environmental loads related to mobile telephony.

In order to meet the defined goal and to address the above outlined environmental challenges associated with modern mobile telephony, the presented thesis aims at the comprehensive environmental analysis of the life cycle of mobile telephone technology including all phases and concentrating on the EOL phase. In particular the thesis aims at:

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[1] LCA.

- the development of an approach to use LCA for communication networks in general and mobile phone networks in particular,
- the assessment of the environmental performance of second generation (2G) and third generation (3G) mobile phone networks concentrating on the EOL phase,
- weighing of the importance of the EOL phase compared with the other life cycle phases and identification of the EOL stage that is environmentally most important,
- the design and evaluation of EOL scenarios for mobile phone networks and the formulation of recommendations to concerned stakeholders.

The goal and scope of the thesis necessitates a detailed analysis of the complete infrastructure of mobile phone networks including the Mobile Stations[1] as well as an in-depth analysis of the present state-of-the-art EOL processing technology. The production and the use phase of the analysed mobile phone technology were included based on existing process information and data sets. In case of the network operation only the energy consumed was taken into account. The base materials the respective network components consist of and the energy consumed in the manufacturing of PWBA were included in the production phase. Auxiliaries used in the PWBA manufacturing remained unaccounted for.
As stated, LCA was chosen as tool to perform the environmental analysis for mobile phone networks and components. The newly developed IMPACT2002+ impact assessment method (Jolliet *et al.*, 2003, Pennington *et al.*, 2005) is applied in order to quantify the environmental impacts of emissions and resource consumptions. The entire thesis project is complemented by an extensive experimental study on the thermal EOL treatment of PWBA.

1.3. ***Thesis road map***

The thesis is based upon four papers (three about life cycle modelling and one of experimental nature), several conference proceedings and unpublished work. The initial chapter (chapter 1) introduces the subject the thesis deals with, circumscribes the topic of the study and informs the reader about the general structure of this document. Chapter 2 presents and discusses the application of the Life Cycle Assessment method to large technical constructions such as mobile telephone networks. It is highlighted how LCA is applied to the EOL phase of mobile phone networks. In chapter 3 the subject of the study is presented. The technical and technological characteristics of mobile telephone networks are described based on the respective technological and technical standards. In another sub-clause of that chapter, the state-of-the-art EOL technology, as adopted to model the respective life cycle phase of mobile phone networks, is comprehensively characterised. Chapters 4 through 7 represent the scientific core of this thesis and present and recapitulate the content of the following papers:

i.) Environmental assessment of End-of-Life treatment options for an GSM[2] 900 antenna rack (Scharnhorst *et al.*, 2005b)

This paper represents an initial screening study on the EOL phase of one particular mobile phone network component, i.e. of a Base Transceiver Station[3]. It contains the life cycle im-

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[1] Mobile Stations is standard terminology ETSI (1996a): Digital cellular telecommunications system (Phase 2): Network architecture (GSM 03.02); European Telecommunications Standards Institute, Sophia Antipolis.
, ETSI (1996b): Digital cellular telecommunications system (Phase 2+): Abbreviations and acronyms (GSM 01.04); European Telecommunications Standards Institute, Sophia Antipolis.. For convenience, MS will be termed *mobile phone*.

[2] Global System for Mobile communication.

[3] BTS.

pact assessment results for six different EOL treatment scenarios and discusses recommendations to the concerned stakeholders.

ii.) End Of Life treatment of second generation mobile phone networks: strategies to reduce the environmental impact (Scharnhorst *et al.*, 2005a)

This article bases on the above described screening study, but now an entire GSM 900 mobile phone network is considered. The earlier developed six EOL treatment scenarios are adopted and the environmental impact is estimated. In order to determine the environmental improvement potential represented by the recovery of precious metals, value correction factors was applied.

iii.) Heavy metal partitioning from electronic scrap during thermal End-of-Life treatment (Scharnhorst *et al.*, 2005d)

This article documents the results of an experimental study on the thermal EOL treatment of PWBAA of a BTS. Cut and milled PWBAA have been incinerated in a Quartz Tube Reactor[1] under various conditions and the volatilisation of heavy metals is estimated. The results are compared with theoretical predictions as well as with results obtained by preparative semi-quantitative in-situ measurements (using a Themo-*G*ravimeter coupled with an Inductively Coupled Plasma - Optical Emissions Spectrometer[2]).

iv.) Life Cycle Assessment of Second Generation (2G) and Third Generation (3G) Mobile Phone Networks (Scharnhorst *et al.*, 2005c)

This paper represents the final scientific article in the series of the four publications. The environmental profiles of a basic GSM and a basic *U*niversal *M*obile *T*elecommunications *S*ystem[3] network are compared with each other. The EOL phase is represented by the environmentally most preferable variant determined in the above described studies. In order to address the technological evolution (with respect to faster data transfer) of the two mobile phone network standards, General Packed Radio Service[4] and Enhanced Data rates for Global Evolution[5] as well as UMTS (R'04[6]) and (R'06[7]) were included and forecasted subscriber numbers were adopted.

Chapter eight completes this thesis document. It recapitulates the key findings and informs on the limitations of the thesis. Based on this, it gives perspectives for future studies in this field.

At the end of this thesis the most important life cycle inventory data used in the performed LCA's and the results of the above named studies are compiled in appendices.

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[1] QTR.

[2] TG-ICP-OES.

[3] UMTS.

[4] GPRS.

[5] EDGE.

[6] That are networks complying with the 3GPP standardisation package *Release 2004.*

[7] That are networks complying with the 3GPP standardisation package *Release 2006.*

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2. LCA Method as Applied to Mobile Phone Technology

This second chapter outlines how the LCA method[1] was applied to mobile phone networks in order to model such networks for environmental analysis by means of network characterisation and decomposition (section 2.1.), life cycle modelling (section 2.2.) and network parameterisation and recomposition (section 2.3.). In line with the topic of this thesis, the focus is on the consideration of the End-of-Life phase[2] of mobile phone networks.

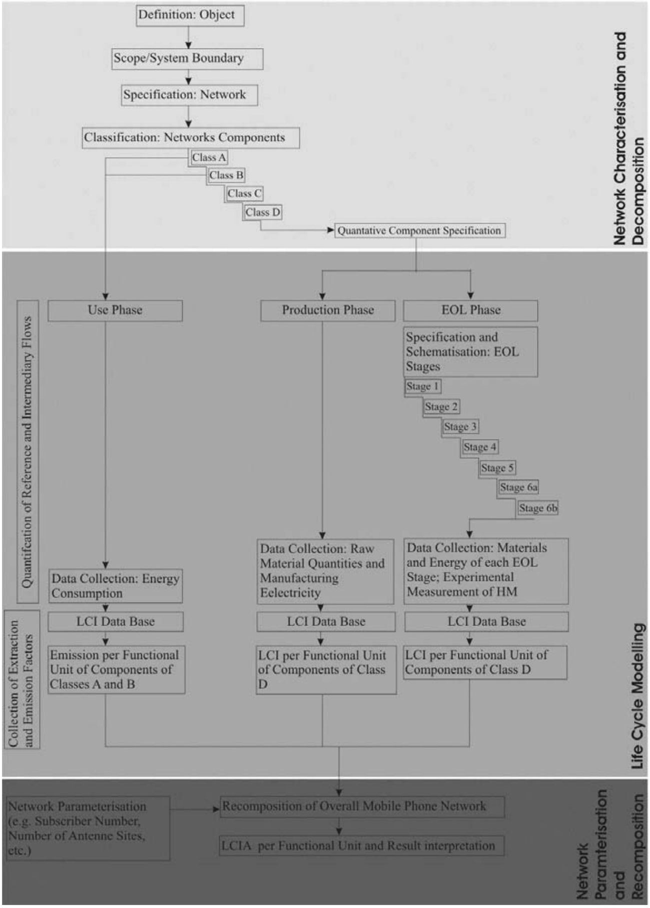

Fig. 2.1: Flow chart of methodological LCA steps performed for the environmental analysis of mobile phone networks concentrating on the EOL phase.

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[1] LCA is a technique for assessing the environmental aspects and potential impacts associated with a product (ISO, 1997).

[2] EOL phase.

2.1. *Network Characterisation and Decomposition*

Once a mobile phone network was selected as the **object** of a LCA study, the initial **scope** of the planned study and the preliminary **system boundaries** had to be defined (Fig. 2.1). This initial delimitation was kept broad and was adjusted and confined later on.

After this introductory step the **network** under study was basically **specified** according to the network generation it belongs to and the access and the transmission techniques that were deployed to operate the network (Figs. 2.1 and 2.2): for example, it was specified whether the network belongs to the first[1], second[2] or third generation[3] of mobile phone networks, whether digital or analogue transmission techniques are deployed, and how the available frequency capacity is managed[4]. In the context of the specification of the considered network, as much background information as possible on the technology the considered network represents and the deployed communication techniques was compiled and analysed from related literature, reports and other sources. In addition, information on the regional circumference of the network under study and statistical data on the quantity of the network components were collected.
Based on this information, the initially broadly defined system and its boundaries were refined. The gathered technological information was used in order to assemble a model of a mobile phone network on the major network component level[5]. This model or abstraction of a network was used later to recompose the mobile phone network for the environmental analysis[6]. According to the system conditions which have been more precisely defined through an iterative process, the key functionality of the object under study was pre-defined. Thereafter a functional unit was defined in order to relate the inputs and outputs associated with the functionality of the object under study. Finally, the reference flow was defined.
In the context of the system refinement, unavoidable allocation principles were defined and a preliminary list of network specific parameters, such as data throughput, subscriber capacity, download capacity, upgradeability, and parameters varying the energy consumption in dependence on the environmental conditions the network is exposed to, was compiled.

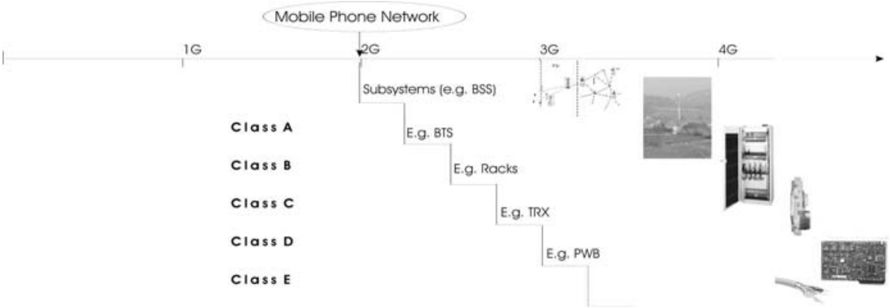

Fig. 2.2: Decomposition of a mobile phone network and classification of the network components.

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[1] 1G.
[2] 2G.
[3] 3G.
[4] The technical and technological aspects of the various mobile phone networks are outlined in chapter 3.
[5] The component levels of a mobile phone network are presented in the following section.
[6] The decomposition of the network is described in the detail in the following section.

In a next step, and in order to facilitate the further environmental analysis of the mobile phone network, the network was decomposed into its sub-systems and major network components[1] (Fig. 2.2) and a detailed quantitative specification of the decomposed components was performed. The decomposition was performed by hierarchically **classifying** the **network components** into classes *A* through *D*. Components that belong to hierarchically lower classes represent parts of components that belong to hierarchically higher classes, for example components of class B are parts of class A components[2]. To components of ***class A*** belong all major network components, for example Mobile Stations[3], Base Transceiver Station[4], NodeB, Base Station Controllers[5], Radio Network Controllers[6], Mobile Switching Centres[7], etc. The devices installed in these network components, for example racks, cables, air conditioners, etc., belong to ***class B***. Transceivers, amplifiers, routers, etc., which are installed in the class B components belong to the component ***class C***. Finally, Printed Wiring Board Assemblies[8], cables, housings, shelves, etc., of which class C components consist of, belong to the basic ***class D***. If necessary or of advantage a further disaggregation of the class D components into ***class E*** *components*, for instance PWBA layers, cable shieldings, etc., was performed. The network component specification step was finalised by the detailed compilation of the **quantitative specifications** of the physical dimensions of the class D components, e.g. masses, sizes and eventually energy consumptions when operated. In order to facilitate the subsequent life cycle inventory process, similar class D components (e.g.: PWBA, cables, housings, etc.) were grouped according to specific parameters. For example PWBA were grouped according to the number of layers, board size and weight. Whenever possible such a grouping was also applied to class C components (for example air conditioners were grouped according to the air flow per hour).

2.2. *Life Cycle Modelling*

After the network under study was sufficiently decomposed, the initial specifications and definitions of the overall study scope and of the system boundaries were reviewed and used as a basis for a more exact final definition of the system that was concentrated on[9]. This definition included first of all a clear alignment of the focal point of the LCA study, i.e. it was defined whether an individual life cycle phase represented the core scientific object, and, if so, which phase was of specific interest. Thereafter, and according to the defined objective of the study, the processes that had to be included in order to model the system properly were specified for each life cycle phase. In this context the qualitative and quantitative process modelling accuracy was to be set up, i.e. it was necessary to define whether certain processes were modelled explicitly or whether they were adopted from existing studies.

The life cycle modelling began by quantifying the reference and intermediary flows based on data collections for the use, production and EOL phases. According to the focus of this thesis, the EOL phase of mobile phone networks, i.e. the treatment of the electronic scrap, required an explicit modelling. In a first step the various EOL stages were **specified** and **schematised** (similar to the above described network decomposition) in order to discover the individual

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[1] The sub-systems and major network components of modern mobile phone networks are specified in the respective technical standards.

[2] This classification of the network components has no relation to for example energy consumptions of the respective components.

[3] MS; for convenience mobile stations will be termed *mobile phones*.

[4] BTS.

[5] BSC.

[6] RNC.

[7] MSC.

[8] PWBA.

[9] LCA represents an iterative method. The results at the end of an LCA study can require another adjustment of the system settings (e.g. the system boundaries) and calculations need to be repeated (ISO, 1997). Therefore, it is avoided to term the system definition as *final*.

EOL treatment stages and processes that represent the total EOL phase[1] (Fig. 2.3). This approach envisages the partitioning of the EOL phase into six consecutive **stages**[2], which in turn, and depending on their inter-combination, represent the overall complexity and quality of the applied EOL treatment strategy (Fig. 2.3).

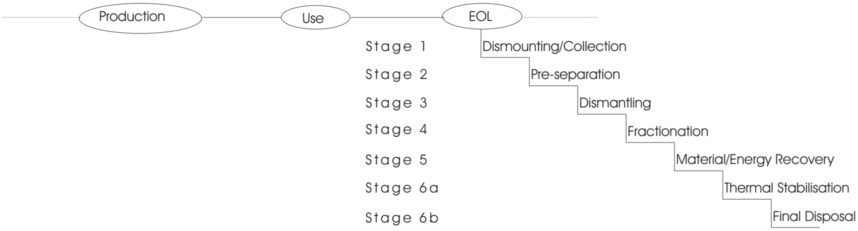

Fig. 2.3: Subdivision of the EOL phase of mobile phone networks into consecutive stages.

Subsequently, detailed technological and technical background information on the applied EOL strategies was compiled starting with the sub-contractor that initially dismounts the class A network components (**stage 1**). Thereafter, information on the material fractionation (**stages 2-4**) and material recovery (**stage 5**) was compiled. Finally, information on the final inertisation (**stage 6a**) and disposal stages (**stage 6b**) was collected.

Based on the compiled know-how, processing schemes were assembled in order to model the *EOL treatment* of the mobile phone networks. This schematisation included a specification of the processing infrastructure to be covered in the life cycle model of the mobile phone network. The schematisation was followed by a qualitative and quantitative **data collection** of the processing infrastructure materials and the up and downstream processes (e.g.: production of the material of which the processing infrastructure consists of). For the data of extraction and emission related to each reference flow, particular attention has also been paid to the inventory of thermal EOL treatment processes, for example treatment of electronic scrap in Municipal Solid Waste Incineration plants[3] and transfer coefficients were derived from **experimental measurements** on the volatility of heavy metals when treating electronic scrap thermally (Scharnhorst *et al.*, 2005c).

The production and the use phase, neither core scientific objects in this thesis, were modelled based on elsewhere inventoried and aggregated process data sets.

In the case of the *production phase*, raw material and manufacturing energy data were qualitatively and quantitatively compiled for the quantitatively specified class D network components. Subsequently, existing data sets of **raw material** processing and **energy generation** were assigned to the various class D network components. In a few exceptions of not available but important raw material production processes, for example the production of various precious metals, the fabrication of such base materials was explicitly qualitatively and quantitatively inventoried. Extractions and emissions for each considered reference flow were taken from existing LCI databases.

For the *use phase* only **energy consumption** data of class A (mobile phone) and B (all other components except mobile phones) network components were qualitatively and quantitatively compiled and existing data sets on energy generation were assigned to the class A and B net-

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[1] Though similar, this subdivision is not identical with the decomposition applied to the network components. For example stage 2 processes are not part of stage 1 processes (as class B components are parts of class A components). Also, each EOL stage can be performed independent of the other stages. But the order in which the various processes (stages) are performed is fix. It is not possible to first perform stage 3 and then stage 1.

[2] This partitioning in turn allows for the development of different EOL scenarios which is addressed in chapters 4 and 5.

[3] MSWI.

work components. Extractions and emissions related to energy production were taken from existing LCI databases.

2.3. *Network Parameterisation and Recomposition*

In the previous stages the EOL processing infrastructure and its operational conditions have been inventoried. Likewise, the production and the use phase at class D level (production and EOL) and class A and B network component level (use) were completely inventoried.

In order to continue the LCA for mobile phone networks it was necessary to **recompose** the networks in compliance with the previously set-up mobile phone network model on class A component level and to link the various EOL stages with each other to replicate practised EOL strategies. The model for the network replication was an existing mobile phone network. Consecutively, the components of the various classes (e.g. classes D through A) were assigned to the hierarchically next higher network components until class A network components were fully modelled. By finalising this step, a basic mobile phone network was modelled at non-operational conditions.

After the completion of the EOL phase modelling, and in order to simulate operational conditions, the network use and the EOL treatment conditions were defined by the application of the earlier compiled list of appropriate **modelling parameters**[1]. They were, among others, seasonal parameters[2], traffic parameters[3,4] and subscriber parameters[2]. Specifically for the EOL phase, recovery and value correction parameters were applied in order to vary the efficiency of recycling strategies[5]. In order to study the environmental consequences related to different EOL strategies, various scenarios were developed comprising or omitting one of the diverse EOL stages (Scharnhorst *et al.*, 2005a, Scharnhorst *et al.*, 2005b).

The life cycle modelling of a mobile phone network was finalised by quantifying the environmental impact and assigning the impact scores to:

- the life cycle phases and the network components,
- the various processes in the life cycle phases of the components,
- the process related emissions and resource consumptions.

The LCA of a mobile phone network was completed by the interpretation of the results, the drawing of conclusions and the formulation of stakeholder recommendations (Scharnhorst *et al.*, 2005d).

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[1] See section 2.1.

[2] in order to vary the power consumptions at different seasons,

[3] in order to vary the power consumptions at different seasons,

[4] in order to vary the load of the network,

[5] More details on the realisation of the life cycle modelling can be found in chapters 4 through 7.

2.4. ***References***

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3. Technical Characterisation of the Studied Objects

In this chapter the studied technologies, i.e. the mobile telephone networks (section 3.1.) and the End-of-Life treatment[1] facilities (section 3.2.), are introduced.
Sections 3.1.1.-3.1.2. contain a detailed characterisation of the design, the architecture and the composition of the GSM and the UMTS mobile phone network technology on the basis of the respective original standard packages as well as of the relevant literature. It also provides information on the communication techniques deployed and the services offered.
The sections 3.2.1.-3.2.3. provide an extensive characterisation of the state-of-the-art End-of-Life treatment technology applied to process electronic scrap of for instance mobile phone networks.

3.1. *Mobile Telephony*

3.1.1. Evolution from Yesterday towards Tomorrow

Within living memory there existed and there exists the wish to communicate, i.e. to transport human information, via distances without being physically at the place of the respective dialogue partner or partners. This kind of information exchange was initially a privilege of kings and emperors and, later on, of senior officials, so is it today a service that is accessible to everyone all the time.
Since the very early days of distant communication, the transmission methods and facilities have evolved drastically and the complexity of the deployed techniques has increased. Today one can principally distinguish two distant communication methods according to the way a message is dispatched by the sender and received by the recipient:

- fixed communication and
- mobile communication.

Mobile communication as such can be seen as a consequential continuation and advancement of the fixed communication method. First efforts to provide what today is understood as *mobile communication* were made in the first part of the past century. Together with the growing economic power in the middle of the 1920ies, the so-called “golden 20ies”, phone calls from moving trains enabled the dispatching and reception of messages independent of the location (Reuter, 1990). However, the following economic depression and the Second World War afterwards saw a deplorable slow down and nearly a break in the evolution of mobile communication technologies and techniques. First with the implementation of the so-called *A-Netz* in Germany in 1958 (Reuter, 1990) and with comparable analogue networks elsewhere in Europe new incentives for the application and evolution of mobile communication standards and services were given. Eleven years later the capacity of the so-called German *B-Netz* (the second generation of national analogue mobile phone networks) was fully utilised (Reuter, 1990). This fact, and the permanently growing request to make mobile communication accessible to everyone, initiated the era of digital mobile communication. One of the first, and presently the most successful, exponents of this particular mobile communication technique is the Global System for Mobile communication[2]. The initial ideas for this standard, in the European region the first standard allowing for truly international mobile telephony, date back to the late 1970s and early 1980s (Hillebrand, 2002). In general, it is based on the analogue

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[1] EOL treatment.
[2] GSM.

Northern Mobile Telecommunication systems (NMT) which has been deployed as a transnational mobile telephone standard in the Scandinavian countries (Sweden, Finland, Norway, Denmark and Iceland) since 1981/82 (Lehenkari and Miettinen, 2002). In contrast to the NMT and many other standards, the GSM standard features the following characteristics (ETSI, 1996a, 1996b, 2000b):

- radio linkage in the 900 and 1800 MHz band respectively,
- channel width of 200 kHz,
- smaller cell coverage (in particular in urban areas),
- reuse of frequencies,
- seamless handover between cells,
- application of Frequency Division Multiple Access/Time Division Multiple Access[1],
- frequency hopping, and
- smaller antenna stations and lighter mobile phones.

At least since the commercial implementation of the first GSM 900 networks[2] in Europe in 1991 (Hillebrand, 2002) mobile communication, and mobile telephony in particular, became affordable for everyone. Up to now more than 500 GSM networks (both GSM 900 and GSM 1800) have been launched world wide (GSMAssociation, 2004). The subscriber numbers, which increase in thousands per second, have now exceeded the number of 1.545 billion people[3] (GSMworld, 2005). Likewise the scale of services provided via mobile phone networks has increased from simple mobile telephony, i.e. transmission of voice, to a multitude of news services, weather forecasts and picture broadcast, etc. (Halonen *et al.*, 2003, Rudolf, 2003, Sanders *et al.*, 2003). However, this increasing spectrum of ever more complex and frequency capacity consuming services required the technical evolution of the limited GSM mobile phone standard. In particular for non-voice data[4] transmission, such as web-browsing and download services, faster data transmission rates were, are, and will be needed. Also, the GSM standard, though developed originally to be applicable globally, is not a real global standard. For instance, in the Latin American and the Central African and the Asian-Pacific region GSM has not become accepted and implemented yet (Coveragemaps.com, 2005). To meet the increased requirements concerning data capacity and in order to provide truly universally harmonised mobile telephony and communication, the Universal Mobile Telecommunication System[5] has been under development since 1985 (Banet *et al.*, 2004, Hillebrand, 2002). The UMTS standard is in principle based on the GSM standard. However, the architecture of a UMTS network differs from that of a GSM network[6] and the communication technique deployed is completely different. The key features of the UMTS standard are (ETSI, 2002c, 2002d):

- air interface operated in the 1900 and 2100 MHz band,
- channel width of 5 MHz,
- cells are small and very small (macro, micro and pico cells),
- no real discrete traffic channel separation, i.e. all subscribers use the same radio frequency,
- application of Code Division Multiple Access[7], and
- non-voice data transfer rates of presently 1980 kbit/s (downlink) and future transfer rates of more than 10 Mbit/s (ETSI, 2003e, 2004, Holma and Toskala, 2004).

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[1] FDMA/TDMA.

[2] That are GSM networks operated in the 900 MHz band.

[3] Tuesday, 11 October 2005, 8:58:13 AM.

[4] If not otherwise explicitly stated, the term “data” means both speech and non-voice data.

[5] UMTS.

[6] GSM networks that do not deploy General Packet Radio Service (GPRS; see chapter 3.1.2.) nor Enhanced Data rates for Global Evolution (EDGE; see chapter 3.1.2.).

[7] CDMA

After a short period of stagnation that followed the rush during the national license auctions, first commercial UMTS networks were rolled out in 2004/05 in Europe. Forecasts on the future evolution of UMTS prognosticate an economic success comparable to that of GSM (Delpho, 2005, Schullitz, 2001).

After this brief introduction to the historical-technical evolution of mobile phone networks, the next section is devoted to the technological and technical characteristics of GSM and UTMS mobile phone networks.

3.1.2. **Design, Infrastructure and Communication Technique of GSM and UMTS Networks**

General

Characteristic for mobile phone networks (also called *cellular networks*) of any standard is that the entire area of a single network is split up into so-called *cells* and *clusters* (Banet *et al.*, 2004, Duque-Antón, 2002, Eberspächer *et al.*, 2001).

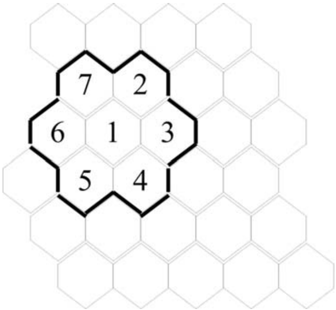

Fig. 3.1: Sketch of the cell structure of modern mobile phone networks and the clustering of cells, typical for 2G mobile phone networks (adopted from (Duque-Antón, 2002) and (Eberspächer *et al.*, 2001)).

A cell is the area that is covered by one single mobile phone network antenna station (ETSI, 1996a, 2003b)[1]. In early mobile phone networks such cells had large radii of tens to a 100 kilometres. Today, cell areas vary from a few meters (micro cells) to less than ten kilometres (macro cells) at maximum (Ofcom, 2005). A particularity is the shape of the cells. The second generation GSM networks have cells that have a fixed size and shape, i.e. the cell sizes are static except in case the network configuration is altered. That allows for a relatively simple planning of the network configuration depending on, for instance, the anticipated number of subscribers and on the power radiation of the antenna. On the other hand, this static configuration leaves relatively little potential for fast adjustment of the network settings to altered conditions, for example increased subscriber traffic. In contrast, in UMTS networks the cell sizes and shapes vary depending on the traffic, i.e. the cells *breath* (Banet *et al.*, 2004, Harris and Noll, 2000). This implies a complex planning of the network configuration but allows for fast and dynamic adjustment of the network settings, for example cell subscriber capacity, to changed conditions.

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[1] In UMTS a cell is defined as that area that is provided with one bearer frequency. For instance, an antenna station that uses three bearer frequencies covers three cells Banet, F.-J., Gärtner, A. and Tessmar, G. (2004): UMTS - Netztechnik, Dienstarchitektur, Evolution *3-8266-5034-4*. Hüthig Telekommunikation: Bonn..

The reduced cell sizes (in comparison with the early analogue mobile phone networks) hold two very interesting technological challenges, namely the reduction of the size of the antenna stations and the re-use of the limited radio frequency capacity at distant antenna stations without interference. Essentially, a defined area of a mobile phone network is covered by a number of antenna stations that all use different radio frequencies. This defined area is called a *cluster* (Fig. 3.1). Outside that area frequencies can be re-used (Eberspächer *et al.*, 2001).

GSM (Phase 2[1,2]*)*

Whereas all mobile phone networks complying with standards before the GSM standard, i.e. all analogue mobile phone standards, are denoted as first generation (1G) networks, mobile phone networks complying with the GSM standard[3] (since Phase 1, which was finally adopted in 1992) belong to the so-called second generation (2G) of mobile phone networks. As its speciality, the GSM standard for the first time envisaged the consequent implementation of small but highly engineered antenna stations arranged in the above described clusters of comb-like cells (Duque-Antón, 2002, Eberspächer *et al.*, 2001, Siegmund, 1999).
The architecture of a mobile phone network, i.e. the number and the arrangement of the single network components as well as the complexity of the broadcast engineering installed in the various components, strongly depends on the selection of the radio transmission technique(s), the access methods and modulation techniques deployed. The latter also determines the data throughput of a mobile phone network, which is one of the most important parameters describing the capacity efficiency of a network.
In GSM a combination of the above mentioned FDMA[4]/TDMA[5] techniques, in association with the Frequency Division Duplex technique,[6] is applied to bridge the air interface between the Mobile Stations[7] and the Base Transceiver Stations[8] (Duque-Antón, 2002, ETSI, 2001b). Using FDD the frequency band assigned to GSM is split up into two frequency bands being separated by 45 MHz. The lower band (890-915 MHz[9]) is used for the uplink[10] and the upper band (935-960 MHz[9]) for the downlink[11] data transfer. A GSM network thus allows a single subscriber simultaneous and continuous transmission and receiving of data. The FDMA technique is used to separate each of the frequency bands into 124 traffic channels of 200 kHz bandwidth per channel (Duque-Antón, 2002). The TDMA method is deployed to assign typically eight time slots, each covering a specified period in the millisecond range, to these traffic channels. One of this time slots is assigned to one mobile phone subscriber and thus a single traffic channel can be shared simultaneously by eight subscribers (Duque-Antón, 2002, ETSI, 1996b). Applying Gaussian Minimum Shift Keying modulation[12] typical data transfer rates achievable in GSM networks range from 2.4 kbit/s to 14.4 kbit/s (Bekkers and Smits, 1997, Schnabel, 2004, Steele *et al.*, 2001)[13]. In networks complying with the original GSM

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[1] GSM networks complying with the ETSI standard packages of the Phase 2 (also known as *Release 1996*) do not deploy GPRS or HSCSD nor EDGE technique.

[2] The GSM network technology that is investigated in this thesis complies with the newer standard package of the so-called Phase 2 (also known under the notation *Release 1996*).

[3] Or any other GSM like standard.

[4] Frequency Division Multiple Access.

[5] Time Division Multiple Access.

[6] FDD.

[7] Mobile Station is standard terminology ETSI (1996a): Digital cellular telecommunications system (Phase 2): Network architecture (GSM 03.02); European Telecommunications Standards Institute, Sophia Antipolis.
, ETSI (1996c): Digital cellular telecommunications system (Phase 2+): Abbreviations and acronyms (GSM 01.04); European Telecommunications Standards Institute, Sophia Antipolis.. For convenience, MS will be termed *mobile phone*.

[8] BTS; see below.

[9] In the 900 MHz band.

[10] From the mobile phones to the BTS.

[11] From the BTS to the mobile phones.

[12] GMSK.

[13] Appendices B1 and B2 and D8 and D9 provide detailed information on the data traffic capacity anticipated for the investigated GSM network/components.

standard (Phase 1 and 2) digital communication techniques are deployed and data[1] are processed circuit switched, sharing the same traffic channels. As a whole, a typical GSM network consists of a fixed switching network part and the subscriber-own mobile stations, better known as *cellular* or *mobile phones* (Fig. 3.2):

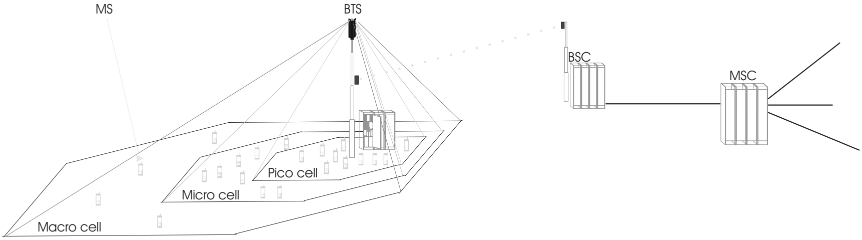

Fig. 3.2: GSM mobile phone network (components and interfaces).

All mobile phones together form the Mobile Sub-System[2]. The switching network part is split into the Base Station Sub-System[3] and the Network Switching Sub-System[4]. To the BSS belong the so-called Base Transceiver Stations[5], that are the antenna stations, and the Base Station Controllers[6], that are switching units which manage a number of BTS. The NSS consists of the Mobile Switching Centre[7]. A special variant of the MSC, the so-called Gateway MSC[8] provides the connection with the fixed networks (Fig. 3.2) (ETSI, 1996a). In the following, the subsystems and the respective major GSM network elements are briefly outlined:

a.) Mobile Sub-System – MSS

All mobile phones are associated with this subsystem. The mobile phones often are not seen as really a part of the mobile phone networks (which in turn is in possession of a single operator) as they physically are located by the subscribers. A single mobile phone consists of a phone device and Subscriber Identity Module[9] card that personalises the mobile phone to the respective subscriber. First the insertion of that card enables the subscriber, depending on his subscriber profile, to make and receive phone calls and to send and receive non-voice data streams. Without that card only emergency calls can be made. The SIM card stores subscriber specific data and provides encryption algorithms for authentication.
The mobile phone itself transforms human voice into signals, transmits them and provides for the re-transformation of received signals into human voice. Additionally, it measures the signal strength of the BTS the mobile phone is attached to and reports the results to that BTS.

b.) Base Station Sub-System – BSS

This subsystem consists of the BTS that are linked to the BSC via either beam radio or via the back bone cable network. Almost all information exchange processes, e.g. radio channel management, radio resource indication, channel encoding, signal strength measurements, hand

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[1] Both, voice and non-voice data.
[2] MSS.
[3] BSS.
[4] NSS.
[5] BTS.
[6] BSC.
[7] MSC.
[8] GMSC.
[9] SIM.

over and data encryption, are initiated, managed and performed in this subsystem (ETSI, 1999).

The BTS represents the outermost of all in a GSM network arranged switching network components. It is that network element which serves one individual cell and the subscriber's own mobile phones are connected to the BTS via radio transmission (ETSI, 1996a). The BTS itself has little or no managing tasks within the BSS but performs most of the signal processing operations. Among others it: receives and transmits the signals to and from the diverse mobile phones, converts the signals from analogue to digital and vice versa, modulates and demodulates and amplifies the signals, and transmits the signals to the switching core network (Tab. 3.1). Depending on the number and arrangement of the attached aerials, a single cell can be partitioned into two or more sectors. A typical BTS (macro cell type) consists of numerous telecommunication aerials mounted on top of a pile (depending on the site also the roof of a high building might be used instead), a cabin, several racks and back-up batteries (Scharnhorst *et al.*, 2005b)[1]. The racks installed at a BTS site form the electronic heart of the BTS. They typically consist of various transceivers (TRX), antenna connection units, amplifiers and other modules (LucentTechnologies, 2000, SiemensAG, 2000, Wilén, 2000)[2]. To provide for redundancy all devices are installed at least twice. Depending on the configuration and the number of the racks installed at a BTS, approximately 96 subscribers can be served at once (assumed that 3 racks are equipped with 12 TRX and 8 channels per TRX).

Fig. 3.4a: Example of a GSM BTS (macro cell) in an urban area (near Winterthur (CH)).

Fig. 3.4b: Example of GSM BTS well-integrated into the landscape by colouring the mast in green (near Winterthur (CH)).

The BSC is that part of a GSM network that executes most of the above addressed managing functionalities within the BSS (Tab. 3.1) (ETSI, 1999, 2000b). Typically up to four BSC racks, equipped with highly engineered switching electronic devices, form a BSC[3]. The switching rack devices comprise among others: multiplexer boards; various exchange terminals; switch boards; and processor units (Enderin *et al.*, 2001, ERICSSON, 2002, 2004). Depending on the configuration between 40 and more than 100 BTSs can be connected to one single BSC rack (ERICSSON, 2002, Nokia, 2000, SiemensAG, 1999, 2003).

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[1] A detailed qualitative and quantitative description of a BTS is compiled in Appendix B1.

[2] Detailed information on BTS racks are compiled in Appendix A1.

[3] A detailed qualitative and quantitative description of a BSC is compiled in Appendix D2.

b.) Network Switching Subsystem – NSS

This subsystem forms the core network part, i.e. the central part of any mobile phone network. It consists of various MSC, GMSC and numerous registers (databases), attached to the MSC. To a MSC at least three, sometimes also four such databases are physically attached:

Home Location Register[1]: subscription specifications, location of the subscriber terminal and terminal status are stored here.
Visiting Location Register[2]: the actual status of the subscriber terminal is stored here.
Equipment Identity Register[3]: the status of the subscriber terminal and identity number is stored here.
Authentication Centre[4]: subscriber rights are stored here and information for data encryption is provided.

To the key tasks associated with this subsystem belong, among others: the terrestrial channel management, the definition of the final call type, the mobility management and the provision of algorithms for data encryption (Tab. 3.1).
The MSC is the core switching element (i.e. the *thinking brain*) of the core network and its special variant, the GMSC provides for the connection with other mobile phone networks and with the fixed networks. A typical MSC consist of numerous server and gateway cabinets[5].

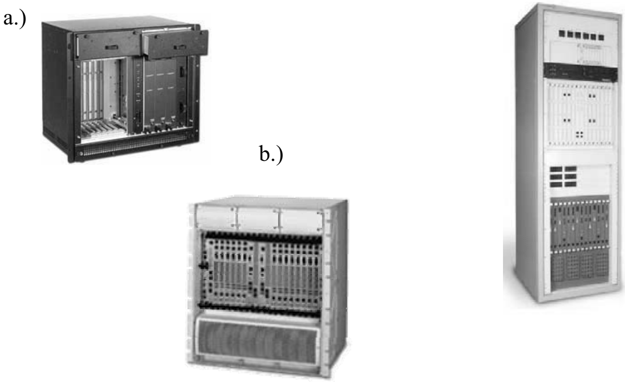

Fig. 3.5: Various cabinets and sub-cabinets installed at an MSC (to the left: Lucent Feature Server (a.) integrated solution, b.) stand-alone solution); to the right: Lucent Flexent Wireless Access Gateway; all pictures provided by courtesy of Lucent Technologies).

Depending on the function, the cabinets contain various servers, different interface modules, gateway units and routers (LucentTechnologies, 2001a, 2003a, 2003b). Commonly, two BSCs are connected to one MSC and one MSC is linked with one GMSC, which in a GSM network is sufficient for an area of approximately one million inhabitants (Bekkers and Smits, 1997). Routing, i.e. the fast switching of voice, data or short messages as well as call-forwarding,

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[1] HLR.
[2] VLR.
[3] EIR.
[4] AuC.
[5] A detailed qualitative and quantitative description of a MSC is compiled in Appendix D3.

call-lock and conference circuits constitute the key tasks of an MSC (Tab. 3.1) (Duque-Antón, 2002).

GSM (Phase 2+[1]: GPRS[2] and EDGE[3])

Modifications of the original GSM standard allowing for faster non-voice data transfer rates and implementing the packet switched data transmission mode belong to the so-called Phase 2+ of the GSM standardisation (also known under the notation *Release 1997* and all subsequent releases (Halonen *et al.*, 2003)).
As a first exponent of this phase, GPRS was introduced in 1995 (Sanders *et al.*, 2003) in order to boost the remote data transfer rates of the GSM networks. Using this service and applying Quadrature Phase Shift Keying modulation[4], non-voice data (e.g. e-mails, Web-documents, etc.) are transmitted at a maximum of 31.2 kbit/s (uplink) and 62.4 kbit/s (downlink) (ETSI, 2001a). Theoretically up to 171.2 kbit/s are possible but not practiced (Rudolf, 2003). The non-voice data are processed packet switched (Ketchum, 1995, Lauer, 1995), which allows for the faster transfer rates. The implementation of the GPRS and, later on, the EDGE technique in the existing GSM networks necessitated the upgrade of those GSM networks with so-called Serving GPRS Support Nodes[5], Gateway GPRS Support Nodes[6] and a few other elements (Halonen *et al.*, 2003). SGSN and GGSN are equipped with racks that typically contain router and server elements (Fig. 3.6) (Lucent, 2004a, 2004b)[7].

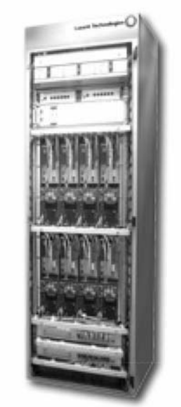

Fig. 3.6: SGSN rack (Flexent Serving GPRS support Node; picture provided by courtesy of Lucent Technologies).

Further information on the modification of the physically underlying GSM network (e.g. additional network components) are compiled in Appendix D8 and can be found in the relevant literature (ETSI, 2000c, 2003c, Halonen *et al.*, 2003, Sanders *et al.*, 2003).
The EDGE 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 sig-

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[1] GSM networks complying with the ETSI standard packages of the Phase 2 (also known as *Release 1996*) do not deploy GPRS or HSCSD nor EDGE technique.

[2] General Packet Radio Service.

[3] Enhanced Data rates for Global Evolution.

[4] QPSK.

[5] SGSN.

[6] GGSN.

[7] Detailed information on SGSN and GGSN racks are compiled in Appendices D6 and D7.

nal modulation scheme (8Level Phase Shift Keying[1]) allows another increase in data transfer rates per each traffic channel (ETSI, 2000d, 2003a). Maximal available data rates up to 192 kbit/s (uplink) and 554 kbit/s (downlink) are theoretically possible (Schnabel, 2004).

Network standard	**GSM**	Function	**UMTS**	Function
Network element	MS	Signal conversion (conversion of … data into discrete signals and vice versa) Signal strength measurement Data encryption	Ue	Signal conversion (conversion of … data into discrete signals and vice versa) Signal strength measurement Data encryption
	BTS	Signal strength measurement Speech coding/decoding Channel coding/decoding Error protection Interleaving	NodeB	Signal strength measurement Channel coding/decoding Signal spreading/despreading Error protection Softer handover Inner loop power control
	BSC	Radio channel management Frequency hopping Internal handover Channel transcoding	RNC	Radio resource management[2] Call admission control Soft handover Ciphering[2]
	MSC	Channel allocation Channel release Data call External handover Mobility management Call control	MSC	Channel allocation Channel release Channel transcoding Handover Mobility management Call control Encryption algorithm supply
			SGSN	Mobility management Session management Packet routing Authentication Encryption
			GGSN	Packet routing Authentication

Tab. 3.1: Key function of the major network components (Banet *et al.*, 2004, Bekkers and Smits, 1997, Eberspächer *et al.*, 2001, Steele *et al.*, 2001).

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[1] 8PSK.

[2] Controlled by the MSC.

UMTS (R'99[1,2])

Mobile phone networks complying with the UMTS standards[3] are termed as third generation (3G) mobile phone networks. UMTS networks, as well as mobile phone networks complying with other 3G standards, belong to the so-called IMT-2000[4] family and represent the consequent technological and technical evolution of mobile telephony (Banet *et al.*, 2004). Like GSM networks, UMTS networks consequently deploy digital communication techniques and the network is cellularly structured. In contrast to GSM networks[5], currently operated commercial UMTS networks represent hybrid networks (Banet, 2005), i.e. they comprise a circuit- and a packet-switched core network part. For the transmission of speech the so-called voice service (Banet, 2005, Banet *et al.*, 2004) at 12.2 kbit/s is deployed and voice data is processed in the circuit switched mode (Banet *et al.*, 2004, Holma and Toskala, 2004). Non-voice data are processed in the packet switched mode. In contrast to the GSM standard, the UMTS standard[6] enables higher data transfer rates (up to 384 kbit/s[7]) (Schnabel, 2004) (Holma and Toskala, 2004). Also, the cells of a UMTS network are not static but alter their size and shape depending on the subscriber traffic. Finally, the arrangement of particular devices within the wired network has been modified compared with GSM networks (Banet *et al.*, 2004).

In principle, and similarly to GSM networks deploying the GPRS or the EDGE technique, the UMTS standard envisages the application of the FDD and the Time Division Duplex[8] techniques. Accordingly, the frequency spectrum assigned to the UMTS standard is separated into 1920-1980 MHz[9] (FDD-uplink), 2110-2170 MHz[9] (FDD-downlink) and into 1900-1920 and 2010-2025 MHz[9] (TDD-up- and -downlink), respectively. However, in presently operated UMTS networks only the FDD technique is utilised (Gärtner, 2005). The peculiarity of the UMTS standard lies in the combination of access methods, FDMA/CDMA (in Europe Wideband-CDMA[10]), that are deployed for the radio transmission, i.e. the signal exchange between the Mobile Equipment[11] and the NodeB. As in GSM networks, the FDMA method is used to partition the above mentioned frequency spectra into traffic channels of 5 MHz each. In contrast to the TDMA method the simultaneously applied CDMA method does not foresee any discrete channel separation. Instead, all subscribers use the same frequency spectrum and a unit wideband signal is generated out of the diverse narrowband subscriber signals and is transmitted through the network. Subscriber specific codes are used in order to differentiate the respective user signals. Applying QPSK allows for the high data transfer rates mentioned above. Further on, increased rates will be achieved by applying 16Quadrature Amplitude Modulation[12] (Banet *et al.*, 2004, Holma and Toskala, 2004).

Like a GSM network a typical UMTS network consists of a switching network part and the subscriber own mobile stations and data access cards (which are plugged into e.g. notebooks) (Fig. 3.7):

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[1] The first UMTS networks commercially operated in Europe operated according to the 3GPP/ETSI standard package *Release 1999* (denoted as R'99).

[2] The UMTS network technology that is analysed in this thesis complies with the basic standard package known under the notation *Release 1999* (R'99).

[3] Or any other standards comparable to UMTS and other than 1G and 2G standards.

[4] International Mobile Telecommunications-2000.

[5] GSM network that do not deploy GPRS or EDGE.

[6] UMTS (R'99) networks.

[7] The first commercially operated UMTS networks in Europe deploy only the FDD-mode. This mode limits the data transfer rate to 384 kbit/s.

[8] TDD.

[9] The FDD and TDD frequencies apply only for Europe TOPBusinessInteractive (2002): UMTS Basics - die Grundkonzepte des Universal Mobile Telecommunication System *3-935340-23-0*. J. Schlembach Fachveralg: Weil der Stadt..

[10] W-CDMA.

[11] ME is standard terminology ETSI (2000a): Digital cellular telecommunications system (Phase 2+): Abbreviations and acronyms (GSM 01.04 version 8.0.0 release 1999); European Telecommunications Standards Institute, Sophia Antipolis.. For convenience, ME will be termed *mobile phone*.

[12] 16QAM.

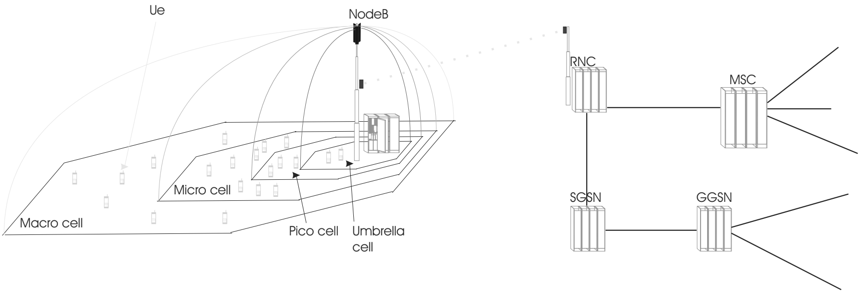

Fig. 3.7: UMTS mobile phone network (components and interfaces).

Like the GSM standard, the UMTS standard envisages the allocation of the individual network components to subsystems (Fig. 3.7). The Mobile Sub-System[1] comprises all User equipment[2]. The switching network part is divided into the Radio Network Subsystem[3] and the Core Network[4]. The RNS consists of the NodeB[5] and Radio Network Controller[6]. According to the switching modes, the CN is divided into the so-called Circuit Switched Domain[7] and the Packet Switched Domain[8] (ETSI, 2002c). Whereas the CSD consists of the earlier described MSC and GMSC, the PSD comprises the SGSN and the GGSN. Below, the subsystems and the respective major UMTS network elements are described:

a.) Radio Network Subsystem – RNS

This part of a UMTS network consists of the NodeB that are connected with the RNC via direct beam radio or via the back bone cable network. Similar to a GSM network, most of the network switching tasks are allocated to this subsystem (ETSI, 2002a). The RNC additionally serves as a switch separating the non-voice data that are processed packet switched from the voice data that are processed circuit switched (AdLink, 2004).
The NodeB, like the BTS, represent the outermost elements of a UMTS network and the subscriber’s own mobile phones and data cards[9] are connected to the NodeB via the air interface. The service area of a NodeB can be divided into numerous sectors, which are defined by the orientation of the NodeB aerials. Within each sector different bearer frequencies can be deployed, which in turn form the cells (Banet *et al.*, 2004). Like a BTS, a typical NodeB consists of numerous telecommunication aerials mounted on top of a pile, a cabinet, several racks (depending on the size of the station) and numerous back-up batteries[10]. A characteristic NodeB rack contains, among other items, a number of exchange terminals, amplifiers and antenna connections units (LucentTechnologies, 2004b, SiemensAG, 2001)[11]. Depending on the size of the NodeB rack and its configuration, up to 700 subscribers simultaneously can be served with voice transmission (LucentTechnologies, 2004b). The above mentioned peak data transmission rates are typically provided per bearer frequency and assigned to one single user

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[1] MSS.
[2] ME; equivalent to the MS in GSM networks.
[3] RNS.
[4] CN.
[5] NodeB; equivalent to the BTS in a GSM network.
[6] RNC; equivalent to the BSC.
[7] CSD.
[8] PSD.
[9] That are cards which are plugged into e.g. Notebooks.
[10] A detailed qualitative and quantitative description of a NodeB is compiled in Appendix D8.
[11] Detailed information on NodeB racks are compiled in Appendix D4.

(Gärtner, 2005). Modifications of the NodeB with amplifiers, additional sectoring and installation of aerials can increase the data throughput shareable by numerous users (Holma and Toskala, 2004, Niemelä and Lempiäinen, 2003, Wacker *et al.*, 1999). Differences between the BTS and the NodeB mainly concern differences in the functionality and the engineering assembly (Tab. 3.1).

The RNC is the managing part of the UMTS network. It performs most of the initiating, switching and controlling tasks that occur in the RNS (Banet *et al.*, 2004, ETSI, 2002b). Depending on the network configuration, between 180 and up to 750 NodeBs can be supported by a single RNC cabinet (LucentTechnologies, 2001b, 2004a). A representative RNC cabinet consists of a number of electronic components such as: timing units; exchange terminals; and various processor and extension boards (Gestner and Persson, 2002, LucentTechnologies, 2001b).

Fig. 3.8: NodeB rack (Lucent Macrocell Indoor; picture provided by courtesy of Lucent Technologies).

b.) Core Network – CN

As mentioned above, this subsystem of a UMTS network is divided into the CSD and the PSD. The elements of the CSD are the same as for the NSS of a GSM network, namely: MSC, VLR, HLR, EIR and AuC (Banet *et al.*, 2004). In the PSD the SGSN and the GGSN of the GPRS backbone are integrated[1]. The elements of the CSD also have the same tasks as in the NSS of a GSM network, namely the voice-data transmission, i.e. telephony, and the management of subscriber data. In the PSD non-voice data are processed (Tab. 3.1).

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[1] A detailed qualitative and quantitative description of the elements of the CS- and the PS-domain is compiled in Appendix D8.

UMTS (R'04 and R'06[1])

A first substantial modification of the original UMTS standard represents the implementation of the standard package *Release 2004*[2]. This package indicates an evolution towards: *i.)* packet switched voice data transmission and *ii.)* the implementation of the TDD mode for high-speed non-voice data transfer (Banet, 2005, ETSI, 2003d, 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). Though optionally available, it is assumed that networks complying with these standard packages still perform voice transmission in the circuit switched mode.

The most recently adopted standardisation package *Release 2006*[3] (ETSI, 2005) in particular aims at the further increase of data transfer rates using High Speed Downlink Packet Access[4] and High Speed Uplink Packet Access[5] (ETSI, 2003e, 2004). By application of the 16QAM modulation technique, uplink data transfer rates up to 5800 kbit/s (Ihlenfeld, 2005) and downlink rates up to 14400 kbit/s are envisaged (ETSI, 2001c). This standard package concentrates on the simultaneous packet switched processing of voice data and non-voice data (All-IP) (Holma and Toskala, 2004).

3.2. *End-of-Life Treatment Technologies*

At some point in the service life of an electronic device, such as a mobile phone or an antenna rack, its useful lifetime will come to an end due to damage, technical or technological incompatibility or for other reasons. The electronic devices then no longer provide the operational services they were originally designed for, but they still represent a significant pool of secondary raw materials and energy resources. In order to benefit from these resources and to conserve the natural resources, electronic scrap is processed and secondary raw materials and energy are recovered. All End-of-Life treatment[6] strategies and technologies analysed in this thesis project comply with the regulations valid in Western Europe. Present state-of-the-art EOL technology as applied to electronic scrap consists of mechanical and thermal processing steps. Residuals which cannot be further processed from an ecological or economic point of view are made inert by means of incineration and finally disposed of in appropriate landfill sites (Scharnhorst *et al.*, 2005b).

The following sections are devoted to the description of the three major EOL treatment steps: fractionation; thermal material and energy recovery; and thermal inertisation and final landfill.

3.2.1. **Fractionation**

The electronic scrap of mobile phone networks represents a highly, and mostly unknown, complex mixture of devices, materials and substances. The complexity increases as this scrap is collected together with other electric and electronic scrap. In order to properly direct the various scrap streams depending on their material contents, fractionation is applied. Outputs of this stage are more or less accurately separated material fractions.

---

[1] The first UMTS networks commercially operated in Europe operated correspond to the 3GPP/ETSI standard package *Release 1999* (R'99).

[2] Denoted as (R'04).

[3] Denoted as (R'06).

[4] HSDPA.

[5] HSUPA.

[6] EOL treatment.

Below, the fractionation strategy, as applied in Switzerland and as adopted in the performed life cycle studies of mobile phone equipment, (Scharnhorst *et al.*, 2005a, Scharnhorst *et al.*, 2005b) is presented (Fig. 3.9).

After the reception of the scrap, weighing and documentation, the scrap is pre-separated manually according to defined device categories[1]. Subsequently, larger electronic components of mobile phone networks, such as antenna racks, are pre-disassembled. This includes the removal of the frames and magazines, and partly of large electronic sub-components, for example servers. The pre-disassembled electronic components are then further disassembled in a semi-manual step. This includes the removal of batteries and large glass parts and the collection of the residuary electronic components such as Printed Wiring Board Assemblies[2], housings, cables, etc. With this step the manual work is finished and the scrap is processed mechanically. In a first mechanical step the electronic scrap is crushed in a cross-flow separator (BückmannGmbH, 2001c). The output is a gross-granular mixture of metals, ceramics and plastics. It may also contain battery residuals. These residuals need to be removed by hand. After the crushing the scrap mixture is separated magnetically and most of the ferrous metal content is removed. The remaining scrap comprises then non-ferrous metals, plastics and ceramics. Using a cut mill the scrap is crushed into a fine grained mass. Thereafter a standard cone sifter provides for the separation of that scrap into light and heavy non-ferrous metal, plastic and ceramic parts depending on the specific material density (BückmannGmbH, 2001b). Finally, a sedimentation table is used in order to separate the residual fine particles by means of air flow and depending on differences in the specific material densities (BückmannGmbH, 2001a). Light metal matrices, for example aluminium, are then further processed in e.g. aluminium remelters. Iron and steel materials are delivered to steel remelters. Heavy metal and precious metal matrices finally are processed in specialised thermal metal recovery plants (see section 3.2.2.) (Scharnhorst *et al.*, 2005b). In contrast, plastic materials or their base materials are not (or only to a limited extent) recycled (Ludwig *et al.*, 2005). Instead, plastics are mostly incinerated and the energy content is, where possible, recovered.

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[1] For example *white goods* (e.g. refrigerators), *brown goods* (TV-sets), etc.

[2] PWBA.

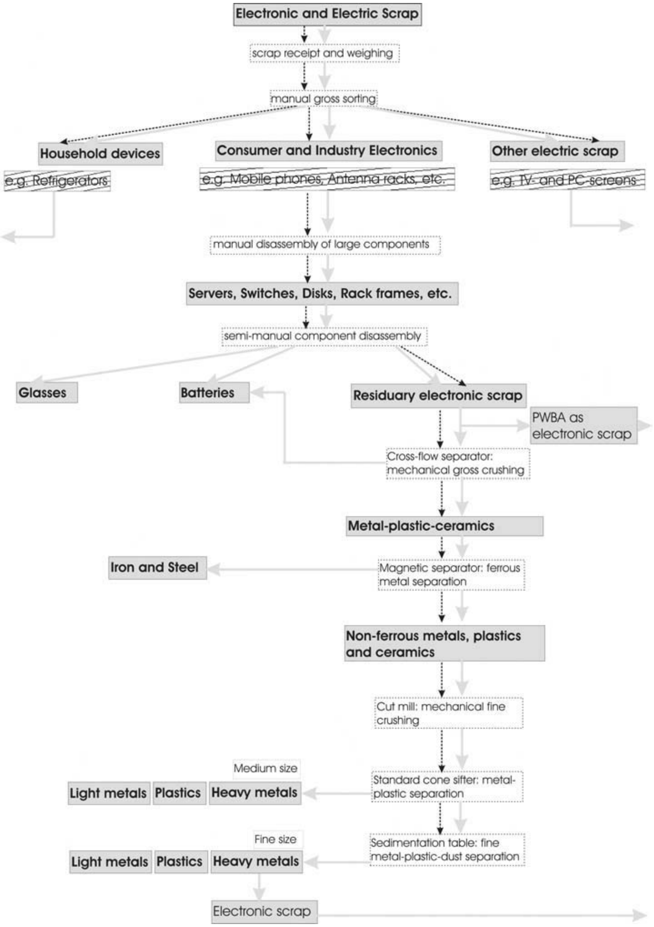

Fig. 3.9: Flowchart of electronic scrap separation (Ludwig *et al.*, 2003, Stengele, 2004). If no fractionation is applied, then entire PWBAs leave the system and are processed in the thermal EOL treatment facilities. If fractionation is applied, heavy metals (which are precious metals) leave the system and are processed for refinement in the thermal EOL treatment facilities.

3.2.2. Thermal Material and Energy Recovery

Either entire non-disassembled electronic devices or the material fractions extracted in the mechanical pre-treatment are processed in specifically equipped thermal EOL treatment facilities (BOLIDEN, 2002, VATech, 2002). Common goals of all of the applied thermal methods is the recovery of precious materials, such as gold, silver, palladium, lead, etc., and the reduction of the amount of electronic scrap as requested by European regulations (CEC, 2003), that, if not treated, would be disposed of in landfills. In the following sections these EOL treatment methods are outlined, based on which the studies investigating the environmental performance of a single BTS rack (Scharnhorst *et al.*, 2005b) and of a GSM network (Scharnhorst *et al.*, 2005a) were performed.

Material Recovery from PWBAs

PWBAs represent that part of electronic components that contains most of the recoverable energy content and most of the recoverable precious materials[1]. Sound treatment is required in order to recover for example copper, gold, silver, tin, palladium, etc. Among others the following companies in Europe operate such facilities and realise good recovery rates:

BOLIDEN (Sweden),
UMICORE (Belgium),
Siemens-VAI (Austria).

In the studies on the environmental performance of a BTS rack (Scharnhorst *et al.*, 2005b), a GSM network (Scharnhorst *et al.*, 2005a) and a GSM and a UMTS network (Scharnhorst *et al.*, 2005c) the BOLIDEN strategy, applied at the Rönneskär smelter site, was adopted and modelled in order to represent European conditions.
The entire BOLIDEN industry complex at Rönneskär consists of a number of sub-facilities each specialised for a certain process step (Fig. 3.10):

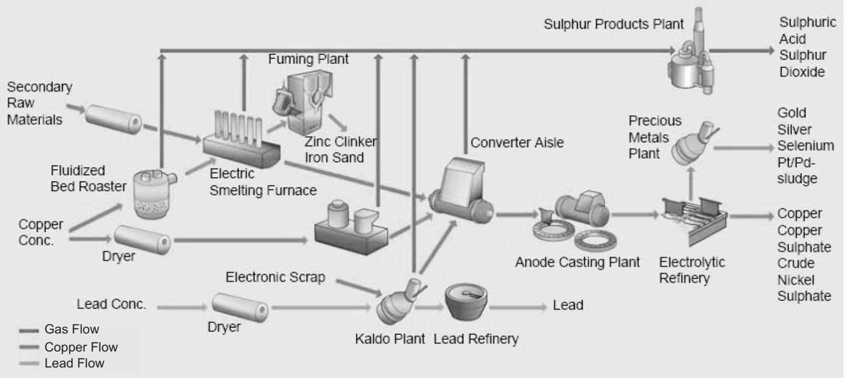

Fig. 3.10: Flowchart of the Rönneskär smelter complex (adopted from (HELCOM, 2002)).

The largest part of the smelter complex is used to produce primary copper and sulphur products. Based on technical modifications in the 1980s-90s, the production of secondary precious raw materials was integrated. According to the applied process technology the incoming electronic scrap (primarily scrapped PWBA) is first of all separated from the rest of the scrap. In a first treatment step the electronic scrap is then processed in the so-called *Kaldo Plant*. This is a furnace, which is used for both the processing of lead from concentrated ore and, in particular, the smelting of electronic scrap (BOLIDEN, 2002, Mark and Lehner, 2002). The Kaldo furnace is a large-scale smelting unit which is operated discontinuously. The electronic scrap is filled (furnace is then out of smelt operation) by front-end loaders. Afterwards the furnace is tilted back to its operational position and under the initial addition of oil (added in order to start the thermal treatment) and the continuous addition of oxygen, the scrap is melted (Mark and Lehner, 2002). In the further course of the process, the energy content of the plastic scrap parts is used in order to keep the smelting process running (Kindesjö, 2002). Off-gases (SO_2) are collected and processed in the sulphur product plant and the slag is treated in the concentrator plant (Mark and Lehner, 2002). A key industrial product of this process is so-called

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[1] A detailed qualitative and quantitative inventory of a PWB typically deployed in GSM BTS racks is compiled in chapter 5.4.

black copper. This copper contains large impurities such as precious metals (Perez-Tello *et al.*, 2004). In order to refine pure copper and to separate the precious metals, the black copper is processed in the *Converter Aisle* plant. This conversion step is based in principle on the Peirce-Smith Converter technology (Davenport *et al.*, 2002). Black copper (matte) is melted in a large refractory lined and steel covered furnace and impurities (in particular Fe, S) are removed by blasting air and oxygen into the molten matte via submerged tuyeres. The impurities are either vaporised or retained in the slag. The latter (containing among others Fe and Zn) is processed in the electric smelting furnace. The SO_2-containing off-gas is collected in a water-cooled steel hood and is then transferred to the sulphur products plant (BOLIDEN, 2002, Davenport *et al.*, 2002). The converted blister copper (containing 97% copper) is subsequently processed in the *Anode Casting Plant*. In this step the hot liquid blister-copper is poured from an anode furnace into flat copper moulds. These moulds are arranged circularly, forming a wheel around the anode furnace (Davenport *et al.*, 2002). In case of the BOLIDEN plant two wheels are simultaneously fed with liquid anode copper from the anode furnace (Isaakson and Lehner, 2000). Using liquid ammonium the copper is deoxidised and SO_2 is stripped off by means of air-oxygen (Davenport *et al.*, 2002). Thereafter the cast anode copper is processed in the downstream *Electrolytic Refinery* plant, where it is converted into cathode copper. The infrastructure of such a plant comprises large water filled basins in which anodes (copper) and cathodes (typically steel sheets) are immersed. The process is put in operation by applying voltage and closing the circuit between the anodes and cathodes. Key product of this process is the extraction pure copper (less than 20 ppm impurities (Robinson, 2002)). As a by-product a slime containing precious metals (i.e. the copper impurities) such as Ag, Au, Pb, Se, etc. is collected (BOLIDEN, 2002, Robinson, 2002). Finally, this slime is processed in the *Precious Metal Plant*, thus ending the BOLIDEN treatment process. In a hydrometallurgical process and by adding a solvent, the anode slime is dissolved in water and H_2SO_4 (Jenkins, 2002, Salomon-de-Friedberg, 2002) and precious metals and other impurities are high-pressure leached (BOLIDEN, 2002, Ludvigsson and Larsson, 2003). Subsequently, copper telluride and nickel sulphate is recovered from the solvent and the leached residuals are dried. In the next step, the residuals are melted in another furnace and selenium is recovered and silver is converted. This silver is then cast into silver anodes and pure silver is obtained by processing the silver anodes in a subsequent electrolytic refinery process. As a by-product, gold containing slime is accumulated which is finally leached using wet chemical-chlorination method and pure gold and palladium/platinum sludges are precipitated (BOLIDEN, 2002, Isaakson and Lehner, 2000).

Material Recovery from Mobile Station Rechargeable Batteries

Batteries of mobile phones (Nickel-Cadmium[1], Nickel-Metal-hydride[2], Lithium-Ion[3]) are problematic to process. Only a few companies in Europe have specialised in the EOL treatment of these mobile phone components. Below, the processing technology, as applied by the Swiss BATREC (Wimmis) to rechargeable mobile phone batteries, is outlined. Based on this technology the EOL treatment of mobile phone batteries was modelled in the performed life cycle investigations in order to represent European conditions (Scharnhorst *et al.*, 2005a, Scharnhorst *et al.*, 2005b, Scharnhorst *et al.*, 2005c).

The entire BATREC facility consist of one furnace complex, two waste water treatment stages, one exhaust gas treatment unit and a mercury precipitation stage (Fig. 3.11) (BATREC, 2004). All types of batteries can be processed in the BATREC facility. Nickel,

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[1] NiCd.

[2] NiMh.

[3] LiIo.

cadmium, mercury, iron, manganese and zinc are the main products regained at the BATREC site (BATREC, 2003).

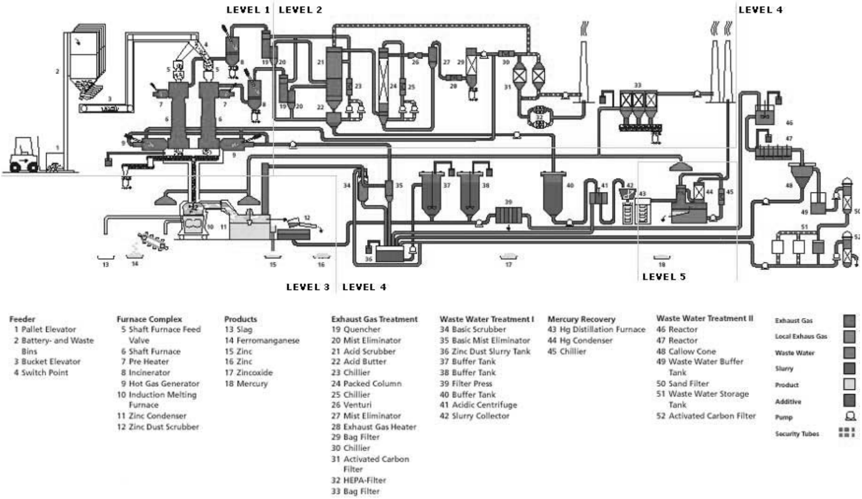

Fig. 3.11: Flow chart of the BATREC facility (adopted from (BATREC, 2004)).

In the facility the treatment of battery scrap is separated into four major stages. The first stage comprises the battery scrap intake, the manual battery separation into large containers and the storage in a warehouse. Lead rechargeable batteries are separated from the other batteries and stored to be processed elsewhere. In the next stage, the battery containers are weighed and the content is documented. In the third stage, the actual thermal material recovery of the batteries takes place and the separated batteries are fed into the shaft furnace. There the battery scrap is pyrolised and water and mercury is vaporised. Together with carbonised organic matter the water and mercury vapour is passed over to the afterburners where dioxins and furans are destroyed at high temperatures. The exhaust gas is then water-cooled and processed in the exhaust gas treatment unit and diverse filter facilities[1] are applied to retain hazardous substances (BATREC, 2004). The non-vaporised battery components leave the shaft furnace and are melted in a refractory lined induction furnace at about 1500°C (BATREC, 2003). Ferromanganese remains liquid in the furnace bowl and is poured off. Zinc is vaporised and is recovered in the zinc condenser. The furnace complex is operated continuously for up to twelve weeks. Then the refractory needs to be removed (BATREC, 2003).

In the final processing step the accumulated waste water is purified in the waste water treatment stage and cyanide, fluoride and other heavy metals are separated. The solid residues are returned to the pyrolysis process and the treated waste water is led into the sewage system.

Material Recovery from Base Transceiver Station Back-up Batteries

Back-up batteries of antenna stations mostly are lead rechargeable batteries. As in the case of mobile phone batteries, the back-up batteries are difficult to process. However, the recovery of lead is useful and promising technologies have been developed. In the studies performed in conjunction with this thesis, the so-called QSL technology (deployed by the Berzelius

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[1] For instance, active carbon filter, tube filter, high-efficiency particulate air filters.

Stolberg GmbH), was adopted to model the EOL processing of the back-up batteries. Below, the QSL-technology is described.

The entire Stolberg complex comprises various interlinked facilities, namely: a mixing facility, the QSL-reactor and filters and a pre-de-coppering unit, a de-heating vessel, a hot gas EGR[1] and a wet gas EGR[1] section, a cadmium plant, a de-arsening unit and a H_2SO_4-plant. The complex is completed by a power station. With the exception of process breaks for service and inspection, all facilities are operated continuously. The core unit of the plant is the QSL-reactor. This is a large, (length = 33.0 m, ∅ = 3.0-3.5 m) horizontally aligned reactor made of stainless steel and lined with refractory material (chrome-magnesia). The reactor is separated into two zones: an oxidation zone and a reduction zone. In a first step, the lead containing battery scrap is fed into the oxidation zone of the reactor and other materials (water, fuel oil, air, oxygen, coal dust, raw gas, pressure air and coal) are added. At temperatures of 1200°C the scrap is melted. The slight tilt of the reactor enables the flow of the liquid matter from the oxidation to the reduction zone. In this area of the reactor lead sediments on the bottom of the reactor. The slag of the QSL-reactor is poured off at this stage. The addition of coal dust and air leads to the formation of metallic lead which is then poured off and subsequently processed in the de-coppering unit. Finally the lead is cast and ready for use. The recycling of lead is associated with the production of large amounts of hot SO_2-containing off-gas that must be treated (Berzelius, 2005).

The SO_2-gas contains significant amounts of dust, arsenic and cadmium. In order to purify the gas and to recover energy and valuable materials, the hot off-gas is first led over a de-heating unit equipped with large metallic plates and the temperature is cooled down from more than 1200°C to 370°C. Overheated steam is produced and off-gas dust is retained in the hot gas EGR. The dust is returned to the QSL-reactor. The steam is directed to a power station where the thermal energy is converted into electrical energy.

In order to retain cadmium, the cooled off-gas is then conveyed via a flue dust filter and cadmium dust is separated (Anonymous, 2003, Berzelius, 1993). The cadmium dust is subsequently processed in the cadmium plant. H_2SO_4 (<20%) is added and cadmium and zinc are deposited and separated from the liquid residuals.

After the hot gas EGR, the off-gas is processed in the de-arsening unit. By flowing the off-gas via another plate cooling unit, the gas is further cooled down from about 400°C to 70°C. At this temperature, As_2O_3 condenses nearly completely. The remaining arsenic content is mixed with a solvent and processed in a graphite heat exchanger. There the residual arsenic is crystallised as As_2O_3. Finally the As_2O_3 is packed.

The off-gas is then stripped over the wet gas EGR and fine particles are retained (Seiler, 2005). The QSL-treatment is completed by processing the off-gas in the H_2SO_4-plant. There the off-gas is dried by trickling it in a drying tower. A wire-mesh filter at the lower outlet of the tower retains acid droplets. Thereafter, the dry SO_2-gas is blown into a contact oven where it is heated to 440°C and SO_3 is formed. Finally the SO_3-gas is passed over to an end absorber and there H_2SO_4 is produced by the addition of water (Berzelius, 1993).

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[1] Exhaust Gas Recirculation.

3.2.3. **Thermal Inertisation and Final Disposal**

Materials that cannot be processed with the common state-of-the-art EOL treatment technologies need to be reduced to sterile ash or glassy residuals by means of incineration in Municipal Solid Waste Incineration[1] plants (Bundesrat der Schweiz, 1991, CEC, 2000). The incineration of the materials that cannot be processed provides for inertisation with respect to the mobility of eventually environmentally harmful substances or elements contained in the residuals. As a well-accepted by-product, energy is recovered and fed back into industrial systems. Following the incineration step, the ashes are subsequently dumped in an appropriate landfill site.
In the subsequent sections the typical MSWI and landfill technologies, as adopted to model the respective steps in the life cycle assessment of the mobile phone network equipment, are outlined.

Thermal Inertisation of Electronic Residuals

Modern conventional MSWI plants[2] (so-called grate incinerators) consist of one or more large combustion units that are partitioned into a primary and a secondary combustion chamber (Li *et al.*, 2004, Hellweg, 2000, Sakai and Hiraoka, 2000). Numerous consecutively arranged filter units are switched after the combustion chamber, as well as diverse ash retention facilities. An energy conversion section, i.e. one or more generators, complements the MSWI plant (Fig. 3.12).

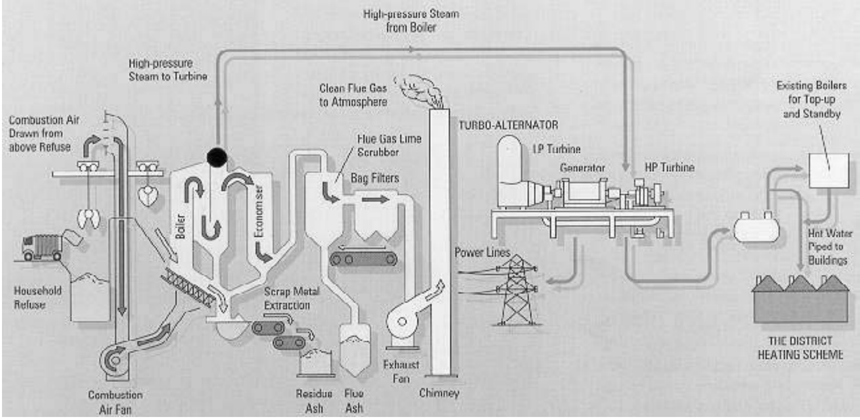

Fig. 3.12: Schematic sketch of a modern MSWI plant (adopted from (CEC, 2002)).

The delivered electronic scrap is initially collected and discontinuously fed into a combustion chamber. There are a multitude of furnace technologies available, but the most common are the fluidised bed and rotary kiln technology (Gibson, 1977, Ottoboni *et al.*, 1998). In any case, the combustion chambers are operated under oxidising conditions, i.e. at oxygen surplus. The furnaces are typically operated between 900-1200°C (Galli and Jorgensen, 2005, Morselli *et al.*, 1993) and auxiliaries such as fuel and sand are added (USEPA, 2000). The remaining grate ash is separated from metallic residues that have not melted during incinera-

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[1] MSWI.

[2] In the presented thesis environmental data on conventional grate incineration technology were adopted to model that EOL step.

tion and is retained in containers. The combustion chamber is connected with a set of turbines that drive one or more generators and electrical energy is generated. The dispersed furnace dust[1] is processed in various filter units, e.g. hot gas EGR, wet gas EGR, etc. (Doka, 2003a). There, non-metallic particles and volatile metal complexes are retained. Finally the cleaned air is exhausted via a mostly towering chimney.

Landfilling of Slag

Depending on the environmental relevance, MSWI residuals are landfilled in various dumps that comply with the governmental regulations for the specific ashes. Typically, sealed overground deposits equipped with a drainage system are used to landfill MSWI ashes[2]. In order to protect against leaching and re-mobilisation, the ashes have to be solidified with cement. When closing the dump, the site will be monitored for at least ten years afterwards (Doka, 2003b).

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[1] Fly ash.

[2] Environmental data on such residual landfill sites have been used to model that EOL step in the presented thesis.

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4. *Network Component Study*: Environmental assessment of End-of-Life treatment options for a GSM 900 antenna rack[1]

4.1. *Introduction*

Since the implementation of the innovative second generation[2] of mobile telephone standards in the early 1990's cellular, mobile phone technology became a steadily increasing and rapidly evolving mobile communication technology. Initially, only a few 2G networks in few countries were operated covering main roads, main places and other "hot spots" of mobile communication traffic. Today the number of 2G networks exceeds 620 in nearly 200 countries worldwide (GSMAssociation, 2004).

Linked to the increasing numbers of networks is a substantial rise of network components, in particular of antenna stations. For example more than 6350 antenna stations were operated in Switzerland in 2002 (Rothus, 2002) and the tendency is growing. According to recent prognoses the implementation of third generation[3] mobile telephone networks necessitates a 30% higher amount of antenna sites (Hugentobler, 2000).

Tightly associated with the above outlined trends is a growth in the number of network components that need to be replaced. This is due to the fact that they either do not longer provide sufficient subscriber capacity or they have reached their physical End-of-Life[4] or the components do not longer fulfil the technological standards.

During the past years adverse environmental implications caused by treated network component materials as well as inadequate EOL treatment were increasingly recognised by national governmental authorities, manufacturers, recyclers as well as by the broad public. Restrictive regulations seek to prevent the dumping of valuable electronic scrap and aim to ensure increased recycling rates of electronic devices (CEC, 2003b). Supporting regulations prohibit the usage of numerous materials assessed to be environmentally toxic (CEC, 2003a, 2003b). To meet the requirements of the regulations the manufacturers of mobile telephone network equipment have endeavoured to replace environmentally critical materials and recyclers have constantly updated the EOL treatment strategies. However, several problems remain:

a) Regulations on environmental safe EOL treatment methods are not consistent world wide.
b) To date environmental impacts related to the EOL treatment of mobile phone network scrap have not been quantified in a life cycle perspective.
c) Likewise impacts of EOL treatment scenarios for single network components have not been quantified in detail.

A few studies were carried out on the entire life cycle of end user network components (RANDA-GROUP, 2000). For single network element devices, e.g. transceiver units built in antenna racks, some EOL scenarios were investigated in general (Furuhjelm *et al.*, Grunewald and Gustavsson, 1999). The importance of the EOL phase of a network component compared with other life cycle stages has been demonstrated by Tanskanen *et al.* (Tanskanen and Takala, 2001). However, most studies lack a sound examination of the EOL phase analysing emissions, emission paths and emission sources in detail.

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[1] This chapter is based on the paper: Scharnhorst, W., Althaus, H.-J., Hilty, L. and Jolliet, O. (2005): Environmental assessment of End-of-Life treatment options for an GSM 900 antenna rack. International Journal of Life Cycle Assessment; **online first**.

[2] 2G.

[3] 3G.

[4] EOL.

In the study presented here, the environmental performance of a generic antenna rack, as it is deployed in Base Transceiver Stations[1] complying with the Global System for Mobile communication standard[2], was analysed. Treatment scenarios varying from direct disposal excluding any kind of EOL treatment to current state-of-the-art EOL treatment strategy were developed. To assess the environmental impacts the IMPACT2002+ method (Jolliet *et al.*, 2003) was applied.

This paper compiles the results for a representative GSM antenna rack and compares the different EOL scenarios. In particular it aims at addressing the following questions:

- Which of the EOL scenarios represents the preferable alternative?
- Which stage within the EOL phase contributes dominantly to the overall environmental impact in the entire EOL phase, and why?
- Does the rack contain materials posing a distinguished environmental risk during the EOL phase?

The paper is structured according to the ISO14040 series (ISO, 1998) into goal and scope definition, inventory, impact assessment and interpretation and is finished by a discussion and recommendations to concerned actors.

4.2. *Method, Goal and Scope*

4.2.1. Study Objective

The goal of the study reported here is the

- identification of an environmentally preferably combination of currently used EOL treatment processes for a generic antenna rack, and the
- determination of environmentally critical EOL treatment processes and materials causing critical impacts in these processes.

The study was carried out applying the Life Cycle Assessment[3] method. The results are intended to provide in-depth knowledge on the environmental consequences related to the processing of mobile phone network scrap. The outcome is also meant to support the decision making of network operators, network component manufacturers as well as recyclers.

4.2.2. System Description

Functional Unit and Reference Flow The treatment of one representative GSM 900 antenna rack in the EOL phase was selected as functional unit. One antenna rack to be treated represents the reference flow. In further studies, these results could also be integrated in the overall assessment of a network, defining the required number of rack per network functional unit (e.g. per served customer or per transferred Megabit[4]).

Data Requirements The data for the background system (infrastructure data, primary material production data, etc.) comply with the requirements set for the ecoinvent-database (Frischknecht *et al.*, 2004). For the collection of foreground system data (EOL processing data, technical rack specifications) the following requirements are set:

- representative for Western-Europe and
- representative for the past five years (in case of EOL process data) and for the period between 1999 through 2004 (in case of rack specific data[5]) respectively.

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[1] BTS.

[2] GSM.

[3] LCA.

[4] Mbit.

[5] The adopted rack data had to meet the specifications set in the GSM standards as outlined in chapter 3.

For validation purposes EOL treatment data of similar processing steps are compared with each other. Likewise the technical data compiled for the investigated antenna rack are compared with existing rack types. If EOL treatment data are missing approximations based on closely related process data are used.

System boundaries and System Expansion The investigated system comprises all EOL treatment stages applied to a representative antenna rack. The EOL phase of a rack begins with the dismounting of the rack and ends with the production of secondary materials and the final disposal (incineration and landfilling) of waste products (Fig. 4.1). System expansion, i.e. the inclusion of the production phase for all antenna rack materials, was applied to the modelled EOL phase[1]. In conformity with ongoing ISO practices, the use phase was assumed to be equal in each of the developed EOL treatment scenarios and thus was not modelled (Fig. 4.1).

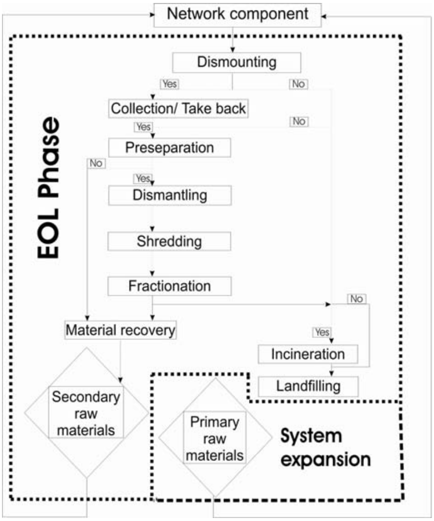

Fig. 4.1: Flow chart and system boundaries of the EOL phase of the antenna rack (dotted line) and system expansion (dashed line).

Cut-off The cut-off rules as applied in Swiss ecoinvent-database are adopted for the background system (Frischknecht *et al.*, 2004). Thermal energy, generated in the incineration processes, was not considered to substitute primary energy generation consumed in the base material production phase. Minor material losses occurring in the EOL treatment of the rack (the foreground system) are inventoried, but no subsequent processing was carried out.

Allocation The background system (for example the materials of the EOL infrastructure) was modelled based on the Swiss ecoinvent-Database and the allocation principles applied in ecoinvent were adopted to the background system.

Allocation based on physical properties (Ekvall and Finnveden, 2001) is applied to the foreground system infrastructure (for example shredder use is allocated to mass of treated scrap).

Further allocation has been avoided by applying system expansion and by modelling the system as closed-loop, i.e. all recovered materials are recycled and again used in the production phase of the BTS rack.

Impact Assessment The IMPACT2002+ method (Jolliet *et al.*, 2003) is used to determine the environmental impacts related to the emissions released and the resources consumed by the

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[1] The rack assembly was not included.

studied system. The method links emissions and resource consumptions compiled in the life cycle inventory to so called midpoint categories representing the environmental impacts as effect scores of various reference substances. These scores are linked to damage categories representing the impacts on human health, ecosystem quality, climate change and resources respectively (Humbert *et al.*, 2004). To discuss the individual environmental impact categories in detail, and to cross-compare the shares of the individual impact categories with reference to the damage categories, the impact assessment was finalised at the normalised endpoint level. In addition, robustness of results is tested using CML2001 (Guinée *et al.*, 2001) and the Ecoindicator 99 (H,A) methodology (Goedkoop and Spriensma, 2000).

Interpretation and Weighting The results of the impact assessment are interpreted impact category by impact category. No additional normalisation and weighting and thus no additional aggregation were applied.

Review Process The collection of the data and the modelling of the EOL phase were subject to internal critical review.

4.2.3. Description of the Antenna Rack investigated

The investigated rack is representative for antenna racks used in mobile telephone networks that comply the GSM standard as adopted in 1996 (ETSI, 1996a).

Fig. 4.2: Example of an antenna rack (Siemens BS-241).

To perform the earlier outlined functionalities[1], antenna racks can be operated in different modes which determine the hardware configuration of the racks. The operation mode given in (Tab. 4.1) was assumed to be applied in practice to the investigated rack[2].

OPERATION PARAMETER	SPECIFICATION
FDD	Yes
FDMA/TDMA	Yes
speech coding	9.6 kbit/s
normal circuit switched mode	Yes
GPRS	No
HSCSD	No
Transceiving units	12
channels/transceiving unit	8
max Nr. of subscribers	96 (Scharnhorst, 2003)

Tab. 4.1: Operation mode for which the investigated BTS rack is designed.

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[1] See chapter 3.

[2] Detailed information on the rack inventory is compiled in Appendix B1.

4.2.4. **Description of the EOL Treatment System**

Per definition in the study presented here the EOL phase of an antenna rack begins when this network component does not longer provide its service(s) properly:

- due to damage,
- because other functionalities or services being required, the device cannot provide or
- due to changes in network technology, requiring the replacement of the device.

The EOL treatment of antenna racks embarks two major intentions, namely: *i.)* to eliminate electronic scrap, *ii.)* to recover (useful) materials thus avoiding environmental burdens due to primary production or disposal of materials.

When processing the antenna rack in the individual EOL treatment facilities the following major material streams can be identified:

- electronic scrap/materials (already extracted from scrap) that presently cannot be treated,
- scrap/ materials that can be treated, and
- by-products generated while processing the electronic scrap

At a certain moment any further processing of scrap and/or materials extracted so far is ecologically and/or economically worthless. At that stage the above defined major flows either leave the EOL system as output(s) to be processed elsewhere or the flows end as the EOL phase ends and no output(s) to technosphere are generated. In the study documented here the EOL phase was abandoned as soon as:

- un-recyclable material mixtures are landfilled,
- materials recovered have a purity which allows processing in the production phase and
- by-products are landfilled.

A complete and ideal EOL treatment of an antenna rack as it is typical for Western-European conditions can be distinguished into eight EOL stages:

i. Dismounting: The antenna site is visited by service staff dismounting the rack and installing the new antenna rack, using electric tools. The old rack is transported to a depot where it is stored before further can processing take place.

ii. Service (Storage): The racks are in a depot during a few days to several months. Depending on the racks state, it is then either re-used or the processing in the EOL phase continues.

iii. Pre-separation: The rack is transported from the depot to a pre-separation facility. There the rack is disassembled, i.e. the individual rack devices such as air conditioners, cables and diverse electronic cards are removed and the rack shell is deconstructed. Diverse electric tools are used in the disassembly and deconstruction processes.

iv. Dismantling: The separated rack devices are further decomposed into units like housing, cables and Printed Wiring Board Assemblies[1]. Subsequently the collected units are transferred to a fractionation facility.

v. Fractionation: The decomposed rack units are shredded, separated, cut and sifted. The fractionation process is completed by a sedimentation process. The fractionation steps are performed using a number of different separation facilities. Iron, non-iron metals and plastic mixtures represent the major fractions which are efficiently extractable at the moment. Metal fractions high in iron or aluminium content are then transferred directly to steel works and aluminium plants respectively. To recover precious materials heavy metal fractions are transferred to appropriate smelter plants. The plastic elements are commonly incinerated and the residuals are landfilled.

vi. Material recovery: Precious materials contained in heavy metal fractions are extracted by processing the fractions stepwise in diverse units such as furnaces, converters, an-

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[1] PWBA.

ode casting units, electrolytic refinement facilities and metal smelters. Presently materials being efficiently extractable among others are copper, gold, silver, palladium, platinum, and selenium. The recovered metals mostly have a pureness which allows direct processing in downstream production processes. Depending on toxicity and other aspects, the by-products generated during the recovery process are both incinerated (in order to stabilise the by-products) and then landfilled, or they are directly landfilled.

vii. Incineration: Materials such as plastics or other materials, which currently cannot be efficiently recycled as such, but possess an energetic value or need to be incinerated due to environmental safety issues, are incinerated in suitably equipped incineration plants. Ashes and slag are transferred to the final disposal stage.

viii. Final disposal: All materials being unrecoverable and by-products, which accrued during the numerous EOL treatment processes, are transported to and disposed of in qualified landfills.

To analyse the environmental implications related to the EOL treatment of an antenna rack the following six scenarios were developed based on the above outlined EOL treatment stages (Fig. 4.3).

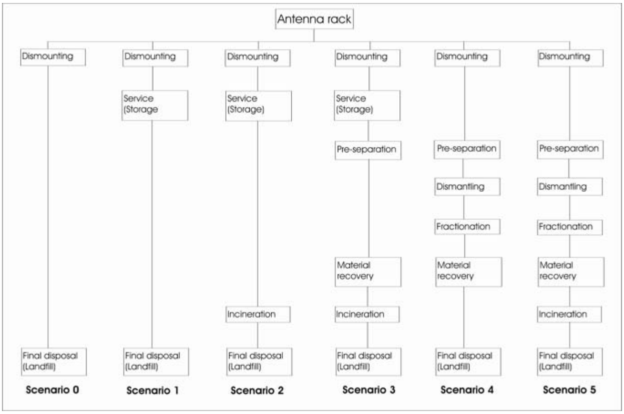

Fig. 4.3: Composition of the investigated EOL treatment scenarios.

Scenario 0: Landfill The dismounted antenna rack is assumed to be landfilled directly. No material recovery was assumed (recovery rate = 0%). The scenario includes the dismounting of the rack, transportation of the rack to the landfill site and the landfilling of the rack.

Scenario 1: Storage + Landfilling Similar to scenario 0 the dismounted antenna racks is assumed to be landfilled. Prior to landfilling the rack is stored for 20 days in a depot. Again, no material recovery was anticipated (recovery rate = 0%). The process is the same as in scenario 0 and a storage process is included.

Scenario 2: Incineration + Landfilling The rack is incinerated before landfilling in this alternative. This scenario comprises the same conditions as described in scenario 1 (recovery rate = 0%) plus an incineration process.

Scenario 3: Material recovery After dismounting the rack it is transported to a pre-treatment facility where the bigger rack units, such as the shelves and frames, made of aluminium and steel are dismounted. These units are directly processed in aluminium plants and steel works respectively. Potentially 90-95% of the steel scrap can be processed such that secondary steel is produced. Approximately 5% remain as waste (VSSV, 2005). According to Swiss waste and recycling statistics about 75% of domestic tin and steel sheet waste are recycled (BUWAL, 2004). Accordingly, the yield of the recovery is assumed to be 75% for aluminium and steel respectively (BDSV, 2001, BUWAL, 2004, VSSV, 2005). The recovered metals substitute the primary metals. The remaining 25% of the processed steel and aluminium are lost in the EOL treatment processes or are not realisable due to low quality.

The rack interior, i.e. the PWBA, cables, etc., is transferred directly to precious metal plants. The recovery rate for precious was chosen to be 35% based on (HELCOM, 2002) and (Lehner, 2001). The remaining 65% of the processed metals are assumed to be lost.

By-products generated during the precious metal recovery and materials unrecoverable with present EOL treatment technology are incinerated and finally landfilled. The scenario consists of a dismounting step, a service and pre-treatment step and a material recovery step as well as of an incineration and a landfill step. Transportation processes connecting the aforementioned processes are considered as well.

Scenario 4: Advanced Dismantling and Recovery The dismounting step is followed by an elaborate decomposing and dismantling step wherein the rack is disassembled into cables, PWBA and device housings. 75% of the PWBA are sorted out and transferred directly to an ordinary copper smelter where only copper is recovered. All other elements are transferred to a fractionation facility where they are shredded, separated, cut and sifted. Outputs are iron-metal fractions, non-iron metals and plastic fractions. Whereas the plastic fraction is transferred to an incineration process most of the metal fractions are transferred to either steel works or aluminium plants. The heavy metal fraction is transported to and processed in a specialised precious metal recovery plant. By-products and materials being unrecoverable with the present technologies are directly landfilled. This scenario consists of the same steps as scenario 3 plus the pre-treatment process and the fractionation process. The same conditions (recovery rates) as applied in scenario 3 are adopted, except that the recovery rate for precious metals was set to 25%.

Scenario 5: Advanced Dismantling, Recovery and By-product incineration This scenario consists of the same steps as scenario 4 but includes the incineration of by-products and the materials being unrecoverable with present EOL technologies prior to landfilling.

Whereas scenarios 0 and 5 represent extreme cases, scenario 3 represents the most realistic alternative. Scenarios 1 and 2 are also rather unlikely for larger network components. However, they can be realistic for smaller gadgets like mobile phones.

4.3. *Life cycle inventory – Component modelling – End-of-Life treatment modelling*

The compilation of inventory data and the scenario assembly were carried out using the GaBi4 software (IKP&PE, 2003). For background system, datasets provided by the Swiss national data base for life cycle inventories –ecoinvent (ecoinventCentre, 2003)- and datasets provided by the database included in the GaBi4 software were adopted. Cumulated data sets including emissions and resource consumptions of upstream processes were adopted from the ecoinvent data base.

Rack Modelling: Based on general technical specifications of diverse antenna racks and their interior (ERICSSON, 2003, LucentTechnologies, 2000, 2001, SiemensAG, 2000), an average GSM antenna rack is composed[1]. The rack interior, i.e. rack devices such as connectors, filters and transceivers, is modelled as an interface to the elementary flows. That means that for each of these rack devices a mass balance, specifying qualitatively and quantitatively the elementary input into the respective rack device was created. The output is represented by the rack device itself, specified by its total mass. To the entire rack the functional unit defined earlier is applied.

Rack specific information was compiled from original rack data sheets published by the manufacturers listed above, from web-sites (GSMworld, 2005) and books (Bekkers and Smits, 1997, Burgmer and Ehritt, 1995, Eberspächer *et al.*, 2001). Information on network operation modes were obtained from directly from a network operator (Swisscom, 2003). Specific technical data on rack devices as e.g. transceivers were collected a few technical specifications sheets (SiemensAG, 2002) (Palm, 2000) and were empirically determined by the author. Mass balance data, i.e. qualitative and quantitative information on the specific materials the devices are made of, were partly adopted from literature (Furuhjelm *et al.*, 2000) and partly approximated.

The rack data compiled for the investigation are valid for Western-Europe. The rack inventoried represents GSM mobile communication technology typical for the period between 1999 through 2002 and refers to 2G specifications (ETSI, 1996d). The data are expected to differ from antenna racks operated in networks that comply with other standards. The antenna rack was assumed to be configured for indoor use and is fully equipped, i.e. there is no room for rack expansion. Replacement of rack devices such as transceivers or any other unit was not envisaged during rack operation time. The rack analysed in the study represents a model rack and does not correspond to any existing antenna rack type.

EOL System Modelling: The EOL system consists of several EOL stages (e.g. dismounting of the rack, dismantling and fractionation stage, etc.). Those stages are modelled as EOL modules connected with each other. Each of the modules consists of numerous processes, e.g. electricity generated and consumed within a specific EOL stage. Two different kinds of processes contributing to the EOL treatment were distinguished: *directly* and *indirectly contributing* processes. For example, all transports of the antenna rack to be treated, the facilities (e.g. tools, devices, smelters, etc.) needed to treat the antenna rack and the infrastructure, which houses the facilities, belong to the former ones. Indirect contributing processes are not modelled explicitly in the study but are part of the direct contributing processes (ecoinventCentre, 2003). For example, the infrastructure needed to produce the concrete plates needed to build a certain EOL treatment building was not modelled explicitly in the study but is included in the respective ecoinvent concrete generation data set[2].

Information on dismounting and storage of antenna racks was gathered from manufacturers (Hausammann, 2004). Additional information was approximated based on manufacturer information. Transport related data were estimated based on the current Swiss GSM network topology (Kaden, 2003). Data on the rack processing during the pre-treatment, fractionation and material recovery stages were partly obtained from recyclers (Stengele, 2004) and compiled from literature (Ludwig *et al.*, 2003). To a minor extent data were approximated. Inventories for the EOL facility infrastructure were created based on technical specifications found on the web (BückmannGmbH, 2001a, 2001b, 2001c). Inventory data on EOL infrastructure materials, for example concrete, steel and electricity, were adopted from the ecoinvent database (v1.01) (ecoinventCentre, 2003). Transport related data were adopted from the GaBi4 database (IKP&PE, 2003). A few data sets on the incineration and landfilling are adopted from the ecoinvent database. In many cases, however, inventory data related to those EOL

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[1] An overview on the rack specifications adopted for the study is given in Appendix D8.

[2] A detailed overview on the EOL modules and the processes they comprise is given in chapter 3.2.

processes did not exist and are approximated based on closely related ecoinvent data sets. The EOL scenarios developed also consider direct rack incineration and/or landfilling and the corresponding processes were inventoried for those alternatives. Emissions to the environment from incineration and/or landfilling of racks were determined by transfer fractions and transfer coefficients. The fractions and coefficients were determined based on available literature or were approximated based on physical and chemical characteristics[1]. Inventory results for energy carriers and CO_2 emissions are presented below in the impact assessment section (Tabs. 4.2 and 4.3).

All data used in the analysis are applicable to Western-European conditions. The data represent the technical properties of the EOL treatment technology between 1999 through 2004. The pre-treatment, dismantling and fractionation data represent Swiss conditions. Specifications on the material recovery process apply to the Swedish BOLIDEN plant (HELCOM, 2002, Isaakson and Lehner, 2000, Ludvigsson and Larsson, 2003). The data on precious metal recovery rates are calculated based on information found in reports (HELCOM, 2002) and by Lehner (Lehner, 2001). The process assemblies as modelled represent approximations and may not always reflect the effectively occurring conditions at the different EOL treatment facilities. The ecoinvent data sets on landfilling include long term emission data occurring during the next 60.000 years. It is assumed that in many cases all matter disposed of is leached out. This assumption was adopted for the landfill processes compiled for direct landfilling of the antenna rack.

4.4. *Life Cycle Impact Assessment*

4.4.1. Overall Impact Assessment Results

Figure 4 presents impact assessment results at midpoint level in the following impact categories: carcinogenic effects[2], non-carcinogenic effects[3], respiratory organic effects[4], respiratory inorganic effects[5], terrestrial ecotoxicity[6], aquatic ecotoxicity[7], ionising radiation[8], ozone layer depletion[9], photochemical oxidation[10], non-renewable energy[11], mineral extraction[12], global warming potential[13].

In a first step the different scenario are compared both a midpoint and endpoint levels. In a second step results are discussed in more details for the impact category contributing to human health, ecosystem quality, resources and climate change, also discussing normalized results at damage level.

Two major EOL treatment groups can be identified based on the impact assessment results: *i.)* scenarios 0, 1 and 2 excluding material recovery/ recycling and *ii.)* scenarios 3, 4, and 5 including material recovery/recycling (Fig. 4.4). The differences between these groups are especially large with reference to terrestrial and aquatic ecotoxicity as well as to carcinogenic and non-carcinogenic effects.

Comparing the environmental impacts of the different EOL treatment scenarios category by category indicates that scenario 3 causes the least impacts (Fig. 4.4) and represents the envi-

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[1] A comprehensive compilation of the transfer coefficients and fractions, together with the relevant references cited, is given in Appendix A2-A5.

[2] CarcEff.

[3] NoncarcEff.

[4] RespOrg.

[5] RespInorg.

[6] TerrEcox.

[7] AquEcox.

[8] IonRad.

[9] Ozone.

[10] PhotoOx.

[11] NonReE.

[12] MinEx.

[13] GlobWarm.

ronmentally preferable option. The results further indicate that all electronic scrap containing precious metals should be treated in specialised metal recovery plants facilitated to recover precious metals. The increased precious metal recovery rate of 10% between scenario 3 and scenarios 4 and 5 leads to a reduction of 15% in case of effects on human respiratory organs (Fig. 4.4). Simple processing of precious metals containing electronic scrap in ordinary copper remelters should be avoided (scenarios 4 and 5) as precious metals cannot be recovered as efficiently as in specialised metal recovery plants. Scenario 2 (immediate rack incineration and subsequent landfilling) causes large environmentally impairing emissions and should be avoided.

The production of primary materials to substitute lost materials causes major contributions to each impact category. Energy generated for and consumed in the production of primary materials as well as the different primary material production processes themselves, including the disposal of by-products, cause environmentally harmful emissions. Indirect emissions released from landfilled by-products, generated in the primary material production stage, contribute to the impacts on human respiratory organs and photochemical oxidation processes.

Long-term emissions of arsenic, zinc, antimony and copper as well as of aluminium related to landfilling cause distinct toxic impacts on terrestrial and aquatic ecosystems (all scenarios), but are associated with large uncertainties. These emissions also cause significant carcinogenic and non-carcinogenic effects on human health. Comparatively less or no detectable impacts are observed for lead, cadmium and other heavy metals known to cause toxic impacts.

Compaction of electronic scrap and/ or treatment residuals by means of thermal treatment prior to landfilling (scenarios 2 and 5) causes the release of highly volatile materials, e.g. arsenic and bromine, contributing to the terrestrial and aquatic ecotoxicity as well as to carcinogenic and non-carcinogenic effects. These materials increase the environmental impacts and thus thermal treatment prior to landfilling should be avoided, unless the ashes are well stabilised and enable to reduce long-term emissions and unless a significant heat recovery and electricity production can be achieved while incinerating by-products.

The results also prove that elaborated pre-treatment and fractionation of the scrap (scenarios 4 and 5) does not further reduce the environmental impacts related to the EOL treatment of the rack. Instead material losses are associated with the pre-treatment and fractionation which then need to be substituted by primary materials. This may lead to slightly increased adverse effects on the environment worsening the overall environmental performance of the rack during the EOL phase.

Little impact is attributable to the service stage (scenario 3). Mainly radioactive emissions from the electricity generation cause ionising effects. The dismounting and the storage of the rack causes very little impacts being negligible compared to the impacts of the other EOL treatment stages.

In the following sub-sections the respective contributions of the midpoint categories are discussed in more detail for each damage category.

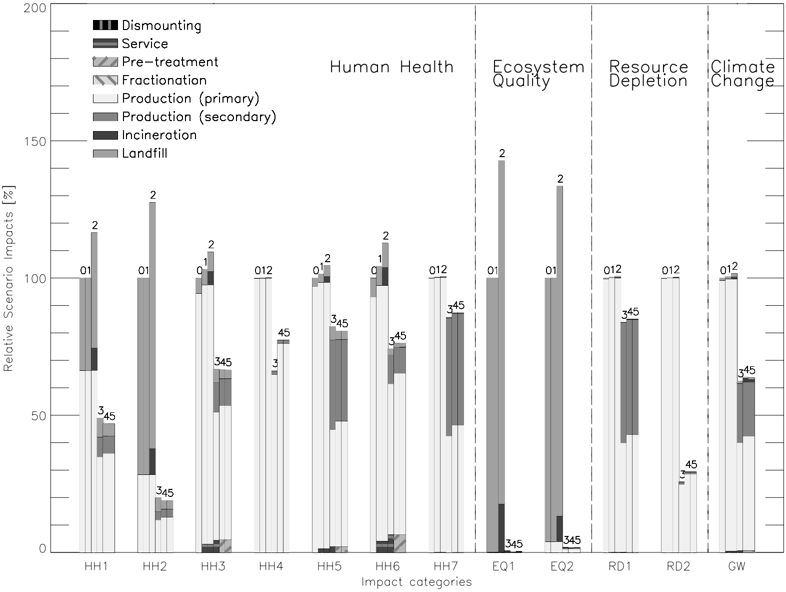

Fig. 4.4: General EOL treatment scenario comparison and contribution of the major EOL treatment stages to the overall impact of each scenario. In each impact category (abbreviations of the x-axis are given in the footnote[1]) scenario 0 was set to 100% and the other scenarios were related to it. If not otherwise stated the following abbreviations were applied to the single EOL scenarios: 0 = scenario 0, 1 = scenario 1, 2 = scenario 2, etc..

4.4.2. **Human health**

Human health is primarily impaired by effects on human respiratory organs caused by inorganic emissions (impact category: respiratory inorganics; Fig. 4.5), the ranking between scenarios at damage level remaining the same as for midpoint results. In nearly all EOL treatment scenarios, Fig. 4.5 shows that the substitution of lost materials by primary material production processes (system expansion) dominates the ***respiratory inorganic*** impact category. Key critical process is the production of primary palladium accounting for more than 85% of the total impact due to inorganic emissions. The roasting of the platinum group metal ores in Russia causes considerable sulphur dioxide emissions into air (Althaus *et al.*, 2003). To a lower extent SO_2 is released to air during the production of primary platinum, eventually leading to secondary particles. About 5% of the total impact is attributable to that production process. Material recovery processes exert lower effects. The contribution of all other EOL stages to the inorganic respiratory impact category is negligible.

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[1] HH1 … Carcinogenic effects [kg$_{eq}$ Chloroethylene in air/kg$_{Emissions}$]
HH2 … Non-carcinogenic effects [kg$_{eq}$ Chloroethylene in air/kg$_{Emissions}$]
HH3 … Respiratory organic effects [kg$_{eq}$ Ethylene in air/kg$_{Emissions}$]
HH4 … Respiratory inorganic effects [kg$_{eq}$ $PM_{2.5}$ in air/kg$_{Emission}$]
HH5 … Ozone depletion potential [kg$_{eq}$ CFC_{11} in air/kg$_{Emissions}$]
HH6 … Photochemical oxidation [kg$_{eq}$ Ethylene in air/kg$_{Emissions}$]
HH7 … Ionising radiation [Bq$_{eq}$ C_{14} in air/kg$_{Emissions}$]
EQ1 … Terrestrial ecotoxicity [kg$_{eq}$ Triethylene glycol in air/kg$_{Emissions}$]
EQ2 … Aquatic ecotoxicity [kg$_{eq}$ Triethylene glycol in air/kg$_{Emissions}$]
RD1 … Non-renewable energy [kg$_{eq}$ crude oil (860kg/m^3)/kg$_{Resource}$]
RD2 … Mineral extraction [kg$_{eq}$ iron (in ore)/kg$_{Resource}$]
GW … Global warming [kg$_{eq}$ CO_2 in air/kg$_{Emissions}$]

Heavy metals (arsenic, zinc and antimony), leached out of the landfilled rack and transferred to the surrounding soil and water, wreak major ***non-carcinogenic effects*** (scenarios 0-2). In these alternatives, about 70% of the total impact is attributable to the final disposal and is linked to a high level of uncertainty. More than 23% is related to the primary material production stage. If including the material recovery stage (scenarios 3-5), direct arsenic and zinc emissions to water released during the primary production of palladium and partly of platinum to substitute lost metals, can cause distinct non-carcinogenic effects. The direct emissions released from these two production processes account for more than 25% and 12% respectively to the overall impact. The disposal of by-products, e.g. redmud in the production of aluminium and dust accrued during the production of primary steel to substitute lost metals, cause indirect arsenic and zinc emissions to water respectively. The heavy metal emissions to water, stemming from landfilled by-products of the aluminium production, account for ~ 15% of the total impact. About 11% of the total impact is attributable to the landfilled dust from steel production.

Carcinogenic effects are caused by arsenic emissions to soil and water from the degradation of the rack in the landfill. Arsenic emissions to water and Benzo(a)pyren emissions to air are dominantly related to the production of primary materials to substitute lost materials. Mainly heavy metal releases to water of landfilled by-products from the primary aluminium, iron and steel production contribute to that category. Benzo(a)pyren emissions to air occur while liquid aluminium is produced and while generating the energy consumed in the palladium production. NMVOC emissions to air exert impacts on respiratory organs (impact category: respiratory organics). Emissions of Halon 1211 released in gas transportation processes in Russia contribute to the ozone depletion category.

Emissions initialising ***photochemical oxidation*** reactions in the lower atmosphere are primarily released in the primary material production stage (causing more than 60 % of the total impact) where materials to substitute lost materials are produced and partly in the pre-service/ fractionation stage (causing nearly 10% of the total impact). In this context NMVOC emissions due to energy generation processes and due to diesel consumed for scrap transports are critical.

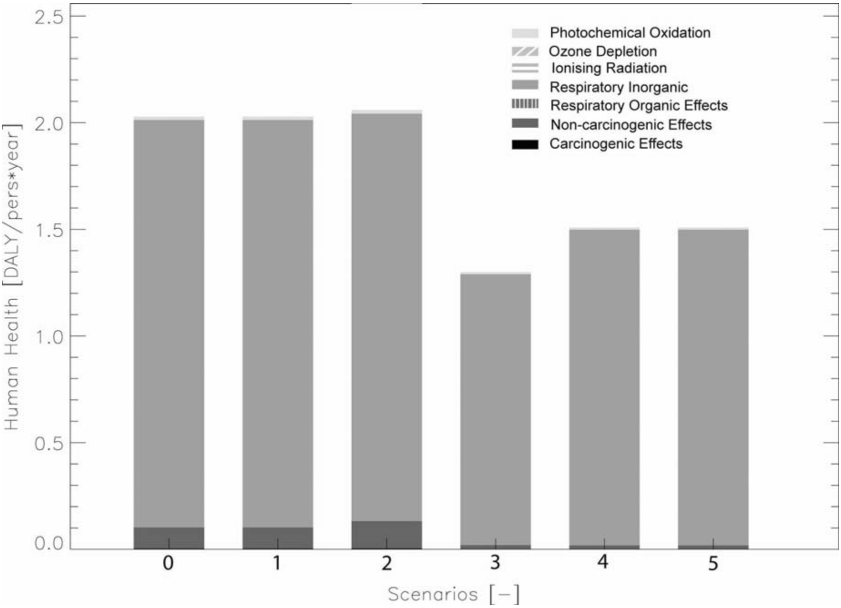

Fig. 4.5: Contributions of the individual impact categories at endpoint level to the impact on human health for all scenarios.

4.4.3. **Ecosystem quality**

The overall ecosystem quality is dominantly affected by impacts on the terrestrial ecosystem (impact category: ***terrestrial ecotoxicity***; Fig. 4.6), the ranking between scenarios at damage level remaining the same as for midpoint results. If only the final disposal of the rack (scenario 0-2) and the production of primary materials to substitute lost materials are considered while excluding material recovery processes, then emissions released to soil in the final disposal stage dominantly affect the terrestrial ecosystem. Copper emitted to soil during the degradation of the rack in the landfill accounts for nearly 96% of the total impact. If material recovery processes are included and residuals of all processes considered are landfilled without previous incineration (scenario 4), emissions released during the production of primary palladium and steel to substitute lost metals dominate that impact category. The production of primary palladium accounts for nearly 40% of the total impact. The production of primary steel accounts for 26% respectively. Copper and partly zinc released to air represent the major toxic emissions. Copper is emitted directly in the production of palladium. Landfilled by-products of the primary steel production contribute to the copper and zinc emissions.

If no material recovery but disposal is foreseen (scenario 0-2), the aquatic ecosystem is affected by both, heavy metal emissions to soil and water as well as by other inorganic emissions to water during the final disposal stage, i.e. during landfilling. Especially copper emitted to soil (~ 45% of the total impact) and water (~ 35% of the total impact) and aluminium emitted to water (~ 17% of the total impact) contribute dominantly to that impact category. If including material recovery processes, but excluding residual incineration prior to landfilling, emissions released during the production of primary aluminium (accounting for 51% of the total impact)and palladium (~ 16% of the total impact) to substitute the metals lost as well as the production of secondary steel contribute to the aquatic ecotoxicity. Indirect aluminium emissions to water (nearly 50% of the total impact) mainly stem from the deposition of redmud in landfills. Direct aluminium and nickel emissions occur during the processing of palladium in South Africa and to a lesser extent in Russia. Aluminium emissions from steel production primarily are attributable to the disposal of sludge from steel rolling. Zinc emissions in this context are detected for the disposal of dust from the production of unalloyed electric steel.

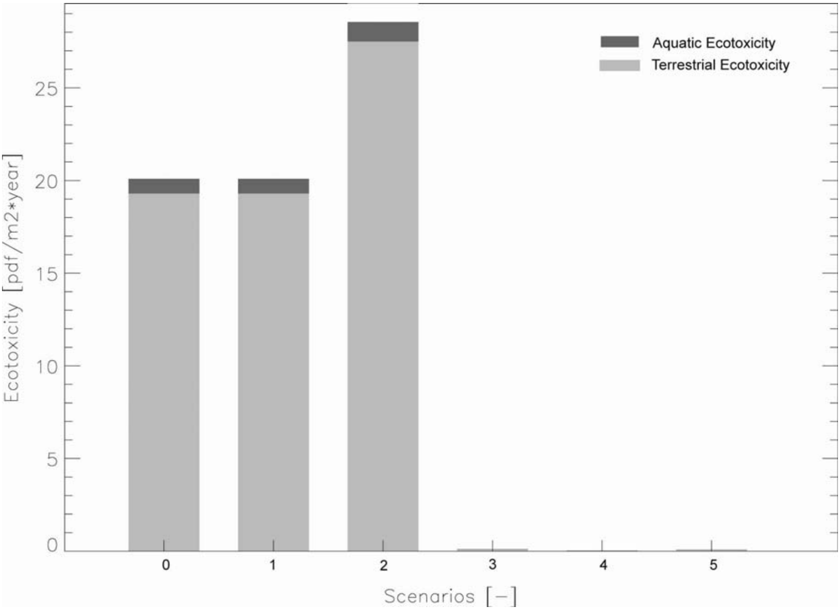

Fig. 4.6: Contributions of the individual impact categories at endpoint level to the impact on ecosystem quality for all scenarios.

4.4.4. Resource consumption

Depletion of ***non renewable energy resources*** shows the largest contribution to the overall impact represented by this damage category (impact category: non-renewable energy; Tab. 4.2 and Fig. 4.7). Mainly natural gas, crude oil, hard coal and Uranium are consumed by the production of primary steel, aluminium and palladium.

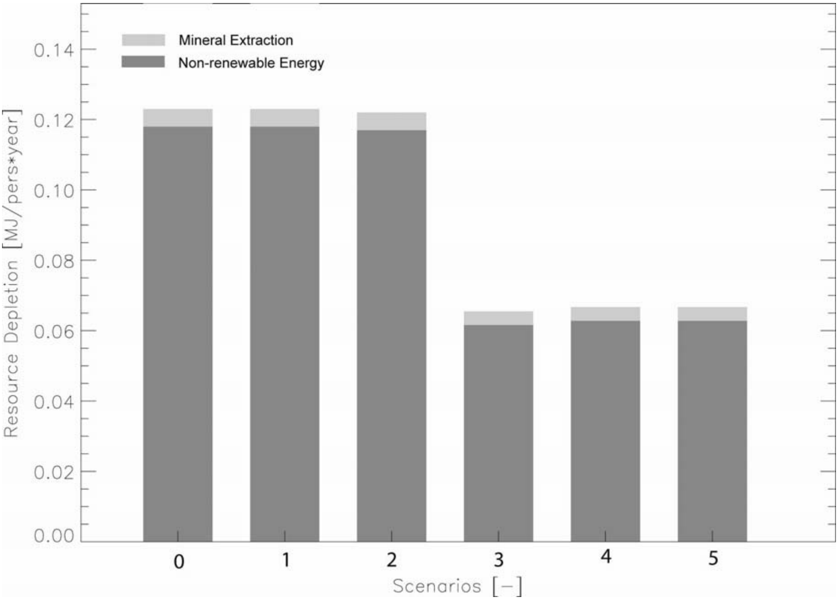

Fig. 4.7: Contributions of the individual impact categories at endpoint level to the impact on the resource depletion for all scenarios.

Mineral resource depletion is significant while primary materials are produced. Disposing of all materials and producing new materials (system expansion, scenarios 0-2) leads to largest mineral resource depletion. Iron ore mined for primary steel production accounts for nearly 96% of the overall mineral resource depletion caused by the rack materials production.

Stages	Dismounting	Service	Pre-treatment	Fractionation	Primary prod.	Secondary prod.[1]	Incineration	Landfill
Scenarios	*0-5*	*1-2*	*3-5*	*4-5*	*0-5*	*3-5*	*2-3 and 5*	*0-5*
Hard coal [MJ]	0	3	1	1	1485	611	4	0
Lignite [MJ]	0	3	1	1	716	490	1	1
Natural gas [MJ]	0	10	10	1	2329	6070	12	9
Crude oil [MJ]	0	64	95	1	2021	466	104	94
Uranium [MJ]	1	8	2	3	2240	1120	4	1120

Tab. 4.2: Selected resources consumed by the EOL treatment stages of the different scenarios while the antenna rack is treated and base materials are produced.

4.4.5. **Climate change**

Direct and indirect CO_2 emissions during the production of primary materials in all scenarios and partly in the final disposal stage, cause large impacts on the global warming effect. In this context scenario 0 - 2 represent the environmentally most critical alternatives (Fig. 4.8; Tab. 4.3).

Carbon dioxide emissions in the primary material production stage primarily are attributable to electricity generation processes needed for the production of primary aluminium, steel and palladium to substitute the lost metals (Tab. 4.3). In the case of primary steel production especially the sinter and conversion processes contribute to the overall CO_2 emissions released during that process.

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[1] Based on data on the annual resource consumptions published by the German "*Badische Stahlwerke" GmbH* (BSW, 2004).

Stages	Dismounting	Service	Pre-treatment	Fractionation	Primary prod.	Secondary prod.	Incineration	Landfill
Scenarios	0-5	*1-2*	*3-5*	*4-5*	*0-5*	*3-5*	*2-3 and 5*	*0-5*
CO_2 [kg]	0.14	5.63	7.1	0.32	459.42	176.71	8.41	8.42

Tab. 4.3: Carbon dioxide emitted by the EOL treatment stages of the different scenarios while the antenna racks is treated and base materials are produced.

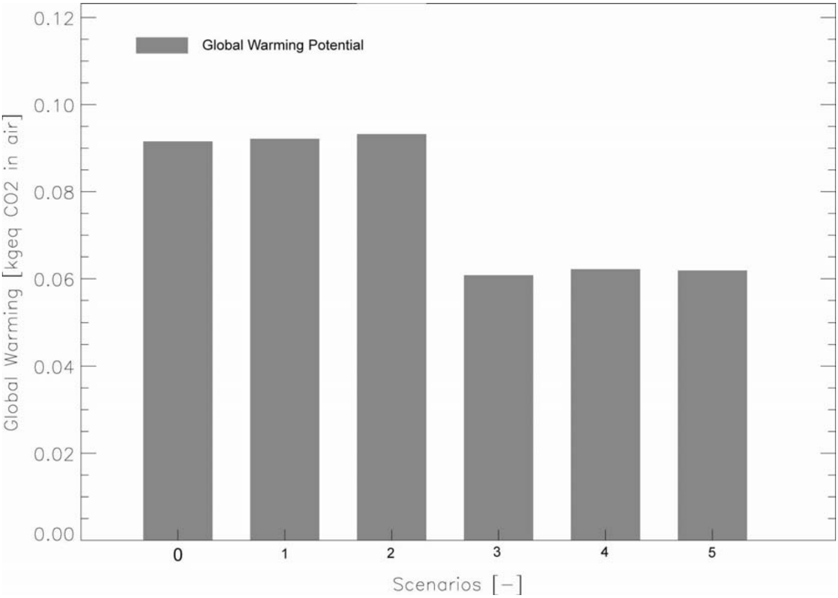

Fig. 4.8: Contributions of the individual impact categories at endpoint level to the impact on climate change for all scenarios.

4.5. *Discussion and conclusion*

General Key impacts during the EOL treatment of the antenna rack and the production of the primary materials needed for the rack manufacturing are attributable to:

a.) direct emissions due to heavy metals leached while the rack is degraded in the landfill,
b.) indirect heavy metal emissions from landfilled by-products generated in primary material production and
c.) direct emissions of heavy metals in primary production of precious metals.

If the antenna rack is recycled and not disposed of directly, the environmental impacts related to the EOL phase are low compared with impacts related to the rack production phase. It is also shown that the final disposal without material recycling can pose significant ecotoxic impacts (Fig. 4.5). However, it has to be mentioned, that in particular the emissions inventoried and assessed for the landfill processes have to be interpreted carefully. Firstly, present LCA methodology consider overall integrated emissions, these emissions related to landfilling occur over long time periods (e.g. 60.000 years). Secondly, neither the ecoinvent data base nor the IMPACT2002+ method distinguishes explicitly the exact chemical state, especially the metal speciation in which the emissions are released to the environment. Finally, background concentrations of naturally existing elements and /or substances are not considered in the present impact assessment methods.

Also, it is assumed that the present impact assessment methods underestimate the effects associated with the depletion of very rare metals, for instance of indium and gallium. No characterisation factors are available for these resources.

It is found that a certain EOL treatment optimum exists and that recycling expenditures due to overly intensive pre-treatment can increase the environmental impact related to the EOL phase, mainly due to additional materials losses in pre-treatment processes. The impact assessment results obtained using the IMPACT2002+ method are checked against results according to CML2001 (Guinée *et al.*, 2001) and the Ecoindicator 99 (H,A) methodology (Goedkoop and Spriensma, 2000). Both methods, CML2001 and Ecoindicator 99 (H,A), yielded results comparable to those obtained using IMPACT2002+ (Tab. 4.4). In many cases the ranking of the dominating processes remains the same for the different impact assessment methods. Human toxicity of CML2001 is dominated by long term antimony emissions to soil from landfilled antimony.

		Assessment method			IMPACT2002+	EI99 (H,A)	CML2001
		Ranking					
Impact category	Life cycle process	IMPACT2002+	EI99 (H,A)	CML 2001			
					kg Triethylene glycol	DALY	kg DCB-äquv.
Human toxicity	Pre-treatment	1	1	6	2.32E-02	3.58E-08	0.617
	Thermal treatment	2	2	2	1.08E-02	1.68E-08	19.587
	Steel secondary	3	3	3	6.76E-03	1.05E-08	9.792
					kg Triethylene glycol	PDF*m2*year	kg DCB-äquv.
Aquatic ecotoxicity	Thermal treatment	1	1	2	2.41E+05	3.158	5.982
	Aluminium secondary	3	2	4	2.35E+04	2.266	1.840
	Steel secondary	2	3	3	1.71E+05	0.839	4.625
					kg Triethylene glycol		kg DCB-äquv.
Terrestrial ecotoxicity	Thermal treatment	1	-	1	3.70E+03	-	0.627
	Aluminium secondary	2	-	2	354.98	-	0.221
	Steel secondary	3	-	3	166.14	-	0.170
					kg Ethen-äquv.		kg Ethen-äquv.
Photochemical oxidation	Thermal treatment	1	-	1	0.914	-	0.0185
	Pre-treatment	2	-	2	0.229	-	0.0183
	Steel secondary	3	-	3	0.048	-	0.0154
					kg CO2-äquv.	DALY	kg CO2-äquv.
Global warming potential	Thermal treatment	1	1	1	45.555	9.56E-06	45.560
	Steel secondary	2	2	2	45.455	9.53E-06	45.383
	Aluminium secondary	3	3	3	15.551	3.25E-06	15.498
					C14 in air äquv.	DALY	DALY
Ionising radiation	Steel secondary	1	1	1	4.39	9.24E-10	9.24E-10
	Thermal treatment	2	2	2	2.86	6.01E-10	6.01E-10
	Aluminium secondary	3	3	3	0.39	8.26E-11	8.26E-11

Tab. 4.4: Comparison and ranking of the impact assessment results (given for EOL scenario 5) for the EOL phase of the antenna rack using the different impact assessment methods.

The aquatic ecotoxicity category of the same method is dominated by vanadium emissions to soil from landfilled plastic incineration residuals. Additionally the robustness of the IMPACT2002+ method has been examined by excluding those emissions contributing less than 1/1000 to the overall environmental impact and then assessing the environmental impacts of the EOL treatment scenarios again. The results remained the same. Based on the results, the following recommendations to actors are formulated.

Recommendations to Recyclers/ Operators As an antenna rack reaches its EOL phase and cannot be used otherwise it should be dismounted and processed. A pre-treatment comprising of merely the disassembly of the rack housing and the removal of the rack sub components (transceivers etc.) is sufficient. All electronic scrap containing precious metals should be treated in specialised metal recovery plants to effectively recover precious metals. After preprocessing the steel and aluminium fractions extracted, they should be processed in steel works or aluminium plants respectively. Precious metals should be recovered in high-standard material recovery facilities.

According to the results, incineration of the electronic scrap, as e.g. printed wiring board assemblies, prior to landfilling should be avoided unless ashes are long term stabilized and recoverable energy is significant. Such additional incineration can lead to emissions of diverse heavy metals, in particular of arsenic in dispersed form, which may react toxic to the environment (Uryu *et al.*, 2003).

Landfilling of entire racks, rack components and even small component units should also be avoided. Precious metals are lost and have to be newly produced which leads to high impacts. Likewise, due to the unnatural high concentration of metals in the landfill site, emissions are released which are toxic to the local environment.

Recommendations to Manufacturers/ Operators To reduce the environmental impacts due to processing of rack materials two issues are of importance. Firstly, rack components, e.g. the rack housing, should have a standardised shape to facilitate re-use. That could lead to a prolonged use time of the rack housing and eventually of the rack ventilation units (supposing that the ventilation capacity is sufficient). Material flows are thus reduced and environmental load is diminished.

Secondly, if feasible the palladium used in contact materials of printed wiring board assemblies should be either recycled at the highest possible rates or it should be replaced by a different material.

Recent information indicates, that the racks of antenna stations (NodeB) complying with the forthcoming Universal Mobile Telecommunication System standard[1] are heavier and have a more complex construction compared with the BTS racks (LucentTechnologies, 2001, SiemensAG, 2002, Wilén, 2000). It is expected that the NodeB racks require more complex EOL treatment methods to ensure environmentally safe recycling and disposal. That increased complexity of both the antenna racks as well as of the treatment methods associated with an expected decrease in the content of precious metals per rack may lead to an increased environmental impact per rack.

However, when comparing a whole GSM network with a UMTS network the latter one might perform environmentally better due to the fact that fewer macro NodeB but more small and lightweight micro and pico NodeB's are installed. A forthcoming study will address these issues in detail.

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[1] UMTS.

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5. *Network study I*: The End of Life Treatment of Second Generation Mobile Phone Networks: Strategies to reduce the Environmental Impact[1]

5.1. *Introduction*

Mobile telephony, today an indispensable service facilitating every-day life, has experienced a tremendous increase in penetration since the implementation of the innovative Global System for Mobile communication[2] standard in the early 1990's. Expressed in figures: today more than 1.53 billion GSM subscribers (GSMworld, 2005) are connected to 626 GSM networks operated in presently 198 countries worldwide (GSMAssociation, 2004). Numerous further countries, in particular in the Latin-American and in the Asian-Pacific region have just started the implementation of second generation[3] mobile phone networks such as GSM networks (GSMAssociation, 2004). The recent rapid network evolution belonging to the intermediate 2.5G generation (GSMAssociation, 2005) as well as the forecasts on the future evolution of mobile telephone networks (Friedl&Partners, 2001, Wallace, 2005) predict network growth rates similar to those achieved with the basic GSM standard.

Tightly associated with the outlined trends on mobile telephony is a fast-growing amount of mobile phone network infrastructure that needs to be replaced. This is due to the fact that the different network components either don't meet the technical or technological requirements any more or they have reached their physical End-of-Life[4] due to damage or defect.

During the past years, adverse environmental implications caused by the processing of network components as well as by improper EOL treatment were increasingly recognised by authorities, manufacturers, operators and recyclers. Restrictive regulations on European level seek to prevent from the dumping of valuable electronic scrap and aim to increase the recycling rates of electronic devices (CEC, 2003b). Supporting regulations prohibit the usage of several materials assessed to react environmentally toxic (CEC, 2003a, 2003b). To meet the regulations and to reduce the overall environmental impacts of mobile phone networks, the manufacturers have endeavoured to replace environmentally critical materials. Recyclers have updated the EOL treatment processes constantly to meet the latest environmental requirements. However, several major issues haven't been addressed sufficiently yet:

a) Regulations on environmentally safe EOL treatment methods and emissions caused by processing the scrap are not consistent world wide.
b) Environmental impacts related to the EOL treatment of entire mobile phone networks have not yet been quantified from a life cycle perspective.
c) Implications of the increased amount of network scrap to be treated due to the change-over from 2G to third generation[5] networks have not been studied so far.

Current and forthcoming governmental regulations require a sound understanding of the environmental performance of mobile phone network components during their EOL phases. To give incentives for processing network scrap in elaborated EOL treatment systems, the potential benefits need to be known.

Several studies have concentrated on the life cycle assessment of networks (Faist-Emmenegger *et al.*, 2003, Faist-Emmenegger *et al.*, 2004, Weidman and Lundberg, 2001). In

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[1] Reprinted from: Scharnhorst, W., Althaus, H.-J., Classen, M., Jolliet, O. and Hilty, L. M. (2005): End Of Life treatment of second generation mobile phone networks: strategies to reduce the environmental impact. Environmental Impact Assessment Review; 25 (**5**) pp: 540-566., with permission from Elsevier.

[2] GSM.

[3] 2G.

[4] EOL.

[5] 3G.

a previous study, the environmental impacts caused in the EOL phase of a single GSM network component has been analysed (Scharnhorst *et al.*, 2005).

So far little attention has been paid to the environmental performance of entire mobile phone networks in the EOL phase. A comprehensive qualitative and quantitative environmental analysis of the different network components is outstanding. Likewise, the relative environmental importance of the EOL phase has not been compared in depth with the impacts of the other phases.

In the study presented here, the overall environmental performance of all major network components of a typical GSM network was investigated. The environmental effects caused in the EOL phase were studied in detail.

To assess the relative importance of the EOL phase, the environmental impacts of this phase were compared with the impacts caused by the other life cycle phases. In order to compare the environmental benefits of different possible recycling strategies six different EOL treatment scenarios, varying from direct disposal excluding any material recycling from electronic scrap to current state-of-the-art EOL treatment techniques, were adopted from a previous study (Scharnhorst *et al.*, 2005). The IMPACT2002+ method (Jolliet *et al.*, 2003) was used to assess environmental impacts.

According to the ISO14040 series (ISO, 1998) the paper is structured into goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation. It is completed by a discussion and recommendations to concerned actors.

5.2. *Goal and Scope*

5.2.1. Study Objective

The goal of the study reported here is

- to identify the relative importance of the EOL phase of a mobile phone network compared with the other life cycle phases,
- to identify the environmental benefits attributable to different recycling strategies
- to determine the most impacting network component from a life cycle perspective,
- to identify an environmentally preferably combination of currently used EOL treatment processes for a generic GSM mobile phone network, and
- to specify environmentally critical EOL treatment processes and materials causing critical impacts in these processes.

The study was carried out applying the Life Cycle Assessment[1] method. The results are intended to deepen the understanding of the environmental consequences related to the processing of mobile phone network scrap and to formulate recommendations how to reduce the overall environmental impacts in the production and the EOL phase. The outcome is also meant to support the decision making of network operators, network component manufacturers as well as recyclers.

Functional Unit and Reference Flow The transmission of 1 data bit from one mobile phone to another one within a representative GSM 900 network was selected as functional unit. One data bit transmitted represents the reference flow.

Data Requirements The following data requirements are set:

- representative for Switzerland and Western Europe,
- representative for the year 1998-2005.

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[1] LCA.

System boundaries The system under study comprises all life cycle phases of a representative GSM mobile phone network (Fig. 5.1). The mobile phone network is assumed to be operated at the maximum possible data transmission rate of 9.6 kbit/s as specified in the GSM standard (ETSI, 1996a, 1996d). This assumption was chosen for a lack of data for the average transmission rate, even though it may imply in a biased modelling of the use phase.
The EOL phase of the network is modelled in detail. The EOL phase of a network or a component of it begins with the dismounting of the respective device and ends with the final output of the secondary raw material production and/or the final disposal (incineration or landfilling) of waste products (Fig. 5.1) (Scharnhorst *et al.*, 2005). The EOL phase is further subdivided into final disposal processes (incineration of waste, by-products) and recovery processes (pre-separation, dismantling, shredding, fractionation, material recovery, secondary raw material production). To represent the effect of the potentially limited range of application of secondary raw materials compared to virgin (primary) material, different value correction factors are applied for substitution of primary materials with secondary materials from recycled electronic scrap (Werner, 2002).

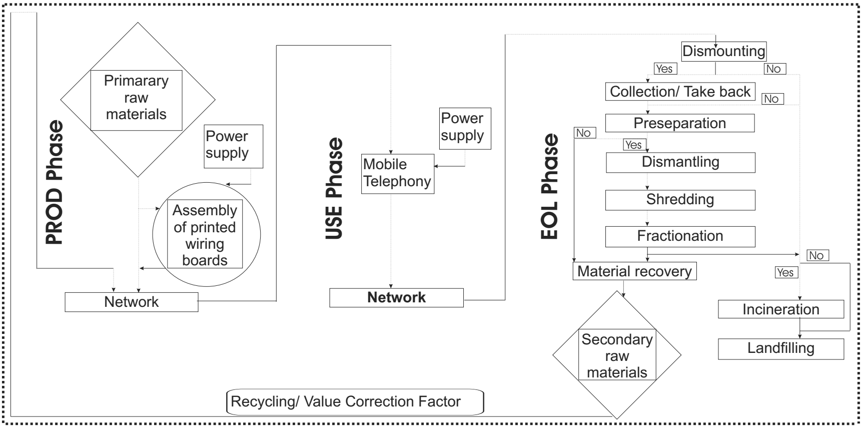

Fig. 5.1: Flow chart and system boundaries of the life cycle phases of the studied mobile phone network.

To depict the environmental benefits attributable to the adoption of more or less advanced recycling strategies, six EOL treatment scenarios developed in (Scharnhorst *et al.*, 2005) were adopted (see Tab. 5.1).

Scenario	Description	Recycling rate for Al and Steel[1]	Recycling rate for materials[2]
0	landfilling	85%	0%
1	collection, storage, and landfilling	85%	0%
2	incineration and subsequent landfilling	85%	0%
3	pre-treatment and material recovery and recycling (by-products/residuals incinerated and finally landfilled)	85%	85%
4	pre-treatment, fractionation and material recovery and recycling (by-products directly landfilled)	85%	85%
5	pre-treatment, fractionation, material recovery and recycling (by-products incinerated and then landfilled)	85%	85%

Tab. 5.1: The scenarios used for modelling the EOL phase (Scharnhorst *et al.*, 2005).

Substitution of metal inputs in the production phase by metal output of the recycling is modelled to study the environmental consequences of the different EOL scenarios. Substitution of energy demand in the production phase by energy recovered in EOL is not modelled due to its negligible impact in the given context. The environmental impacts of the use phase were assumed to be identical for each of the scenarios. Therefore the use phase was excluded from the presentation of the results of the EOL scenario analysis.

Scenarios 0-2 contain the recovery of aluminium and steel of network components other than the switching elements and mobile phones, e.g. the steel of the masts, cabins, etc. The technical recycling rate for these materials is assumed to be 85% (BDSV, 2001) and 15% are lost in the recovery processes and disposed of. A value correction of 85% is assumed due to downcycling in the processes. Scenarios 0-2 do not contain material recycling from scrap of switching network component elements such as racks installed in Base Transceiver Stations[3], etc. The recycling rate equals 0% and thus 100% primary materials need to be produced for these network elements.

Scenarios 3-5 include recovery of metals from the switching elements and the mobile phones. All electronic components of the switching network components (BTS, Base Station Controller[4], and Mobile Switching Centre[5]) and 80% of the Mobile Stations[6] collected by the recyclers, are processed in recycling processes. Plastic materials are separated and processed in Municipal Solid Waste Incineration plants[7]. Likewise, 20% of the mobile phones are assumed to be incinerated directly in MSWI. The incineration residues are finally landfilled. In scenario 3 all precious metals containing electronic components are processed immediately in a facilitated material recycling plant and all residuals and by-products are processed in MSWI and finally landfilled. Scenarios 4-5 include an advanced fractionation of the electronic scrap into a ferrous- and a non-ferrous metal fraction and a plastic fraction prior to material recycling/ secondary raw material production. In scenario 4 the residuals of the secondary raw material production are directly landfilled and in scenario 5 the residuals are first incinerated and the ash is landfilled.

A sensitivity analysis is performed varying the value correction factor in order to determine the effect of quality variations of secondary raw materials recovered from electronic scrap on the overall environmental profile of the network. Based on the results the amount of secon-

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[1] Construction materials of antenna masts and cabins.

[2] Au, Ag, Cu, Pd, Pt, Se in electronic devices.

[3] BTS.

[4] BSC.

[5] MSC.

[6] MS is standard terminology (ETSI, 1996a, c). For convenience, MS will be termed *mobile phone*.

[7] MSWI.

dary raw materials (expressed by the value correction factor) that are substituted for primary raw materials are defined (see Figs.: 3-6). For scenarios 3-5 a value correction factor of 85% for precious and rare metals is chosen. The remaining 15% of raw metals are provided by primary raw materials.

Allocation The background system (for example the materials of the EOL infrastructure, the production of primary raw materials, and the energy generation in the use phase) was modelled using the Swiss ecoinvent-Database and the allocation principles applied in ecoinvent were adopted to the background system.

Allocation based on physical properties (Ekvall and Finnveden, 2001) is applied to the foreground system (e.g. shredder use is allocated to mass of treated scrap).

Impact Assessment The IMPACT2002+ method (Jolliet *et al.*, 2003) is used to determine the environmental impacts related to the emissions released and resources consumed in the system under study. This impact assessment method covers more impact categories than other methods and it includes more substances.

The method links emissions and resource consumptions compiled in the life cycle inventory to so-called midpoint categories representing the environmental impacts as effect scores of various reference substances. The scores in turn are linked to damage categories (endpoints) representing the impacts on human health, ecosystem quality, climate change and resources, respectively (Humbert *et al.*, 2004).

To discuss the individual environmental impact categories in detail, and to cross-compare the shares of the individual impact categories with reference to the damage categories, the impact assessment was finalised at the endpoint level.

Interpretation and Weighting The results of the impact assessment are interpreted impact category by impact category. No additional normalisation and weighting, and thus no total aggregation are applied.

Review Process The collection of the data and the modelling of the entire life cycle of the network were subject to internal peer review performed among the authors.

5.2.2. Description of the GSM Network investigated

The analysed mobile phone network represents 2G mobile phone technology and complies with the GSM standard as adopted in 1996 (ETSI, 1996a, 1996b, 1996d). It comprises the following major network components[1]:

- Mobile phones,
- BTS,
- BSC, and
- MSC.

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[1] The network components are described in detail in chapter 3. A comprehensive overview on the typical architecture representative for a GSM network and the configuration as adopted for the network modelling in this study is compiled in Appendix B1-B2.

In order to model the use phase of the mobile phone network the following specifications for the operation mode were adopted:

OPERATION PARAMETER	SPECIFICATION
Frequency band	900 MHz
FDD	Yes
FDMA/TDMA	Yes
Speech coding	9.6 kbit/s
Normal circuit switched mode	Yes
GPRS	No
HSCSD	No
Transceiving units	12
Channels/transceiving unit	8
Max Nr. of subscribers	96

Tab. 5.2: Operation mode for which the investigated GSM network is designed. These specifications determine the hardware design.

5.2.3. Description of the Life Cycle System

Production Phase The production phase of a mobile phone network essentially begins with the manufacturing of the electronic elements (e.g.: racks, fans, etc.) of the network components (e.g.: BTS). The element manufacturing starts with the extraction of ores and energy sources and ends as the network component assembly is finalised and the component is ready for implementation and use. The production phase consists of the following major steps:

- Extraction of raw materials such as ores and their processing to basic materials such as metal alloys, ceramics or plastics.
- Manufacturing of basic element device units such as cables, shelves or Printed Wiring Board Assemblies[1].
- Assembly of element devices such as transceivers or servers.
- Final assembly of the electronic network component elements, e.g. an antenna rack.

Use Phase This phase follows the production phase and begins with the local installation of the network components and their integration into the network structure. In the course of the further operation the components are used for the services it is designed for. This phase typically includes maintenance such as periodical hardware services and software updates as well as the repair of defective network components, elements or devices (e.g. transceiver, etc.).

EOL Phase The EOL phase begins with the dismounting of the network components that have come to the end of their service life. However, only in case of a radical technology change-over, for example during the transition from analogue mobile telephony to digital (first generation[2] to 2G), entire mobile phone networks will be completely decommissioned and relieved. Typically the network components, or the installed elements, are dismounted step-by-step.

The EOL phase of a single mobile phone network component can be divided into eight major stages: dismounting, collection and storage, pre-separation, dismantling, fractionation, material recovery and production of secondary raw materials, thermal treatment, and final disposal (Scharnhorst *et al.*, 2005). Thermal EOL treatment processes have different functions: (i) compaction and elimination of scrap, (ii) extraction of energy and (iii) extraction of secondary raw materials.

To analyse the environmental implications of different EOL treatment strategies, the EOL scenarios described in (Scharnhorst *et al.*, 2005) were adopted and the following parameters were set:

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[1] PWBA.

[2] 1G.

- the share of network components that are immediately incinerated/disposed of, the other components being processed in recycling facilities, and
- the value correction factor.

5.3. *Life Cycle Inventory – Network Modelling – End-of-Life Treatment Modelling*

The compilation of inventory data, the modelling of the networks life cycle and the scenario assembly were carried out using the GaBi4 software (IKP&PE, 2003). For the background system, cumulative datasets provided by the Swiss national database for life cycle inventories – ecoinvent v1.01 (ecoinventCentre, 2003) – were adopted. Transport processes[1] were modelled using the relevant data sets included in the GaBi4 database (IKP&PE, 2003).

Network Modelling The analysed mobile phone network is modelled according to the specifications documented in the GSM standard (ETSI, 1996a) (ETSI, 1996b) (ETSI, 1996d) (ETSI, 1996e) (ETSI, 1999) (ETSI, 2000). The modelled network represents Swiss conditions (BAKOM, 2004, Orange, 2004, Sunrise, 2005, Swisscom, 2005). Maximum possible data transmission rate of 9.6 kbit/s was assumed for the operation of mobile phone network. The components are modelled based on operator and manufacturer information (Hausammann, 2005b, Swisscom, 2003). The component elements are modelled based on manufacturer documentations (ERICSSON, 2001, 2002, 2003, 2004, LucentTechnologies, 1998, 2000, Nokia, 2000, Palm, 2000, SiemensAG, 1999, 2000, 2003, Wilén, 2000). The network component devices such as connectors, filters, transceivers or servers are approximated by the basic materials of which these are made.

Technical data as well as information on the component element compositions were compiled from original component data sheets published by the manufacturers listed above. Supplementary information was compiled from manufacturer websites (LucentTechnologies, 2005) and from relevant books (Bekkers and Smits, 1997, Duque-Antón, 2002, Eberspächer *et al.*, 2001, Siegmund, 1999). Network infrastructure information such as overall network architecture, operation modes, etc. was obtained from network operators (Orange, 2004, SunriseAG, 2005, Swisscom, 2003) and from related literature (Eberspächer *et al.*, 2001, Scoullos *et al.*, 2001, Siegmund, 1999). Technical data on single network component devices such as transceivers and servers were collected from technical specification sheets (SiemensAG, 2002, SUNmicrosystems, 1999). Partly such data were determined by the author. Mass balance data, i.e. qualitative and quantitative information on the specific materials the component sub-units are made of, were partly adopted from literature and partly determined empirically.

The network data compiled for the investigation are valid for Western Europe and may not hold for other regions. The inventoried network corresponds to the GSM standard (ETSI, 1996b, 1996e, 1998). The network components of the base station subsystem (BTS, BSC) and of the network switching subsystem (MSC) were assumed to be configured for indoor use. The component elements (e.g. racks) are fully equipped, i.e. there was no room for component expansion. The specifications adopted do not hold for outdoor configurations. Replacement of component devices such as transceivers, servers, fans or any other unit was not envisaged during component operation time. The network components analysed in the study represent generic network elements and do not correspond to any existing network component type. The compiled data correspond to the data requirements given above.

Life Cycle Modelling The life cycle of the entire mobile phone network is divided into the production, the use and the EOL phase. The production phase covers the extraction of raw

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[1] i.) Klein-Transporter / 3,5 t zul.GGW / 2t NL / Nah
ii.) LKW-Zug / 38t zul.GGW / 26t NL / Fern

materials and their further processing. It also includes the energy consumed for the fabrication of PWBA. The assembly of individual component element devices (e.g. transceivers, filters, etc.) and the installation of the network components is not modelled. In the use phase only the energy consumed to operate the network is considered. Maintenance services are excluded. The EOL phase is split up into consecutive stages as described. Each of the stages includes sub stages representing the different EOL treatment processes (Scharnhorst *et al.*, 2005). These processes include the EOL treatment infrastructure needed in the respective stage and energy supply. Secondary raw materials produced in the EOL phase are assumed to partly substitute primary raw materials in the production phase. Administration processes were not considered in any of the life cycle phases.

Information on the basic materials the device units consist of was taken from (Goosey and Kellner, 2002, Ludwig *et al.*, 2003); (Conrad, 2000). Information on the production of PWBAs was gathered from literature (Kincaid and Geibig, 1998, Malmodin *et al.*, 2001). For the use phase information on the power consumption of the switching network components was adopted from the manufacturer data sheets listd above. Energy consumption data of the mobile phones were estimated (Stromtip.de, 2000). Information on the dismounting and storage of network components was obtained from manufacturers (Hausammann, 2005a). Transport distances in the EOL phase were estimated based on the present Swiss GSM topology (Kaden, 2003) and of the regional distribution of the EOL treatment facilities in Switzerland and Europe. Information on the processing of network components (pre-treatment, fractionation, etc.) after dismounting was partly obtained from recyclers (Stengele, 2004) and partly from literature (Ludwig *et al.*, 2003). Technical specifications of the recycling facilities were compiled from manufacturer data sheets (BückmannGmbH, 2001a, 2001b, 2001c).

Most process data were adopted directly from the ecoinvent database (v1.01) (ecoinventCentre, 2003). Transport process data were adopted from the GaBi4-data base (IKP&PE, 2003). Most data for incineration and final disposal processes were adapted from the ecoinvent database, based on closely related processes (Scharnhorst *et al.*, 2005). Transfer coefficients and transfer fractions for incineration and landfill processes were adopted from (Scharnhorst *et al.*, 2005). Detailed inventory information is given in (Scharnhorst *et al.* 2005).

The data adopted for the analysis are applicable to Western European conditions and may not hold outside that region. Also, the data are valid for the time period indicated above and may not be applicable in other time periods. The energy consumption data for the manufacturing of PWBA are valid for 1998. Data on the energy consumption in the use phase are valid for the 1999 through 2005. The data for the EOL stages pre-treatment, dismantling and fractionation represent Swiss conditions between 2000 and 2004. Technical specifications on the material recovery processes apply to the Swedish BOLIDEN plant (HELCOM, 2002, Isaakson and Lehner, 2000, Ludvigsson and Larsson, 2003). Incineration and final disposal data are valid for the period from 2000 to 2004.

5.4. *Life Cycle Inventory – Selected Data Sets*

A large data base has been compiled in order to investigate the environmental consequences of the EOL treatment of a 2G mobile phone network. The presentation of all data here is impossible. Therefore a selection of important data used in the study is presented here.

Key components of network component elements in general are the electronic devices, i.e. the PWBA with all the chips, sensors, switching elements, etc. In the tables below the most important inventory data are compiled (Tab. 5.4).

Table 5.3 gives an overview of the available data describing the energy consumed during the production of a typical PWBA (populated). The data (given in MJ/kg) were determined based on the information found in the respective sources. The value derived from (Kincaid and Geibig, 1998) has been selected as reference value in the study presented here due to is transparency.

Source	**Energy consumption during PWBA manufacturing [MJ/kg]**	**Year**	**Comment**
(Malmodin *et al.*, 2001)	652.1	2001	Calculated based on given specification
(Kincaid and Geibig, 1998)	633.1	1998	“; value has been selected for this study
(Anonymous, 2003)	390.7	2003	Calculated based on given specification

Tab. 5.3: Total energy consumed in the manufacturing of PWBA.

The basic material composition of a PWBA is given in Table 5.4. In most cases the data had to be estimated based on data for electronic devices (e.g. PCs) as such. In a few cases it was possible to adapt data directly. The inventoried data was compared with recently measured data for a PWBA of an antenna rack and a mobile phone respectively. The quality of the inventoried data was estimated based on this comparison.

Materials	**Material content [%] in a PWBA (populated)**	**Source**	**Data quality**	**Evaluated[1]**	**Represented by data sets from…**
Metals	**33.40262492**				
Fe	10.6	estimated based on (Ludwig *et al.*, 2003)	O	X	ecoinvent
Al	4.8	(Ludwig *et al.*, 2003)	+	X	ecoinvent
Cu	3.5	estimated based on (Ludwig *et al.*, 2003)	O	X	ecoinvent
Sn	3.0		++	X	ecoinvent
Pb	3	(Ludwig *et al.*, 2003)	++	X	ecoinvent
Br	2.7		++	X	own estimation
Mn	2.1	estimated based on (Ludwig *et al.*, 2003)	+	X	ecoinvent
Zn	1.4		++	X	ecoinvent
Sb	0.45	(Ludwig *et al.*, 2003)	++	X	own estimation
Ni	0.3		+	X	ecoinvent
Cl	0.15	estimated based on (Ludwig *et al.*, 2003)	O	-	ecoinvent
Na	0.15		O	-	ecoinvent
Cr	0.131		++	X	ecoinvent
Cd	0.0395		+	X	ecoinvent
Co	0.0083		++	X	ecoinvent
Hg	0.0009		++	-	ecoinvent
Ag	0.1		++	X	own estimation
Pt	0.02	(Ludwig *et al.*, 2003)	O	-	ecoinvent
Au	0.0005		+	X	own estimation
Pd	0.142863739		+	X	ecoinvent
Ge	0.142863739		O	-	own estimation
Ga	0.142863739		O	X	own estimation
Ta	0.071431869		+	-	own estimation
In	0.071431869		+	-	own estimation
Be	0.071431869		+	-	own estimation
Eu	0.047621246		O	-	own estimation
Ru	0.142863739		O	-	own estimation
Bi	0.071431869		++	X	own estimation
As	0.047621246	estimated based on (Conrad, 2000)	O	X	own estimation
Se	0.043545		O	-	ecoinvent
Ceramics/Glasses	**49**	(Ludwig *et al.*, 2003)	+	X	ecoinvent
Plastics	**17.7**	estimated based on (Ludwig *et al.*, 2003)	++	X	ecoinvent
TOTAL	**100.1026249**				

Tab. 5.4: Material inventory of a representative PWBA of an antenna rack. Data quality: ++ (excellent), + (good), O (sufficient). Data evaluation: X (data available), - (no data available).

In Table 5.5 the most important inputs and outputs related to the EOL treatment of 1 kg of PWBA scrap are compiled. The data refer to the thermal treatment of the PWBA scrap in a smelter unit.

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[1] Compared with measured data.

Input			[kg]
	EOL goods		
		PWBA	1.0000
		other scrap	6.2986
	Technosphere		
		Lignite	0.2792
		Natural gas	0.3393
		Raw oil	0.3046
		Gravel	0.3650
		Hard coal	0.3470
Output			
	Emissions to air		
		Carbon dioxide	3.1602
		Nitrogen oxide	0.0094125
		Sulphur dioxide	0.0053869
		Carbon monoxide	0.0046318
	Emissions to water		
		Hydrocarbons to water	0.071393
	Emissions to soil		
		Oil (unspecified)	0.00053053
	Secondary raw materials		
		Aluminium	1.3355
		Iron	0.04082
		Gold	1.91E-06
		Copper	0.41289
		Palladium	0.00054465
		Selenium	0.00016601
		Silver	0.00038123
		Steel	4.963

Tab. 5.5: Input and output data determined for the thermal treatment of 7.3 kg of network and 1 kg of PWBA scrap.

5.5. *Life Cycle Impact Assessment*

The results of the impact assessment are presented in the following chapter. In a first step, the results at damage level for the three life cycle phases, production, use, and EOL treatment, of the mobile phone network are compiled. In a second step, the environmental implications for different EOL treatment scenarios are presented.

5.5.1. **Human health**

This damage category is dominated by effects of inorganic emissions on human respiratory organs (Fig. 5.2; impact category: **respiratory inorganic effects**). The use as well as the production phase dominates the total impact in nearly equal shares (51% and 45% respectively). The production, operation and EOL treatment of the BTS, i.e. the BTS racks, causes the largest environmental impacts (24%, 37% and 0.4 % respectively of the total category impact). In the use phase particle emissions to air as well as secondary particle creating emissions of SO_2 and NO_x to air during the generation of electricity represent the major impacting sources (39%, 34% and 26% of the use phase impact). The impact of the production phase is dominated by direct SO_2 emissions to air released in the processing of primary palladium and platinum (44% and 19% of the production phase impact). Large SO_2 emissions to air are caused by the roasting of the platinum group metal ores in Russia (Althaus *et al.*, 2003). The contribution of the EOL phase to this impact category is comparatively low (<5% of the total category impact). Major sources are landfill processes of construction waste of BTS cabins.

Major **non-carcinogenic effects** are wreaked by heavy metals emissions to water (in particular zinc and arsenic) during the electricity generation for the use phase. Again the energy intensive operation of the BTS increases the release of these environmentally critical elements (52% of the total category impact). To a lower extent, the energy-intensive fabrication of PWBA for the BTS racks as well as the production of lead for the BTS back-up batteries contribute with 11% of the total category impact. In particular water-borne emissions of zinc and arsenic in the primary lead production contribute to this impact category. In the EOL phase direct emissions of heavy metals such as arsenic and cadmium from landfill contribute to that impact category.

Organic emissions released in the use phase (69% of the overall impact category) contribute mainly to the **photochemical oxidation** reactions category. This impact category is dominated by releases of Non-Methane Volatile Organic Compounds[1] to air during the generation of electricity for the use phase (consumed by the BTS racks). In the production phase the energy produced for the assembly of PWBA and the production of primary steel cause major NMVOC emissions to air. These two processes contribute with 28% and 42%, respectively, to the total production phase impact. In the EOL phase the disposal of construction waste of BTS cabins causes direct NMVOC emissions to air contributing partly to this impact category.

Carcinogenic effects deriving from the use phase are dominated by releases of Benzo(a)pyrene to air (24% of the total impact), arsenic to air (20% of the total impact) and to water (23% of the total impact). The source of these indirect emissions is the electricity generated for and consumed primarily by the BTS racks. In the production phase the production of lead for the BTS back-up batteries causes significant emissions of arsenic to water contributing to this impact category. Indirect Benzo(a)pyrene emissions to air from the energy generated for PWBA manufacturing as well as direct arsenic emissions to water in the production of steel also contribute to the carcinogenic effects deriving from the production phase. Direct impacts by the EOL phase are primarily attributable to landfilled arsenic.

The **respiratory organic effects** are dominated by NMVOC emissions to air released from electricity generation processes. The BTS, in particular the racks, dominate this impact category. In the production phase, the energy supplied and consumed for PWBA assembly as well as for the production of primary steel cause major NMVOC emissions to air (24% and 38% of the total production phase impact). In the EOL phase the disposal of construction waste of BTS cabins causes direct NMVOC releases to air contributing to this impact category.

Ionising radiation and **ozone depletion** contribute only little to this damage category. Both impact categories are dominated by the use phase. The production and the EOL phase cause marginal effects. Radon (Rn222) and carbon (C14) emissions to air originating from electricity generation dominantly contribute to the ionising radiation category. Releases of CFC-114 and Halon 1211 from electricity generation dominate the ozone depletion category. The Halon 1211 emissions are attributable to gas transportation processes and to offshore natural gas and oil production.

Figure 3 indicates that recycling of basic materials shows a distinct reduction of impacts on human health both in the EOL phase and the production phase (if substitution of secondary for primary materials according to the selected value correction factor is assumed).

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[1] NMVOC.

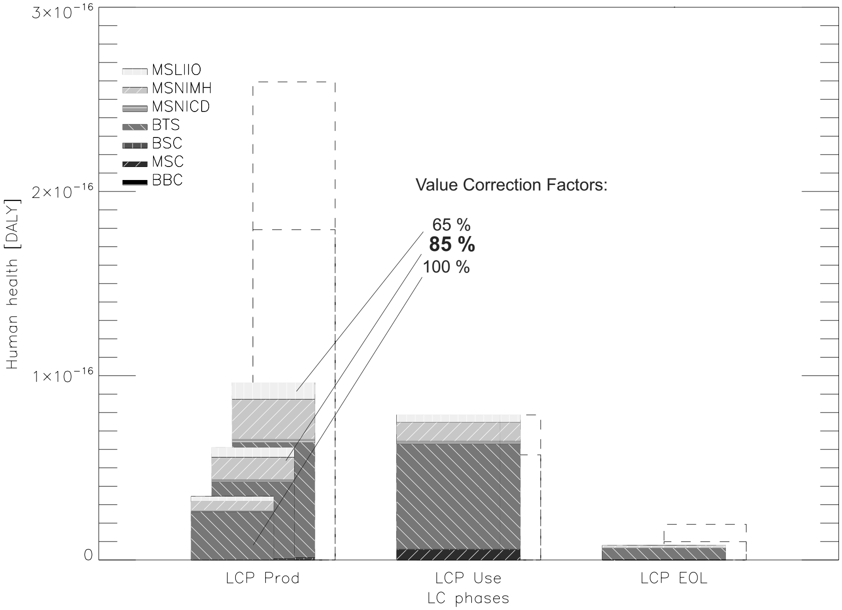

Fig. 5.2: Contributions of the life cycle phases: production (Prod), use (Use) and EOL (EOL) of the GSM network to the overall impact on human health (HH). Scenario 3 was selected to represent the EOL phase. "BBC" denotes the backbone cable network[1]. The dashed bars indicate the networks environmental impact if no recycling takes place at all. In this case not even aluminium and steel from the antenna stations are recycled (cf. Tab. 5.1).

5.5.2. **Ecosystem quality**

Effects on the **terrestrial ecotoxicity** dominate the total ecosystem quality (Fig. 5.3). The EOL phase causes the largest effects (58% of the total terrestrial ecotox category), followed by the use phase (36%). A small impact is attributable to the production phase.

Disposal processes in the EOL phase of the mobile phones and the BTS (accounting for 53% and <5%, respectively, of the total terrestrial ecotoxicity effects) represent the major impact sources. Emissions, in particular long-term emissions, of nickel released from landfilled mobile phones to soil contribute with 46% to the total category impact. To a minor extent, zinc emissions to air during the recycling of the lead containing BTS back-up batteries contribute to this category.

The **aquatic ecotoxicity** category contributes to a lower extent to the ecosystem quality. Here the EOL phase has the lowest impact, compared with the use phase (81% of the category impact) and the production phase (15% of the category impact). Aluminium emissions released to water in the electricity generation contribute significantly to the aquatic ecotoxicity category. Thus, the energy-intensive operation of the BTS (73% of all network components) dominates this impact category in the use phase, while the energy intensive assembly of the PWBA (48% of the production phase impact) contributes significantly to this impact category in the production phase.

Figure 5.3 indicates that recycling of electronic scrap instead of landfilling it entails significant environmental benefits in the EOL phase.

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[1] MSLIIO	…	Mobile phones equipped with Lithium-Ion rechargeable batteries.
MSNIMH	…	Mobile phones equipped with Nickel Metalhydride rechargeable batteries.
MSNICD	…	Mobile phones equipped with Nickel-Cadmium rechargeable batteries.

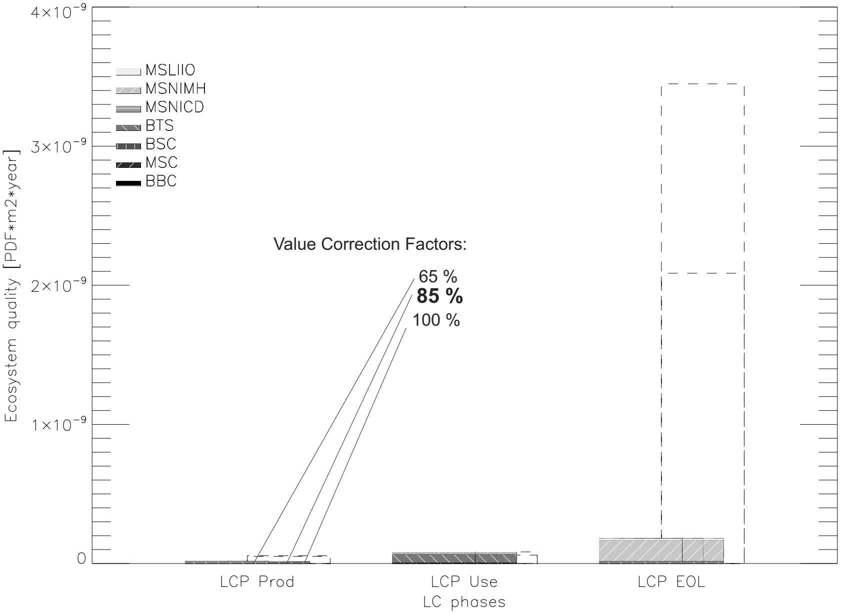

Fig. 5.3: Contributions of the life cycle phases: production (Prod), use (Use) and EOL (EOL) of the GSM network to the overall impact on ecosystem quality (EQ). Scenario 3 was selected to represent the EOL phase. "BBC" denotes the backbone cable network[1]. The dashed bars indicate the networks environmental impact if no recycling at all takes place at all. In this case not even aluminium and steel from the antenna stations are recycled (cf. Tab. 5.1).

5.5.3. **Resource consumption**

The energy-intensive operation of the mobile phone network (use phase) contributes dominantly to the depletion of **non-renewable energy** resources (Fig. 5.4). The switching network components (MSC, BSC, and BTS) contribute with 69% to this impact category and the mobile phones contribute to 10%. The consumption of uranium, hard coal and natural gas in energy supply processes dominate this impact category. The resource depletion effects in the production phase are attributable to the energy-intensive manufacturing and assembly of PWBA.

The other processes such as the production of basic materials have only a minor impact. Recycling and substitution of basic materials does not lead to notable impact reductions. The small effect of the EOL phase can almost exclusively be attributed to the energy consumption for the recovery of the BTS back-up batteries.

---

[1] MSLIIO	…	Mobile phones equipped with Lithium-Ion rechargeable batteries.
MSNIMH	…	Mobile phones equipped with Nickel Metalhydride rechargeable batteries.
MSNICD	…	Mobile phones equipped with Nickel-Cadmium rechargeable batteries.

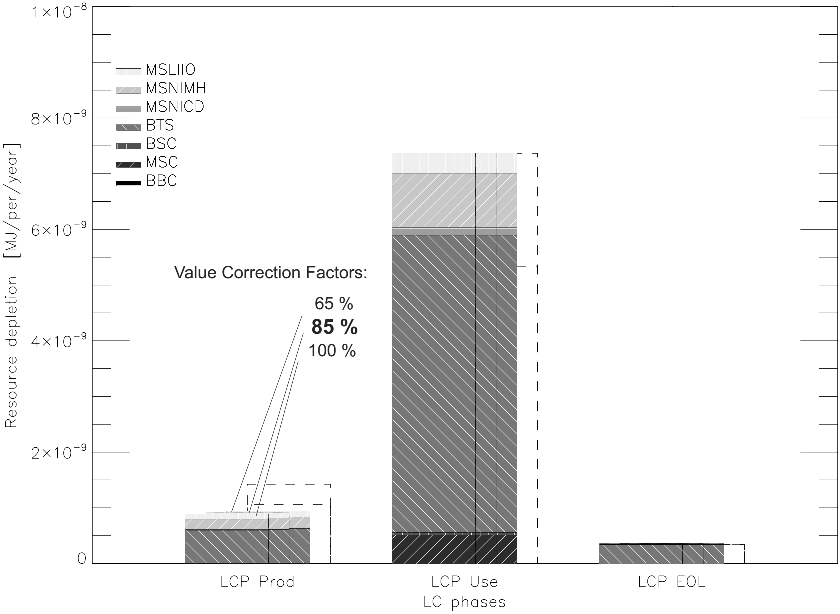

Fig. 5.4: Contributions of the life cycle phases: production (Prod), use (Use) and EOL (EOL) of the GSM network to the overall impact on resource depletion (RD). Scenario 3 was selected to represent the EOL phase. "BBC" denotes the backbone cable network[1]. The dashed bars indicate the networks environmental impact if no recycling at all takes place at all. In this case not even aluminium and steel from the antenna stations are recycled (cf. Tab. 5.1).

5.5.4. **Climate change**

Comparing the life cycle phases reveals that CO_2 emissions from power generation for the use phase dominate the total effect on **global warming** (Fig. 5.5) . The power consumption of the BTS (contributing with 60% to the total climate change effects) and mobile phones (contributing with 16% to the total climate change effect) cause large CO_2 emissions.

The energy-intensive manufacturing of PWBA in the production phase causes large indirect CO_2 emissions and dominates with 56% the effects on climate change in this phase. The production of basic materials such as aluminium, steel or palladium cause only minor direct and indirect effects to climate change. Recycling and substitution of basic materials only leads to a small reduction of CO_2 emissions from the production phase. Consequently, an increase of the value correction factor for precious metals such as gold or silver and other materials known to require energy intensive processing does not lead to a significant reduction in the overall global warming impact.

The small effect of the EOL phase is almost exclusively attributable to the combustion of natural gas in the production of secondary steel.

---

[1] MSLIIO	…	Mobile phones equipped with Lithium-Ion rechargeable batteries.
MSNIMH	…	Mobile phones equipped with Nickel Metalhydride rechargeable batteries.
MSNICD	…	Mobile phones equipped with Nickel-Cadmium rechargeable batteries.

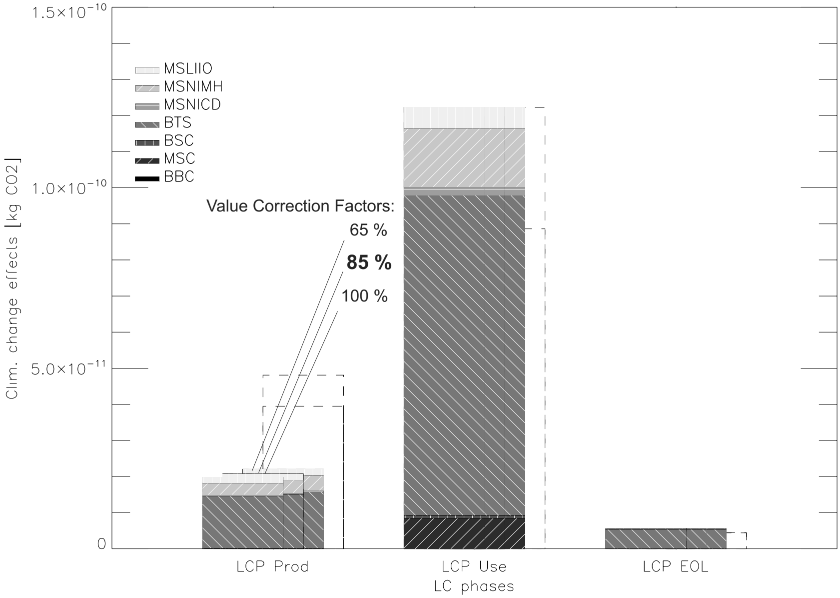

Fig. 5.5: Contributions of the life cycle phases: production (Prod), use (Use) and EOL (EOL) of the GSM network to the overall impact on climate change (CC). Scenario 3 was selected to represent the EOL phase. "BBC" denotes the backbone cable network[1]. The dashed bars indicate the networks environmental impact if no recycling at all takes place at all. In this case not even aluminium and steel from the antenna stations are recycled (cf. Tab. 5.1).

5.6. *EOL Scenario Analysis*

Figure 5.6 shows the environmental impacts of the six EOL scenarios for the mobile phone network. The impacts of the production phase are added to the EOL impacts here, because recovered materials are assumed to be recycled to production (at scenario-specific recycling rates) in order to measure the environmental benefit of recycling. The use phase impacts are not included in Figure 7, because they are not affected by the EOL scenarios. The impact assessment results are given at non-normalised midpoint level in the following impact categories: carcinogenic effects[2], non-carcinogenic effects[3], respiratory organic effects[4], respiratory inorganic effects[5], ozone layer depletion[6], photochemical oxidation[7], ionising radiation[8], aquatic ecotoxicity[9], terrestrial ecotoxicity[10], non-renewable energy[11], mineral extraction[12], and global warming potential[13].

---

[1] MSLIIO	…	Mobile phones equipped with Lithium-Ion rechargeable batteries.
MSNIMH	…	Mobile phones equipped with Nickel Metalhydride rechargeable batteries.
MSNICD	…	Mobile phones equipped with Nickel-Cadmium rechargeable batteries.

[2] CarcEff.

[3] NonCarcEff.

[4] RespOrg.

[5] RespInorg.

[6] Ozone.

[7] PhotoOx.

[8] IonRad.

[9] AquEcox.

[10] TerrEcox.

[11] NonReE.

[12] MinEx.

[13] GlobWarm.

The environmental impact of the production phase dominates in almost all categories (except in aquatic and terrestrial ecotoxicity). The recycling of electronic scrap in the EOL phase (scenarios 3-5) promotes the reduction of environmental impacts. The differences between the scenario groups 0-2 and 3-5 are especially large with reference to terrestrial and aquatic ecotoxicity as well as to respiratory inorganic and non-carcinogenic effects. On the other hand, the differences within scenario groups 0-2 and 3-5, respectively, are not significant, i.e. variations in processing of scrap in these two groups of scenarios are only of minor importance.

Comparing the environmental impacts of the different EOL treatment scenarios category by category indicates that scenario 3 causes the least environmental impacts (Fig. 7) and represents the preferable option therefore. The results further indicate that all electronic scrap containing precious metals should be treated in specialised metal recovery plants. The small increase in environmental impacts on resource quality by the recycling of precious metal scrap (Fig. 6) is countervailed by a significant reduction of environmental impacts attributable to the avoided production of primary materials (Figs.: 3-6). The diagram shows that fractionation has no relevant adverse environmental impacts. Thus, this treatment prior to the recovery of precious materials also can be omitted. It does not improve the production of secondary materials, i.e. the environmental impacts of the secondary material production are not reduced.

The energy for the assembly of PWBA and, to a lower extent, the production of primary materials to replace lost materials causes major contributions to each of the selected impact categories.

Long-term emissions of copper, zinc and arsenic to soil and of copper and aluminium to water due to landfilling cause distinct terrestrial and aquatic ecotoxic as well as non-carcinogenic effects in all scenarios.

Less or no detectable impacts result for lead, cadmium and other heavy metals known to cause toxic impacts.

Scenario 2 (immediate network component incineration and subsequent landfilling) causes a significant amount of harmful emissions and should therefore be avoided.

Thermal treatment of electronic scrap and/or of residuals in MSWI plants prior to landfilling (scenario 2) can cause the release of highly volatile materials, e.g. arsenic and bromine, contributing to all impact categories except respiratory inorganic effects, ionising radiation and depletion of non-renewable energy. These volatile materials can increase the environmental impacts and thus combustion in such plants prior to landfilling should be avoided, unless the ashes are well stabilised, which would reduce long-term emissions, and a significant energy recovery could be achieved by incinerating by-products.

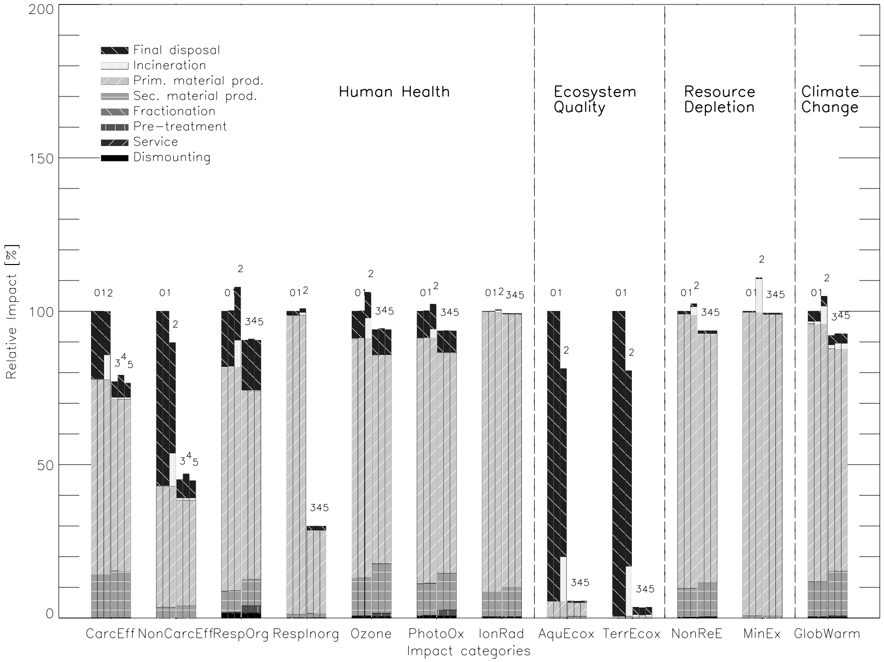

Fig. 5.6: Comparison of the EOL treatment scenarios for a typical GSM network (0 = scenario 0, 1 = scenario 1, etc.). The impact categories (at non-normalised midpoint level) are grouped according to damage categories. In each impact category scenario 0 was set to 100%. Impacts are related to the transmission of 1 data bit (functional unit of the study).

5.7. *Discussion and Conclusion*

General The environmental impacts of a GSM network are dominated by the use phase for most damage categories. In case of human health, the production phase contributes significantly to the overall impact of the network. It is assumed that the contribution of the production phase could be even higher if the auxiliaries consumed in, for instance, the manufacturing of PWBA would have been taken into account.

Ecosystem quality is primarily affected by impacts attributable to the EOL phase. It has been shown that recycling of materials, in particular of precious and rare metals, reduces the environmental impacts both by reducing the EOL phase's own impact and by avoiding the production of primary materials.

Key impacts during the life cycle of a complete GSM network are attributable to:

- a.) the energy intensive operation of the base transceiver stations and partly also the mobile phones,
- b.) the energy intensive manufacturing and the assembly of printed wiring board assemblies (Singhal, 2005),
- c.) distinct inorganic emissions to air during the primary production of precious metals affecting human health, and
- d.) direct emissions of heavy metals from final disposal processes.

The results show that final disposal without material recycling can cause significant ecotoxic and non-carcinogenic health effects (Fig. 5.6). However, it has to be mentioned that the emissions inventoried and assessed for the landfill processes have to be interpreted with reservation. Firstly, current LCA methodology considers overall integrated emissions. These emissions relate to landfill processes occurring over long time periods (i.e. 60.000 years). Secondly, neither the data bases used for the analysis nor the IMPACT2002+ method distinguishes explicitly the particular chemical state of each element, especially the metal speciation, in which it is released to the environment. That means that the method does not take into account whether a certain metal is effectively bio-available or not.

Finally, it is assumed that the present impact assessment methods underestimate the effects associated with the depletion of very rare metals, for instance of indium and gallium. No characterisation factors are available for these resources.

It has also been shown that advanced fractionation, i.e. a material specific separation of electronic scrap prior to material recovery does neither significantly contribute to the environmental impact of EOL treatment nor significantly improve the material recovery processes. Weidman *et al.* (2001) and Grunewald *et al.* (1999) arrive at comparable conclusions. Thus, under the assumptions underlying this study, fractionation can be omitted without environmental disadvantage.

Recommendations to Recyclers and Operators As the network components reach the end of their service life, they should be dismounted and adequately processed. BTS masts as well as BTS-, BSC- and MSC-cabins should be re-used as infrastructure parts.

Disassembling the racks of the switching network elements (BTS-, BSC- and MSC-racks) and the removal of the rack sub-units (transceivers etc.) is sufficient to achieve an environmental optimum. All electronic scrap containing precious metals should be treated in specialised metal recovery plants to effectively recover precious metals. Aluminium and steel should be treated in steel works and aluminium plants. The rest of these materials should be used in other production processes. Landfilling should be avoided.

Additional incineration can lead to emissions of heavy metals, in particular of arsenic and arsenic-compounds in dispersed form, which may react toxic to the environment (Uryu *et al.*, 2003). Therefore incineration of electronic scrap, as e.g. printed wiring board assemblies or

parts of them, prior to landfilling should only be performed if appropriate filter facilities are used and if ashes are long-term stabilized and recoverable energy is significant. The
Landfilling electronic and/or infrastructure components containing precious or toxic metals should be avoided. Precious metals are lost and have to be replaced at the cost of high environmental impacts and, due to the unnaturally high concentration of metals in landfill sites, potentially toxic emissions are released to soil and water.

Recommendations to Manufacturers and Operators To reduce the environmental impacts of mobile phone networks, the following two issues need to be addressed:

i.) reduction of the energy consumption in the use phase,
ii.) reduction of the energy consumption for the manufacturing and assembly of printed wiring board assemblies.

In the use phase, advanced operation plans focussing on the avoidance of full-load traffic of single switching network components can help to reduce the environmental impacts of this phase.

The electronic components, i.e. the different electronic sub-units (e.g. transceivers, servers, etc.) containing printed wiring board assemblies, should have standardised shapes and interfaces to facilitate re-use. Prolonged upgradeability of the sub-units could lead to an extended service life of these units. Furthermore, a reduction of the energy consumption for the operation of components can contribute to a reduced environmental impact.

Wherever possible, the palladium and platinum metals used in contact materials of printed wiring board assemblies should be either recycled at the highest possible rates or they should be replaced by less precious materials.

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6. *Network Component Experiment*: Heavy Metal Partitioning from Electronic Scrap during thermal End-of-Life Treatment[1]

6.1. *Introduction*

Electronic devices, in particular mobile communication equipment, have rapidly penetrated the modern society during the past years. As a result of the rapid technological evolution for example mobile phones commonly have a short service life of only about one year (Scharnhorst *et al.*, 2005a). Correspondingly, the amount of electronic scrap increases drastically. This scrap represents a complex mixture of three major material fractions: *i.)* metals (alloys), *ii.)* plastics and *iii.)* ceramics. Metals, particularly heavy metals, represent the quantitatively dominating fraction. In order to recover valuable materials and to avoid simple dumping, the scrap can be processed mechanically and/or thermally. In Europe typically a combination of mechanical and thermal End-of-Life[2] treatment is applied, the latter one being the key metal and energy recovery option. Thermal EOL treatment of electronic scrap has been recognised as presently the most effective recycling method. However, there exist concerns about the environmental compatibility, in particular with respect to the mobility and the emission rates of heavy metals.

Numerous fundamental experimental studies on the partitioning of heavy metals during the combustion of synthetic scrap samples have been performed (Chiang *et al.*, 1997, Morselli *et al.*, 1993, Paoletti *et al.*, 2001, Wang *et al.*, 1997, Waterland *et al.*, 1991, Wobst *et al.*, 2001). Similar fundamental theoretical studies have been undertaken (Ljung and Nordin, 1997, Soerum *et al.*, 2003, 2004, Verhulst *et al.*, 1996). Particular attention has been devoted to the interactions between plastics and components in plastics during incineration, stressing the formation of toxic organic substances (Wey *et al.*, 2000, Wey *et al.*, 2001, Wobst *et al.*, 2003). Only a few analyses have been carried out studying the thermal behaviour of electronic scrap (Antonetti *et al.*, 2004a, Balabanovich *et al.*, 2003, Blazsó *et al.*, 2002). They indicate that copper is retained at best below five minutes of residence in the incineration chamber of fluidised bed incinerator (Antonetti *et al.*, 2004b). It has also been shown that flame retardants are decomposed simultaneously with the decomposition of at epoxy resins temperatures between 240-400°C (Blazsó *et al.*, 2002). Hitherto, little or no investigations have been performed on the combustion of Printed Wiring Board Assemblies[3] in Municipal Solid Waste Incineration plants[4] and paying attention to the volatility of heavy metals during the incineration. However, present and forthcoming governmental regulations implicitly require a sound and in-depth knowledge on the environmental consequences related to thermal EOL treatment of electronic scrap (CEC, 2003a, 2003b).

In the present study, incineration experiments have been performed, in order to provide basic knowledge on the partitioning of heavy metals during thermal EOL treatment of PWBA. The study in particular addresses the following issues: Under which treatment conditions are which heavy metals volatilized? Under which conditions are heavy metals retained in the bottom ash? Which treatment conditions can prevent the volatilisation of heavy metals? What are

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[1] This chapter is based on the paper: Scharnhorst, W., Ludwig, C., Wochele, J., Schuler, A., Hilty, L. M. and Jolliet, O. (2005): Heavy metal partitioning from electronic scrap during thermal End-of-Life treatment. Submitted to Environmental Science & Technology: ***accepted, pending minor revision***.

[2] EOL.

[3] PWBA.

[4] MSWI.

the expected fractions of metals transferred to the gas phase during incineration, to be further used in Life Cycle Assessment[1] studies involving PWBA?

This paper compiles the results of a set of incineration experiments performed with PWBA-scrap. Representative and identical samples of one typical PWBA, used in antenna racks of modern mobile phone networks, have been incinerated in a Quartz Tube Reactor[2] under different conditions. The ashes have been analysed using an Inductively Coupled Plasma - Optical Emissions Spectrometer[3]. The ICP results were compared with the results of a material composition analysis of an identical PWBA. In preparation of the incineration experiments Thermo-Gravimeter-ICP[4] experiments were performed in order to gain knowledge on the relationships between incineration temperature, redox conditions and volatility of the selected metals. All experimental results were compared with results of thermodynamic equilibrium calculations and with related literature.

The findings of the study will be used in order to approach reliable transfer coefficients for heavy metals, which in turn will be used in LCA studies on the environmental effects related to the EOL treatment electronic scrap.

6.2. *Experimental set-up*

Scrap Samples and Preparation Three identical PWBA were dismounted from antenna racks deployed in antenna stations of modern mobile phone networks. The boards were manually cut into pieces of ~ ∅ 2 mm. For the material analysis and the TG-ICP experiments, the pieces were further milled to the experiment specific final grain sizes as compiled in Tab. 6.1 (Fig. 6.1).

Fig. 6.1: PWBA before cutting (A), manually cut PWBA (B), pulverised PWBA (C).

To perform the TG-ICP- and the QTR-experiments, the cut and milled PWBA-scrap was separated into homogenous samples.

Experiment	Number of PWBA [-]	Mass of PWBA [g]		Cut Method	Grain Size [∅ mm]
		uncut	cut		
Material Analysis	1	217.4	217.0	milling (machine)	< 0.05
TG-ICP	1	217.6	200.0	milling (machine)	0.05
QTR	1	218.2	210.0	cutting (manual)	~ 2

Tab. 6.1: Experiments, cut methods and final grain sizes of the analysed PWBA samples.

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[1] LCA.

[2] QTR.

[3] ICP-OES.

[4] TG-ICP.

The fractions of the analysed heavy metals contained in the investigated PWBA samples are compiled in Tab. 6.3 (Motorola, 2005). Though the heavy metal concentrations were partly low, no enrichment was performed.

Apparatus and Thermal Treatment Conditions The QTR consists of a stationary heating unit zoned into three individual heating sections (Dettmer, 2001),(Keller *et al.*, 2005).

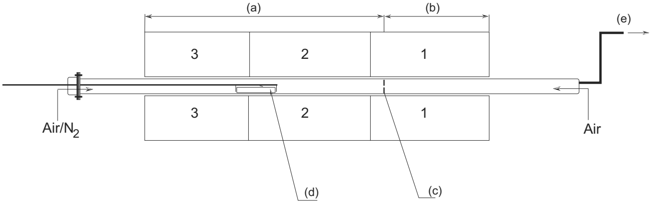

Fig. 6.2.: Longitudinal section of the QTR reactor.

A quartz glass tube is mounted horizontally into the heating unit (Fig. 6.2). Using a blend (c), this tube is separated into two chambers: the incineration chamber (a) and the afterburner (b). A manually moved quartz vessel (d) (100% made of Al_2O_3) carries the PWBA-scrap samples inside the glass tube. Gas/air (primary and secondary streams) is supplied via two inlets at the lower corners of the quartz glass tube. Exhausting air is released via the exhauster pipe (e). Four experiments were performed in the QTR under the conditions listed in Tab. 6.2.

No.	Incineration conditions	Incineration time [min]	Temperatures [°C] in reactor zones			Gas stream [Nl/h]	
			1	2	3	primary	secondary
1	oxidising	60	550	550	550	air 1040	air 500
2	reducing	60	550	550	550	N_2 500	air 500
3	oxidising	60	880	880	880	air 1040	air 500
4	reducing	60	880	880	880	N_2 500	air 500

Tab. 6.2: Incineration conditions.

Preparative incineration experiments were performed using a TG-ICP. Using a Condensation Interface[1] small particles are produced and transferred from the TG to the plasma flame in the ICP-OES (Ludwig *et al.*, 2001, Winkel *et al.*, 2004). Measurements were performed at 100-900°C. The temperature was raised in steps of 4K.

Analytical Techniques The collected incineration residues (residual masses are given in Tab. 6.3) were digested with aqua regia and by applying flow back during six hours and at 100°C. Thereafter, the solution was separated from undissolved particles by means of centrifugation. Residual analysis was performed using an ICP-OES spectrometer.

Thermodynamic Calculations The thermodynamic equilibrium calculation software HSC chemistry (Roine, 2002) was used to determine the speciation of the volatile and non-volatile compounds and to hereby evaluate the evaporation behaviour of selected metal species. The software includes a database comprising 17,000 species. When calculating the evaporation behaviour of a particular element the software searches for all species of this element in the database. Thermal equilibrium calculations were performed for the following the most prominent metals contained in PWBA: Ni, Zn, Pb, Sb, Cd, Br, Ga, As.

The calculations were performed for oxidising and for reducing conditions in a temperature range between 100 through 2000°C. Basis for the calculation was the material composition of a PWBA identical with the incinerated boards (Tab. 6.3 and (Motorola, 2005)).

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[1] CI.

6.3. ***Results and Discussion***

The TG-ICP and the QTR-results are presented and discussed below. Quantitative results for the volatilisation of the metals are compiled in Tab. 6.3[1].

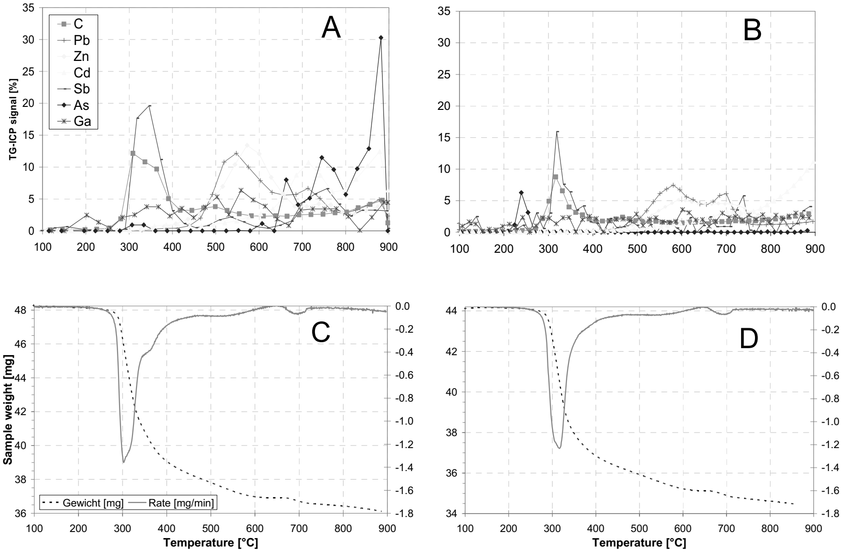

Fig. 6.3: TG-ICP measurements for selected metals under reducing (Dia. A and C) and under oxidising (Dia. B and D) conditions. Beneath the decline in the total sample weights (dashed lines) and the rates of decline are shown (bold lines).

Arsenic *Thermodynamic predictions* As is completely volatilised at 500°C under reducing conditions (Ljung and Nordin, 1997, Soerum *et al.*, 2003, Verhulst *et al.*, 1996) and in the presence of bromide (formation of $AsBr_3$). Under oxidising conditions, the volatilisation of As begins at 450°C (formation of As_4O_{10}). Complete volatilisation is calculated for temperatures above 1500°C (Wochele, 2005).

Experiments The TG-ICP measurements indicate that the volatilisation of As strongly depends on the supply of oxygen during the incineration of PWBA-scrap. Whereas under oxidising condition little As is volatilised at temperatures below 300°C, under reducing conditions the volatilisation begins at temperatures above 600°C. In the QTR-ash no As could be detected neither under oxidising nor reducing conditions (at 550 and 880°C).

Evaluation In contrast to the theoretical predictions and the experimental results obtained the presented study, Waterland *et al.* (Waterland *et al.*, 1991) detected 90% As discharged in the bottom ash of a laboratory scale incinerator. They presumed a formation of more stable arsenates instead of volatile arsenic. In contrast, modelling the environmental fate of GaAs-compounds of PWBA, Uryu *et al.* (Uryu *et al.*, 2003) calculated about 80% of As in the gas phase. Performing field studies, Morselli *et al.* (Morselli *et al.*, 1993) detected 48% As in the bottom ash of a MSWI plant. Likewise, Belevi *et al.* (Belevi and Moench, 2000) measured about 70% of As in the bottom ash of a MSWI.

There are several reasons why As could not be detected in the here documented ash analysis: Under reducing conditions, As might have been completely volatilised. An assumption, which is corroborated by the TG-ICP measurements and the thermodynamic calculations. Also, the

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[1] The results of the thermodynamic equilibrium calculations are compiled in Appendix C1.

cited experiments (Belevi and Moench, 2000, Morselli *et al.*, 1993, Waterland *et al.*, 1991) consider synthetic waste samples and the field conditions can differ significantly from laboratory conditions, which in turn possibly results in differing results. Finally, the As content of the analysed PWBA-scrap was low from the beginning.

Cadmium *Thermodynamic predictions* Due to its low volatilisation temperature, Cd is completely volatilised at 550°C and 880°C and independent of the reducing conditions (Wochele, 2005). Other studies predict similar results depending on the incineration conditions (Ljung and Nordin, 1997, Verhulst *et al.*, 1996).

Experiments The TG-ICP measurements indicate a volatilisation of Cd that increases with increasing temperature under oxidising conditions. A similar behaviour is found for reducing conditions, with the exception of two peaks at about 700°C and below 900°C. In the QTR-residuals no Cd is detected under any condition.

Evaluation Theoretical as experimental investigations predict results comparable with the presented experimental results (Chiang *et al.*, 1997, Soerum *et al.*, 2003, Verhulst *et al.*, 1996, Wang *et al.*, 1997, Wang *et al.*, 1999). In contrast, field studies document a higher retention rate for Cd in the bottom ash (Ljung and Nordin, 1997, Morselli *et al.*, 1993, Waterland *et al.*, 1991, Wobst *et al.*, 2001). Reasons for the differing results might be the sample compositions and the incineration conditions.

Nickel *Thermodynamic predictions* Previous studies predict that Ni remains stable under oxidising and reducing conditions below 1500°C (Ljung and Nordin, 1997, Verhulst *et al.*, 1996). Recent studies indicate that Ni can be the volatilised under oxidising conditions and in presence of Cl at temperatures above 700°C (Soerum *et al.*, 2003, 2004).

Experiments The QTR-experiments show a complete retention of Ni in the bottom ash under oxidising conditions at lower temperatures (100%). Higher temperatures lead to a negligible Ni-volatilisation (+0.04%). Under reducing conditions and at lower temperatures (550°C) about 13% of Ni is removed from the bottom ash. An increase in temperature under the same reducing conditions results in an immobilisation of Ni (0% volatilised).

Evaluation Belevi *et al.* (Belevi and Moench, 2000) indicate that Ni is not or only to negligible amounts transferred to the gas phase. However, it is not excludable that Ni is removed from the bottom ash by entrainment (Belevi and Moench, 2000). This assumption is corroborated by the results obtained for field studies (Belevi and Langmeier, 2000). In essence, it is most likely that during the QTR-experiments Ni was removed from the matrix, i.e. from the QTR-residuals. Principally, the QTR-results are in good agreement with the theoretical predictions (Ljung and Nordin, 1997, Verhulst *et al.*, 1996).

Gallium *Thermodynamic predictions* Ga is predicted to be immobile under oxidising conditions and at temperatures below 1000°C. Under reducing conditions, Ga is predicted to volatilise at temperatures between 100-500°C (formation of $GaBr_3$). At 880°C 70% of Ga is volatilised (formation of $GaBr_2$) (Wochele, 2005).

Experiments The TG-ICP measurements indicate a continuously low Ga-signal under oxidising conditions. The results are almost the same under reducing conditions, with the exception of a slight peak at above 550°C. No Ga could be detected in the QTR-residuals.

Evaluation In contrast to the experimental results of this study, Uryu *et al.* (Uryu *et al.*, 2003) quantified almost 100% Ga in the bottom ash. The missing detection of Ga in the QTR-ashes might stem from the low background concentration of Ga in the investigated PWBA-scrap. Also, when heated, $GaCl_3$ or $GaBr_3$ might be formed and released by entrainment (Dierks, 1994a, 1994b). Finally, the different experimental set-ups possibly result in the different outcomes.

Lead *Thermodynamic predictions* A complete volatilisation of Pb is predicted for 550 and 880°C and under oxidising and under reducing conditions (formation of volatile $PbBr_4$) (Wochele, 2005). The predictions coincide with calculations of Verhust *et al.* (Verhulst *et al.*, 1996). According to Ljung *et al.* (Ljung and Nordin, 1997) the volatilisation of Pb starts at about 550°C. In contrast, Waterland *et al*. (Waterland *et al*., 1991) predict about 80% of Pb retained in the bottom ash.

Experiments The TG-ICP experiments indicate a Pb-volatilisation independent of the supply of oxygen. Most Pb is volatilised between 550 and 600°C. The ICP-signal is nearly twice stronger under reducing than under oxidising conditions.

The QTR-results indicate a decreasing Pb-mobility under oxidising conditions and with increasing temperature. Conversely, the Pb-volatility is increased under oxygen deficiency and with increasing temperature.

The increase in mobilisation under reducing conditions is stronger (average: 54%) than the decrease under oxidising conditions (average: 15%). At 880°C and under reducing conditions, 36% Pb is detected in the bottom ash.

Evaluation The obtained results are in good agreement with previous studies (Chiang *et al.*, 1997, Wang *et al.*, 1997). Belevi *et al.* (Belevi and Langmeier, 2000) confirm the QTR-results but indicate that the volatilisation ratio is only dependent on the temperature and that the supply of oxygen is not of importance. Chen *et al.* (Chen *et al.*, 1998) performed a study on the adsorption efficiency, among others of Al_2O_3. According to their results, Pb can be adsorbed by Al_2O_3 at 800°C. With decreasing temperature the adsorption efficiency of Al_2O_3 decreases. This, and the fact that the quartz-vessel, used in the QTR-experiments, consists of 100% Al_2O_3, may explain that with decreasing temperature a decreasing amount of Pb was found in the ash under oxidising conditions.

Field studies testing MSWI ashes for their Pb-content arrive to slightly different results. For example, Wobst *et al.* (Wobst *et al.*, 2001) detected much less Pb in the incineration residuals at higher temperatures (800°C). Likewise, Morselli *et al.* (Morselli *et al.*, 1993) detected 55% of Pb in the bottom ash at 900°C.

Antimony *Thermodynamic predictions* Complete volatilisation of Sb is predicted for reducing conditions at temperatures below 500°C (formation of $SbBr_3$) and above 700°C (formation SbO). Under oxidising conditions, Sb is predicted to be completely volatilised at temperatures above 750°C (SbO formed) (Wochele, 2005).

Experiments The TG-ICP results show a significant peak at 350°C under reducing and under oxidising conditions. At higher temperatures less Sb is detected. The QTR-results indicate a strong volatilisation of Sb independent of temperature and oxygen supply (between 90% and 98% are transferred to the gaseous phase). Tendentially more Sb is found in the ash at higher temperatures (10% at 880°C; 2-5% at 550°C), independently of the oxygen supply.

Evaluation The presented results are in good agreement with those reported by *Belevi et al.* (Belevi and Langmeier, 2000), which showed that Sb is increasingly volatilised with decreasing temperature. *Belevi et al.* (Belevi and Langmeier, 2000) also indicated that in presence of organic Cl up to 100% Sb can be transferred to the gas phase. This is consistent with the assumption that Cl and Br can promote the volatilisation of Sb by lowering its volatilisation temperature under reducing conditions theoretically (formation of $SbCl_3$ and $SbBr_3$). However, aside Br the PWBA-scrap contains significant amounts of Ca, for example in the ceramic PWBA-components. A recent study (Paoletti *et al.*, 2001) documents that calcium can inhibit the formation volatile $SbCl_3$-compounds at higher temperatures and that it can promote the condensation of stable Sb-complexes. Therefore, more Sb might have been found in the bottom QTR-ash at higher than at lower temperatures.

Zinc *Thermodynamic predictions* The calculations suggest a complete Zn-volatilisation under reducing conditions and in the presence of Br at temperatures above 500°C (formation of $ZnBr_2$). Under oxidising conditions, complete volatilisation of Zn is predicted for temperatures above 800°C (Wochele, 2005). Comparable results were found in other studies (Ljung and Nordin, 1997, Soerum *et al.*, 2003, Verhulst *et al.*, 1996).

Experiments According to the TG-ICP measurements, most of the Zn is volatilised below 600°C under reducing conditions. Under oxidising conditions, Zn-volatilisation starts at about

500°C, increases then and remains on a constant level until 700°C. Above 700°C the Zn-volatilisation decreases continuously. The QTR-experiments indicate that no Zn is volatilised at 550°C, independently of the oxygen supply. Increasing temperature results in a Zn-mobilisation. Under reducing conditions and at 880°C, more Zn is volatilised (80%) than under oxidising conditions (25%).

Evaluation The presence of Cl and Br is assumed to promote the volatilisation of Zn. This is in agreement with investigations on the influence of anorganic and organic chloride on the volatilisation of Zn, which predict a significant volatilisation of Zn in presence of organic chloride and at higher temperatures (Chiang *et al.*, 1997, Wang *et al.*, 1997, Wang *et al.*, 1999). Likewise, *Belevi et al.* (Belevi and Langmeier, 2000) found that about 70% of Zn contained in a synthetic scrap sample is volatilised at 700°C and 80% at 800 and 900°C respectively. The experiments showed that an addition of Cl further increased the volatilised Zn-amount.

	Sample number			
	S1	S2	S3	S4
Mass before incineration [mg]	13.0229	12.3606	13.2455	13.3981
Mass after incineration [mg]	9.5614	8.7866	8.7184	9.6179

	ICP-OES				Initial Element Conc. [%]				Residual Element Conc. [%]				Volatilisation [%]			
Sample[Tλ]	S1[550ox]	S2[550red]	S3[880ox]	S4[880red]	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
Elements																
As	0.0	0.0	0.0	0.0	0.026	0.024	0.026	0.026	0.0	0.0	0.0	0.0	100.0	100.0	100.0	100.0
Cd	0.0	0.0	0.0	0.0	0.001	0.001	0.001	0.001	0.0	0.0	0.0	0.0	100.0	100.0	100.0	100.0
Ga	0.0	0.0	0.0	0.0	0.006	0.006	0.006	0.006	0.0	0.0	0.0	0.0	100.0	100.0	100.0	100.0
Ni	1.605	1.437	1.792	1.64	0.154	0.146	0.156	0.158	0.153	0.126	0.156	0.158	0.1	13.4	0.04	0.2
Pb	0.370	0.637	0.535	0.27	0.070	0.067	0.072	0.072	0.035	0.056	0.047	0.026	49.7	16.1	34.8	64.1
Sb	0.631	0.319	2.132	2.028	1.901	1.805	1.934	1.956	0.060	0.028	0.186	0.195	96.8	98.4	90.4	90.0
Zn	N.D.	0.84	0.68	0.168	0.078	0.074	0.079	0.080	N.D.	0.074	0.059	0.016	N.D.	0.05	25.4	79.9

Tab. 6.3: Experiment conditions (T = Temperature, λ = oxygen supply conditions, N.D. = not detected), volatilisation of heavy metals during incineration in the QTR and initial metal concentration in the PWBA-samples. The concentration of Br was > 6.5% (Motorola, 2005).

6.4. ***Conclusions***

Thermal EOL treatment of electronic scrap represents the presently technically most advanced method to recover/recycle precious metals and to inertise potentially hazardous substances, in particular heavy metals. The laboratory experiments presented here, document the partitioning of potentially toxic metals from complex PWBA matrices. In essence it was found that:

a) reducing incineration conditions favour the formation of volatile heavy metal compounds,.
b) increasing the temperature promotes the formation of volatile Pb- and Zn-compounds under reducing conditions, and
c) in contrast with theoretical predictions and with most of the cited studies, neither As nor Ga were detectable in the bottom ash.

Additional thermodynamic equilibrium calculations for Ga and As mixtures indicated that gallium-arsenate was found as stable phase under oxidising conditions. At this time we can only speculate that gallium-arsenate could play a controlling role in the volatilisation of As or Ga. Under oxidising and under reducing conditions GaAs is, however, not expected to be stable in the analysed system according to our calculations.

Based on the experimental results it was assumed that Ca and Si counteract the volatilisation of metals in particular of Sb. The presence of Cl and in particular of Br, contained in significant amounts in the polymer fractions of PWBA, was considered to be responsible for increased volatilisation of heavy metals.

The performed incineration experiments are afflicted with uncertainties that need to be considered: partially low element concentration in the samples and inhomogeneities in the investigated PWBA-samples. Also, the volatility of the investigated heavy metals strongly depends on the presence of reaction partners inhibiting or promoting metal mobilisation. This aspect however, was not taken into account in the presented experiment. Nevertheless, the results imply that particular attention has to be paid to the volatility of Sb and As, which are increasingly used in modern electronic equipment. If no efficient air pollution control system is available, reducing conditions should be avoided. That implies that a sound collection system for electronic scrap is installed in order to avoid an incineration in improper facilities. Also, transfer of refurbished electronic devices to developing countries could lead to relatively high impacts if environmental safe thermal End-of-Life treatment cannot be ensured.

Methodologically, the obtained results could provide a sound basis for the estimation of generic transfer coefficients for MSWI incineration processes and the quantification of the associated environmental effects by means of LCA (Scharnhorst *et al.*, 2005b). Though MSWI incineration processes theoretically are performed in excess of oxygen, locally occurring reducing conditions cannot be excluded. In order to get maximum estimates it is recommended to determine transfer coefficients based on the volatility results obtained for reducing conditions at 880°C. Element specific emission retention factors, representing the ability of the filter facilities to prevent from emission of heavy metals, should be applied in order to get approximate the transfer coefficients (Scharnhorst *et al.*, 2005b, Farrell, 2000). Transfer coefficients for oxidising conditions, could be used in a sensitivity study, as well as emission without retention factors in order represent conditions without filters (e.g. in developing countries).

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7. *Network study II*: Life Cycle Assessment of Second Generation (2G) and Third Generation (3G) Mobile Phone Networks[1]

7.1. *Introduction*

The presented study aims at providing in-depth knowledge on the environmental consequences related to the life cycles of mobile phone networks complying with the Global System for Mobile communication standard[2] and with the Universal Mobile Telecommunication System standard[3] concentrating on the End-of-Life phase[4]. 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 (General Packed Radio Service[5], Enhanced Data rate for Global Evolution[6]), 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 finally, the first commercial UMTS networks were rolled out in Western Europe. For the future, consultants expect a world wide 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 to short. The change-over and the associated competition between the GSM and the UMTS technology will even exacerbate these problems. In order to reduce the environmental impacts of electrics 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, Life Cycle Assessment[7] 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

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[1] This chapter is based on the paper: Scharnhorst, W., Hilty, L. M. and Jolliet, O. (2005): Life Cycle Assessment of Second Generation (2G) and Third Generation (3G) Mobile Phone Networks. submitted to Environment International: under review.

[2] GSM. This standard belongs to the so-called *second generation* (2G) of mobile phone networks.

[3] UMTS. This standard belong to the so-called *third generation* (3G) of mobile phone networks.

[4] EOL phase.

[5] GPRS. GSM-GPRS networks belong to the so-called *second and a half generation* (2.5G) of mobile phone networks.

[6] EDGE. GSM-EDGE networks belong to the so-called *second and a half generation* (2.5G) of mobile phone networks.

[7] LCA.

- 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 in general providing substantial environmental know-how, LCA studies on large technical systems, such as mobile phone networks, 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, a LCA study was performed concentrating on

i.) the comparison of the environmental performance of a **GSM network** (corresponding to the ETSI[1] standard package – Release 1997 (ETSI, 1996)) and a **UMTS network** (corresponding to the 3GPP[2] standard package – (R'99)[3] (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)[4] (ETSI, 2003) and (R'06)[5] (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 standards and including all of the major network components, which component of the networks dominates the total environmental impact?

d) Does a 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?

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[1] European Telecommunications Standards Institute.

[2] 3rd Generation Partnership Project.

[3] Release 1999.

[4] Release 2004.

[5] Release 2006.

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, 1998b) 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 analysis and is completed by a discussion and recommendations to the stakeholders concerned. In the goal and scope section the system under study was defined, the data representativity was specified, and the impact assessment method was determined. The life cycle inventory part consisted of taking qualitative and quantitative inventories of the environmental data (resources consumptions and emission release rates) related to the production, use and EOL treatment of the separate network components. It also included the assembly of the network model (life cycle modelling). In the impact assessment section the environmental impacts of the network and its components was calculated by assigning impact scores to the various resource consumptions and emission releases. In the final section the results of the impact assessment were interpreted, a sensitivity analysis was performed, conclusions were drawn and recommendations formulated.

7.2. *Goal and Scope*

7.2.1. Study Objective

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 traffic data (i.e. speech and non-voice applications) quantified in bits from a mobile phone via the mobile phone network was selected as functional unit and 1 bit transmitted was defined as the reference flow.

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 for 2005 with respect to EOL treatment.

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 starts with the extraction of ores and energy carriers and ends as the network component assembly is finalised (Scharnhorst *et al.*, 2005a). This phase consists of the following major steps:

- raw material extraction, and
- manufacturing of electronic components and supporting structural elements (Printed Wiring Board Assemblies[1], frames, casings, etc.).

The final assembly of network components was not included in the study as other studies have proven that this stage is of minor environmental importance (Faist-Emmenegger *et al.*, 2003, RANDA-GROUP, 2000, Weidman and Lundberg, 2001). The use phase follows the production phase. In the case of mobile phone networks, it includes the installation and continues with the operation of the network components. In principle, this phase also includes

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[1] PWBA.

maintenance and repair services as well as periodical software updates (Scharnhorst *et al.*, 2005a). However, the latter two stages were not included in the presented study due to their low environmental significance (Faist-Emmenegger *et al.*, 2003).

The EOL phase finalises the life cycle of the mobile phone networks. It 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 precious metals and energy. The recovered materials are recycled and energy is reused. The residuals 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.

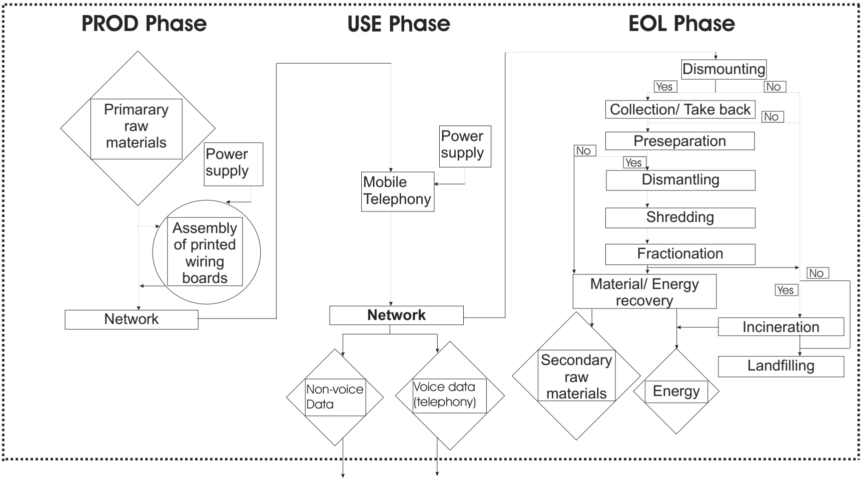

Fig. 7.1: System boundaries of the life cycle phase of the investigated mobile phone networks.

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.

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).

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.

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.

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

7.2.2. **Description of the Mobile Phone Technologies and Techniques considered**

GSM The analysed GSM network corresponds to GSM technology as currently operated in Switzerland. It meets 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, 2000c)[1]. The principal architecture of the analysed GSM network and its modifications (GPRS and EDGE) can be found in Appendix D8. A description of the single network components is available in Appendix D1-D3 and in (Scharnhorst *et al.*, 2005a) and in (Scharnhorst, 2005).

UMTS (R'99) The investigated UMTS network complies with the UMTS technology as currently in practice in Switzerland. It meets the UMTS standard packages as defined and adopted in 2002 - for the basic network architecture (ETSI, 2002c, 2002d) -, in 2000 - for data transfer service (ETSI, 2000b) - and in 2002 - for the interface principles (ETSI, 2002a, 2002b)[1]. The composition of the analysed UMTS network and its modifications (R'04 and R'06) can be found in Appendix D8. A description of the single components is available in Appendix D3-D7 and in (Scharnhorst, 2005).

7.3. *Life Cycle Inventory – Network Modelling – End-of-Life Treatment Modelling*

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 (Bambrilla, 2004, OrangeAG, 2004, SunriseAG, 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 the BTS cover 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 D9.

The technical specifications of the separate network components were compiled from original manufacturer data sheets[2]. Information on the basic network component materials were

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[1] Mobile phone standards are subject to permanent updates. To adopt the present conditions the latest standard versions were adopted.

[2] Sources are given in Appendix D10.

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 D10. 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 of 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; according to it the energy consumption of the network components is altered.
- 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 7.1 documents selected present average conditions adopted for the mobile phone networks and the used parameters. The detailed operating conditions for the networks are compiled in Appendix D9.

	Networks	GSM	UMTS (R'99)
Technical Network Parameters	**Model Parameters**		
Data rate [kbit/s]	DTP	9600	384000
MS (Mobile station)/Ue (User equipment [-]	SP2	6188793	70000
Phone call [s/MS·year]	-	87600	87600
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]	"	95000	66000

Tab. 7.1: Selected average operating network conditions representing present conditions and parameters.

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 from (Kincaid and Geibig, 1998). The production phase was modelled adopting process data compiled in the Swiss Centre for Life Cycle Inventories (ecoinventCentre, 2003). Transport process data were adopted from the GaBi4-software (IKP&PE, 2003).

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 Heating, Ventilation and Air Conditioning[1] 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 (Bambrilla, 2004). Energy consumption data of the network components considered were adopted from the manufacturers listed in Appendix D10, 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 D10. The energy supply processes were modelled adopting data sets of the Swiss Centre for Life Cycle Inventories (ecoinventCentre, 2003).

The EOL phase was modelled according to a scenario estimated to represent environmentally preferable option (Scharnhorst *et al.*, 2005a). It covered the dismounting and collection of the network components and 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 incineration (stabilisation) of residuals and by dumping the stabilised residuals in landfill sites. For all mobile phones it was assumed that 20% are not processed in recycling facilities, but are directly processed in Municipal Solid Waste Incineration plants[2]. For metal recycling rates of 75% (aluminium and steel) and of 95% (precious metals such as gold, palladium, silver) were assumed (BDSV, 2001, HELCOM, 2002, Lehner, 2001, VSSV, 2005). 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[3] 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 physico-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, 2001b, 2001c, Weyhe, 2004). If not otherwise stated, EOL processes were modelled adopting data sets from the Swiss Centre for Life Cycle Inventories (ecoinventCentre, 2003). Transport process data were adopted from the GaBi4-software (IKP&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.

7.4. *Life Cycle Impact Assessment Results (IMPACT2002+)*

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

7.4.1. **Resource Depletion**

This damage category is dominated by the total environmental impact score of the UMTS (R'99) network (71%[4]). Comparing the resource depletion effects of the two network stan-

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[1] HVAC.

[2] MSWI.

[3] Quantifying the volatilisation of e.g. metals.

[4] Total impact of all networks.

dards reveals that GSM networks (basic configuration[1]) under present conditions perform better than UMTS (R'99) networks (factor 8). Upgrading from UMTS (R'99) to (R'04 and R'06)[2] will lead to lower environmental profiles per bit compared with UMTS (R'99) (factors 8[3] and 21[6]). The upgrade of UMTS network technology results in environmental profiles close to that of GSM networks equipped with the EDGE-technique (factor 0.3[6] and 0.8[6] 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%[4] and 56%[7]) (Fig. 7.2). Key processes are the energy consumption by the NodeB (89%[5]) and the BTS (79%[8]). The uranium depletion related to the Swiss electricity generation contributes to the impact score of the use phase (64%[7] in the case of the GSM network and 72%[7] in the case of the UMTS (R'99) network). The production phase contributes only to a limited extend to the total environmental impact of a UMTS (R'99) network (20%[7]) mainly due to the generation of electricity for the production of primary aluminium (54%[8]), which contributes dominantly to the impact score. The production phase of the GSM network accounts for 44%[7] of the total impact score and is dominated by the energy intensive manufacturing of PWBA for mobile phones and BTS racks (71%[8]). 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%[7] and -6%[7] respectively).

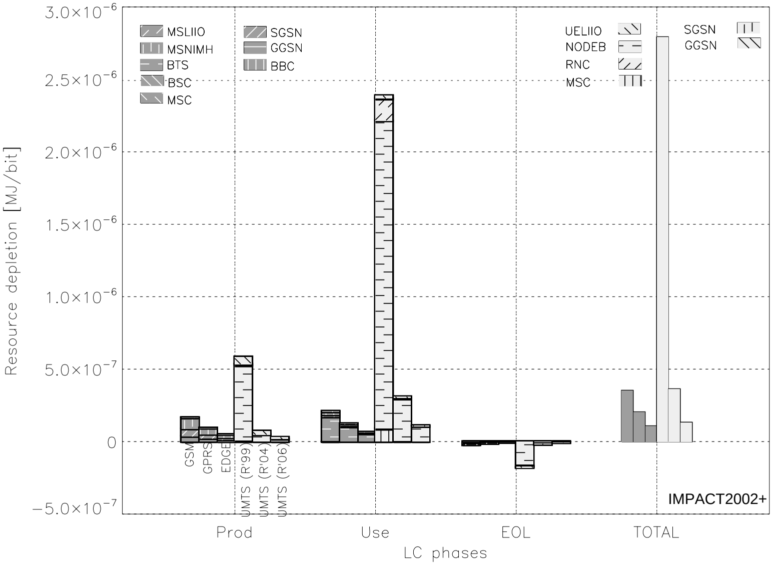

Fig. 7.2: **Resource depletion damage category:** Life cycle phase specific and total impact scores of the GSM network (basic, GPRS- and EDGE-technique) the UMTS networks (R'99, R'04, R'06). Abbreviations (MS LIIO: mobile phones with rechargeable lithium ion batteries, MS NIMH: mobile phones with rechargeable nickel-metal-hydride batteries, BBC: Back Bone Cable network of the mobile phone network).

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[1] ,i.e. no GPRS and no EDGE.

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

[3] 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.

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

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

7.4.2. **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 (71%[1]) (Fig. 7.3). Comparing the climate effects of the two network standards shows that GSM networks (basic configuration[2]) 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)[3] will lead to lower environmental profiles compared with UMTS (R'99) (factor 8[4] and 22[4]). The UMTS network upgrade again results in environmental profiles close to GSM networks deploying the advanced EDGE-technique (factor 0.3[4] and 0.9[4] 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%[5] for a UMTS (R'99) network, 72%[5] and 69%[5] 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%[6] 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%[6]) and the manufacturing of the PWBA used in NodeB racks and mobile phones (32%[6]) 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 impact score of -16%[5] and it can halve the environmental impact score of the production phase. In particular energy savings due to the recovery of aluminium (61%[6]) and silver (18%[6]) 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%[5]). 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%[6]). The use phase is dominated by CO_2 emissions associated with the energy supplied to operate the BTS (78%[6]). The EOL phase can reduce the climate change score by -12%[5] a quarter of the impact score of the production phase. Again, the energy savings due to recycling of silver (54%[6]) and aluminium (36%[6]) account for this reduction.

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[1] Total impact of all networks.

[2] ,i.e. no GPRS and no EDGE.

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

[4] 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.

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

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

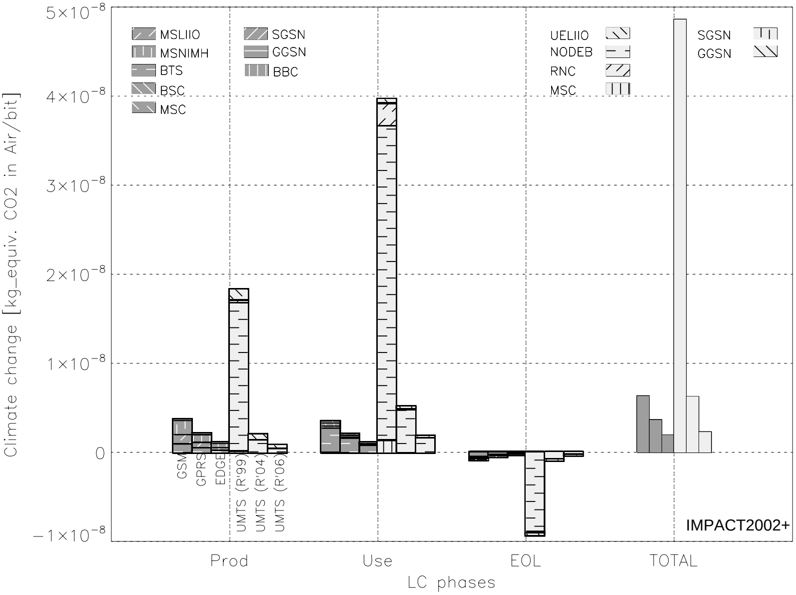

Fig. 7.3: **Climate change damage category:** Life cycle phase specific and total impact scores of the GSM network (basic, GPRS- and EDGE-technique) the UMTS networks (R'99, R'04, R'06).

7.4.3. **Human Health**

Under the defined conditions, the UMTS (R'99) network dominates this damage category and accounts for 70%[1] of the total environmental impact of all networks (Fig. 7.4). Networks complying with the GSM standard perform better compared with the basic UMTS (R'99) network (factor 7[2] in the case of a basic GSM network, factor 13[2] in the case of a GSM-GPRS network, and factor 25[2] 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[2] in the case of UMTS (R'04), and factor 0.9[2] in the case of UMTS (R'06)).

Under the given initial conditions, the use phase of a UMTS (R'99) network slightly dominates the network's total environmental impact score (52%[3]), 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%[4], 19%[4], 29%[4]). The impact score of the production phase is dominated by the production of primary aluminium for the NodeB racks (22%[4]) and the production of primary lead for the NodeB back-up batteries (20%[4]). The energy intensive PWBA manufacturing (12%[4]), and the primary steel production for the NodeB racks and the primary palladium production for the PWBA (each 7%[4]) are still 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%[3] and it can lower the environmental impact of the production phase by a factor 1.6.

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[1] Total impact of all networks.

[2] 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.

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

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

In particular the recycling of aluminium (35%^{4}), steel (18%^{4}) and palladium (11%^{4}) 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%^{3}). This is due to primary and secondary particle generation linked with the energy intensive manufacturing of PWBA for mobile phones and BTS racks, as well as the production of primary palladium, silver[1] and aluminium for the BTS racks (26%^{4}, 15%^{4}, 10%^{4} and 7%^{4}). Additional effects are attributable to the manufacturing of rechargeable nickel-metal-hydride batteries (16%^{4}). SO_2-, NO_x- and particle emissions to air contribute at most to the impact of this phase (48%^{4}, 17%^{4}, 24%^{4}). The use phase of a basic GSM network accounts for 37%^{2} of the human health impact score mainly due to the operation of the BTS (79%^{3}) and the mobile phones (17%^{2}). The recycling of network scrap in the EOL phase can account for a reduction of the network's total environmental impact (-23%^{1}) and it can nearly halve the environmental impact score of the production phase due to recovery of secondary palladium (39%^{2}), aluminium (19%^{2}), steel (13%^{2}).

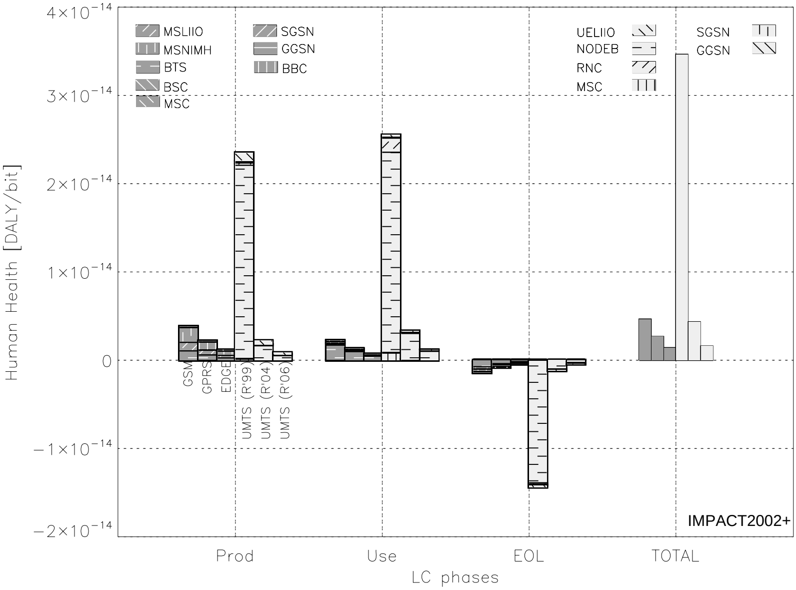

Fig. 7.4: **Human health damage category:** Life cycle phase specific and total impact scores of the GSM network (basic, GPRS- and EDGE-technique) the UMTS networks (R'99, R'04, R'06).

7.4.4. **Ecosystem Quality**

Under the given conditions, the UMTS (R'99) network shows the highest total environmental impact score on ecosystem of all networks analysed (58%^{4}) (Fig. 7.5), 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[5] in the case of a basic GSM network,

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[1] Both metals are important materials in PWB.
[2] Share of total impact of the respective network.
[3] Share of total phase impact of the respective network.
[4] Total impact of all networks.
[5] 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.

factor 7[4] in the case GPRS is deployed and factor 13[4] 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[4] and 1.2[4] 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 still dominated by the use phase (60%[1]) mainly due to the energy consumed by the NodeB. The main emissions are here in decreasing order copper to soil, aluminium to water, copper to air and zinc to soil and to water. The impact of the production phase is dominated by the fabrication of primary lead for the back-up batteries mounted at the NodeB sites and the production of primary aluminium for the NodeB racks (50%[2] and 22%[2] respectively). Additional effects are attributable to the energy intensive manufacturing of PWBA (8%[2]). Particularly emissions of copper to air, aluminium to water, and zinc to air and to soil 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 (58%[1]) with high impact scores attributable to long term emission of copper and nickel to soil from dumped incineration ashes of mobile phones[1] (72%[2] and 27%[2]). Environmental benefits account for 14%[1] 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 26%[1] mainly linked to the operation of the BTS. The impact of the production phase on ecosystems is low compared with the other phases (16%[1]) and is dominated by releases of dissolved aluminium to water and copper to air in the production of BTS racks and mobile phones as well as of copper to air during the production of primary lead for the BTS back-up batteries.

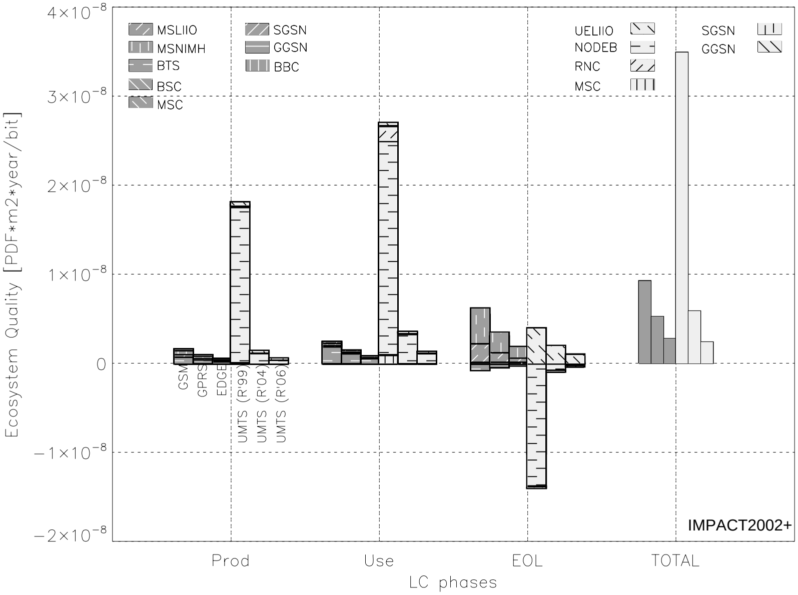

Fig. 7.5: **Ecosystem quality damage category:** Life cycle phase specific and total impact scores of the GSM network (basic, GPRS- and EDGE-technique) the UMTS networks (R'99, R'04, R'06).

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[1] 20% of the mobile phones were assumed to be directly incinerated in a MSWI and then referred to a landfill.

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 releases 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 the production and the use phase. The CML method assesses higher environmental effects of chromium +VI releases to soil than IMPACT2002+. These chromium 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. For to 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 comparably low. The findings of the evaluation are in agreement with an earlier performed method evaluation (Scharnhorst *et al.*, 2005b).

7.5. *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[1]. A comparative sensitivity analysis, complementing the above LCA analysis, was performed for a GSM-EDGE network and a UMTS (R'04) network[2] in order to demonstrate the improvement capabilities of the environmental performance of UMTS networks and the following parameters were varied (Tab. 7.2).

	Scenarios	0	01	01a	02	02a
Networks	Parameters					
GSM-EDGE	Subscriber [-]	6189000	4087473	4087473	1986153	1986153
UMTS R'04	Subscriber [-]	1051000	2101320	2101320	4202640	402640
	Total Download Volume per Subscriber [Mbit/year]	2256	2256	4512	2256	9024

Tab. 7.2: Parameters varied in the sensitivity analysis.

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. 7.6). 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. 7.7: about 40% when the number of subscriber doubles). Similarly, an increasing download volume per subscriber leads to a slight increase

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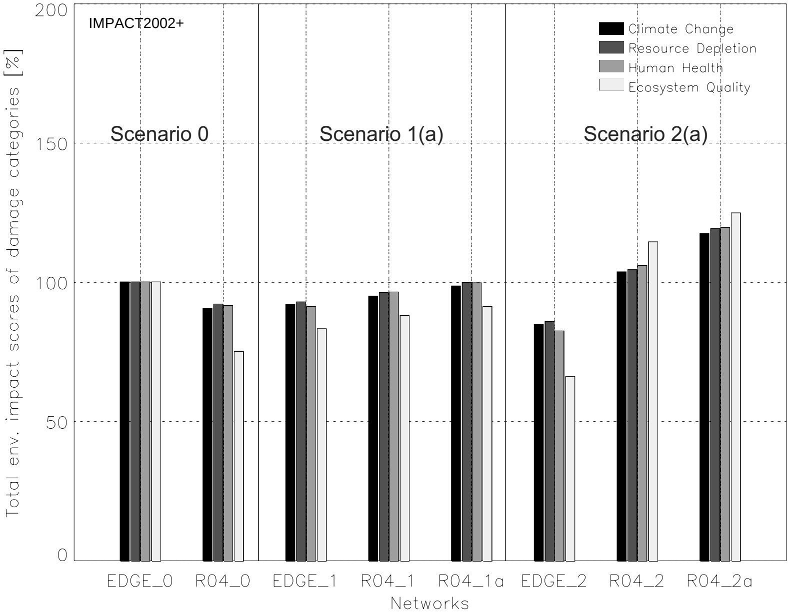
[1] In Switzerland the allocation of frequencies to the operators was associated with the commitment by the operators to provide 50% population coverage by the end of 2004 BAKOM (2004): Faktenblatt UMTS v2.20, Bundesamt für Kommunikation, Bern..

[2] 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.

of 5 to 10% in the overall yearly network consumption when doubling the transferred volume ((R04_1 to R04_1a) in Fig. 7.6) and to a further strong reduction in consumption per bit (Fig. 7.7).

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. 7.6), 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. 7.7). 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. 7.7). The annual environmental impact however, is reduced (Fig. 7.6). 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. 7.7). 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. 7.7). It leads again to a moderate increase in the total annual impact score of the UMTS network (Fig. 7.6). This increase is partly compensated by the further decrease in the GSM-EDGE yearly network consumption.



Fig, 7.6: Total impact scores per year relative to the total impact scores of the GSM-EDGE reference network for all four damage categories[1].

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[1] 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.

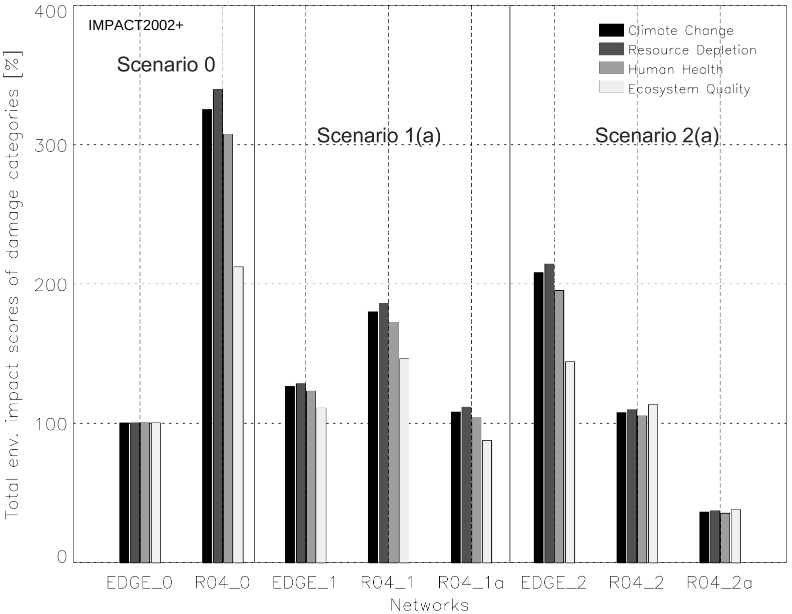

Fig. 7.7: Relative impact scores for all four damage categories relative to the impact scores of the GSM-EDGE reference network.

7.6. *Conclusions and Recommendations*

The presented LCA study gave a comprehensive overview on the environmental performance of presently operated GSM and UMTS networks. It also made a first approximation of the relative environmental performance of UMTS networks using future fast data transmission techniques. The results of this study leads to several conclusions and recommendations from an environmental point of view:

a. the transition period between networks deploying GSM technology (2G networks) and the UMTS technology should be kept as short as possible. A parallel operation of GSM and UMTS networks is environmentally adverse (Figs. 6 and 7).
b. under present conditions, UMTS networks complying with the (R’99)-standard package have a higher relative environmental impact per bit than GSM networks. Under the forecasted conditions (growing subscriber numbers and rising total data download volumes) the UMTS networks (R’04 and R’06) still perform environmentally worse than GSM networks that deploy the advanced EDGE-technique (Figs. 2-5). However, UMTS networks are predestined to provide advanced mobile communication services to a large number of subscribers without the need to extend the network infrastructure. This large subscriber capacity results in a reduced relative environmental impact score per bit as soon as the UMTS networks are efficiently loaded (Fig. 7.7).
c. in the case of the UMTS networks, the use phase dominates and in the case of the GSM networks the use phase accounts for clearly more than one-third of the total environmental impact scores of the networks (Figs. 2-5). Mainly the radio network parts, i.e. the components of the Radio Network Subsystem[1] (in particular the NodeB) and of the Base Station Subsystem[2] (in particular the BTS), dominate. It is of urgent importance to fur-

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[1] RNS (in a UMTS network, see Fig. 2).

[2] BSS (in a GSM network, see Fig. 2).

ther lower the energy consumption of those network elements. This is of particular importance in consideration of the fact that UMTS networks will be implemented in a GSM-like extend and that NodeB consume up to six times more energy than BTS.

d. the energy intensive processes of aluminium production and PWBA manufacturing are dominating the impact score of the production phase of all investigated network types (Figs. 2-5). There is a particular need to thoroughly analyse the PWBA manufacturing for potentials to save energy. Another option to decrease the impact of the production phase lies in 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).

e. EOL phase is important principally through material recycling, whereas EOL emissions could dominantly contribute to ecosystem impacts if a fraction of mobile phones are eventually landfilled or not treated in appropriate facilities. Processing electronic scrap in the EOL phase and the production of secondary raw materials is less environmentally impacting than a production of primary raw materials (Figs. 2-5). The particular environmental benefit of the EOL phase lies in the production of secondary raw materials, which can help to significantly lower environmental impact of the production phase. Therefore, it is recommended to recycle electronic scrap and to regain precious metals as well as energy. Presently, the high environmental impact due to manufacturing of PWBA can not be compensated or lowered by processing of scrapped PWBA in the EOL phase (Fig. 7.2 and 7.3). However, first experiments have been undertaken in order to recover metals and basic plastic materials in a combined way by means of hydrothermal EOL processing (Ludwig *et al.*, 2005). The recovery of plastics, and thus skipping initial plastic processing steps, could help to lower the total amount of energy consumed in the manufacturing of PWBA. However, the results obtained for the EOL phase (in particular that of incineration and landfill processes) have to be considered with care. First of all present LCA methodology considers overall integrated emissions accumulated assuming a linear model at low doses. It does not consider possible changes in dose-responses at low exposures. Secondly, the data bases used and the impact assessment method (IMPACT2002+) distinguish only between a very few metal speciations. That possibly can lead to a biased and blanket characterisation of the environmental impact of several metals/metal speciations.

From an absolute point of view in term of overall annual impacts, UMTS networks per se perform environmentally moderately worse than GSM networks when it comes to GSM-like full geographic coverage. 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 kW (Hausammann, 2005) compared with up to 1.3 kW of a BTS rack (SiemensAG, 2000)). Secondly, in order to cover a geographical areas equal to that a GSM network can cover, up to 30% more NodeB will be required[1] (Hugentobler, 2000). Finally, UMTS networks providing high data throughput per cell using TDD (i.e. Mbit/s) require more NodeB than conventional UMTS networks using FDD. Hitherto, high data rates are only available in small cells (so-called micro cells covering less than a few 100 metres).

It is clear that when comparing GSM and UMTS simply based on mobile telephony (i.e. the transmission of speech), than UMTS again will perform environmentally worse due to the above mentioned technologically 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 methods, does not take into account the added functional value UMTS networks can provide. Therefore, looking only at the absolute impact score can result in misleading interpretations and conclusions. Looking first at the data

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

transfer (i.e. non-voice data transfer), UMTS enables an increased amount of subscribers to access high-speed data transfer services. Secondly, UMTS provides a multifunctionality of services (e.g. mobile telephony, sms, mms, video telephony, television, fax, web-browsing, ftp-services, etc.[1]) that are hardly or not provideable by GSM. What is sure is that keeping two networks in parallel leads on the long term to significantly higher impacts and that transition phase should be reduced at its minimum.

From a technical point of view there is a strong challenge to optimise the energy consumption in the PWBA manufacturing, the HVAC of the antenna stations in general and the energy consumption of the NodeB racks in particular. From a methodological point of view, an improvement of available material inventories (in particular of metals) is urgently needed. Also, it has been proven that the modelling of an entire mobile phone network can be focussed in general 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 all details as their impact share is comparatively low, but for the PWBA.

The LCA method, applied in this study has been perceived to be a useful tool in order to assess the environmental performance even of large technological systems, such as mobile phone networks. However, this method still has some potential to improve and further research efforts have to be undertaken with respect to:

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.

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

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8. Conclusions

8.1. *Key Findings and Limitations*

Aiming at the provision of in-depth knowledge on the environmental consequences associated with the transition from second generation[1] to third generation[2] mobile telephony, the presented thesis indicates that 3G compliant mobile phone networks, here UMTS networks, can provide the communication technology and technique that is needed in order to enable future data capacity intensive mobile communication in an environmentally efficient way. In particular, as UMTS networks provide higher data transfer rates that are practically unachievable with 2G mobile phone networks, larger amounts of data are transferable in a reasonable amount of time. Additionally, high speed data services are available at once not only to a single but to numerous subscribers. Forthcoming UMTS standard packages (R'06 and R'07) concentrate on the implementation of ever advanced mobile communication techniques[3] providing for higher subscriber capacity and data transfer rates without the necessity to physically extend the existing mobile phone network infrastructure.

Presently however, and associated with a low subscriber load, the environmental impacts of UMTS networks per functional unit are higher than impacts of GSM networks. It is expected that, with increasing subscriber numbers and increasing download volume, the environmental impact per functional unit will substantially decrease. Simultaneously, an increase in the absolute impact of UMTS networks compared with GSM networks is expected. The rising environmental impact is in particular attributable to the growing energy intensive Printed Wiring Board Assembly[4] manufacturing on the one hand and, on the other hand, to the energy intensive operation of the NodeB stations. In order to lower the environmental impact of UMTS networks (specifically the absolute impact) it is of urgent importance to lower the energy consumption of these two particular processes.

In the context of the special situation of the technological transition from 2G to 3G networks it is recommended to replace 2G networks (such as GSM networks) as soon and as fast as possible by 3G technology (preferably UMTS compliant networks). A parallel operation of GSM and UMTS networks is environmentally adverse.

In comparison with other information and communication technologies, mobile telephone equipment gains increasing importance with respect to mass consumption under European conditions. For instance the amount of PWBA discarded with mobile phones is about 1.6 times higher than TV-PWBA[5]. Comparing the energy consumption of mobile phones with TV-sets[6] however, shows that the energy consumption of mobile phones accounts only for 2% of that of TV-devices. However, as this thesis concentrated on the EOL phase of mobile phone networks there is a clear additional need for detailed recommendation on the production/use phase which cannot be addressed in the presented thesis.

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[1] 2G.

[2] 3G.

[3] E.g. altered modulation methods.

[4] PWBA.

[5] Under the assumption that a TV-PWBA weighs about 0.5 kg, the use time of a TV-device is about 10.5 years (Brien, 2003) and the number of TV-devices operated in Western Europe accounts for about 100 million units (Bushnell, 2005).

[6] For Swiss conditions, i.e. 6188800 mobile phone subscribers (BAKOM, 2004), an average power consumption of about 3.5 kWh/year (topten.ch, 2005), an average number of 4196000 TV-sets (Beer, 2005)) and an average power consumption of 204 kWh/year (Beer, 2005).

	MS	BTS	BSC	MSC	TV-set	PC
Number of units in Western Europe (estimated for the end of 2005)	3.75E+08[293]	4.17E+05[294]	5210[295]	2605[296]	1.00E+08[297]	2.00E+08[298]
Average use time [years]	1.5[299]	7[300]	8[301]	10[302]	10.5[303]	3-5
PWBA [g/unit]	30[304]	31350[305]	128000[306]	74750[307]	500	400
PWBA total [t]	11250	13060	666	195	50000	80000
PWBA total [t/year]	7500	1866	83	20	4762	26667-16000

Tab. 8.1: Comparing PWBA masses contained in GSM network components with components of other Information and Communication Technologies[308].

Secondly, the studies performed in conjunction with this thesis have demonstrated that it is environmentally beneficial to process electronic scrap of mobile phone networks in EOL treatment facilities that comply with the recent environmental standards in order to recycle secondary raw materials. The recovered secondary raw materials as well as the recovered energy should substitute for primary raw materials and energy produced and consumed in the production phase and thus can help to lower the total environmental impact of the mobile phone network components. With respect to the various EOL stages, the study results suggest that an intensive pre-treatment and fractionation of the electronic scrap is not necessarily desirable; it does not help to further lower the environmental impact. Thermal EOL treatment of electronic scrap, i.e. the extraction of fusible materials such as metals by simultaneously using the plastic content of that scrap as energy carrier, has been identified as the presently environmentally best alternative. Prospective experiments have shown that present state-of-the-art thermal treatment processes carry a promising potential with respect to the parallel recovery of plastic base materials and metals (Ludwig et al. 2005). Concerning stabilisation (incineration) and final disposal, it has been shown that the amount of electronic scrap or waste that is directly incinerated and subsequently landfilled should be kept as small as possible for three reasons: *i.)* economically still valuable secondary raw materials are not recycled to the production phase and need to be replaced by primary raw materials, *ii.)* the production of primary raw materials is almost always more resource and emission intensive than the refining of primary raw materials from secondary raw materials[309] and *iii.)* the incineration and final disposal of electronic scrap can pose an environmental threat as materials are released in unnaturally high concentrations to the environment.

As an alternative to EOL treatment (here: decomposition of electronic scrap in order to recover/recycle materials and energy), outdated but still functioning network equipment could be dismounted and offered for re-use (technology transfer). That, for instance, would help to close the heavily cited *digital divide* or *information gap* (Riley et al. 2005,Uddin 2005) in the developing countries.

Finally, and in order to keep the environmental impact in the production and the EOL phase low, importance should be attached to enable a simple hardware upgradeability of the mobile

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[293] Value based on: (GSMassociation, 2005).
[294] Approximated based on the average rack configiuration as documented in chapter 3.1.2.
[295] Approximated based on the average rack configuration as documented in chapter 3.1.2.
[296] Approximated based on the average rack configuration as documented in chapter 3.1.2.
[297] Approximated based on (Bushnell, 2005).
[298] Approximated based on (Bushnell, 2005).
[299] Value based on: (Swisscom, 2005, Sunrise, 2005).
[300] Value adopted from the Network Component Study (Chapter 4).
[301] Value adopted from the Network Study I (Chapter 5).
[302] Value adopted from the Network Study I (Chapter 5).
[303] Approximated based on: (Brien, 2003).
[304] Value based on: (Motorola, 2005).
[305] Value based on LCI data as compiled for an average BTS rack operated under Western European conditions in 2004 and referenced in Appendix D10.
[306] Value based on LCI data as compiled for an average BTS rack operated under Western European conditions in 2004 and referenced in Appendix D10.
[307] Value based on LCI data as compiled for an average BTS rack operated under Western European conditions in 2004 and referenced in Appendix D10.
[308] ICT.
[309] There are no primary raw material production processes known to the author that have a lower environmental impact.

phone network infrastructure in the design phase. This enhances the technical flexibility of a network and reduces the amount of electronic scrap when standards change (ERICSSON 2003).

In essence, 3G mobile phone networks represent a challenging and promising next step in the evolution of mobile communication technology. Presently however, they provide a functionality that apparently cannot become reasonably utilised. Efforts have to be undertaken to provide that the available services are of use.

The performed studies concentrated on the environmental aspects of EOL treatment of mobile phone network components in general and of recycling strategies in particular. The economic aspects, i.e. if recycling network component materials is also of economic benefit, were not taken into account. However, a few simple but perspicuous arguments may be mentioned that will endorse the economic benefit of recycling electronic scrap of mobile phone networks:

- Primary resources, for example metals, are contained in low concentrations in ores. Large amounts of soil and rock have to be moved and large fractions of ores have to be processed in order to extract only a limited amount of metals[310]. In contrast, scrap of electronic components such as network components contain metals in very high concentrations[311]. The amount of energy consumed for the extraction of a unit metal from a primary resource (e.g. from ore) will be much higher, and thus more costly, compared with the extraction of a same unit metal from a secondary resource (e.g. from electronic scrap). In addition the costs for metal extraction from ores will rise with the decreasing ore grade associated with the continual resource depletion (Norgate and Rankin, 2002).
- Metals in electronic scrap are present in combination with energy bearers (namely plastics). Today, this vantage is used to operate state-of-the-art thermal metal recovery processes without adding or with adding only a marginal amount of primary energy bearers (e.g. Ludvigsson, 2003, Isaakson, 2000). In contrast, the refining of metals from primary resources needs the addition of largely primary fossil energy bearers (e.g. Ritthoff, 2003). In particular today, as fossil energy bearers increasingly become objects of military conflicts and thus become more and more expensive[312], the energy demands of the thermal EOL processes could by favourably covered by the co-incineration of plastic electronic scrap fractions.
- Finally, the implementation of the “producer-takes-care”-principle in the European legislation imposes not only a duty for the manufacturers of network components to take back the components produced by them (e.g. CEC, 2003). It also enables free access to secondary resources that otherwise would have to be extracted and imported from distant places.

From a methodological point of view the obtained results suggest that:

- The LCA method represents a useful framework when assessing the environmental performance of large technical systems such as mobile phone networks.
- Using the IMPACT2002+ method, the environmental impacts related to the production, operation and EOL treatment of mobile phone networks could be estimated in a comprehensive manner.
- The application of tiered approaches to mobile phone networks (and probably to networks as such) facilitates environmental analyses. Studies focussing on networks showed that it is not necessary to include all network components in the analysis, as many of them are not or are only of limited environmental importance.

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[310] For instance 1 t of rock contains 4.1 mg gold.

[311] For instance a single PWBA (~ 30 g) in a mobile phone contains 0.01 g gold.

[312] cf. http://www.frankfurt-main.ihk.de.

The presented thesis represents basic work in the field of environmental assessment of large technical facilities such as mobile phone networks. The work on the methodological framework LCA, including the more specific fields of inventory (LCI), modelling (LC mod) and impact assessment (LCIA), are still ongoing. This implies that the results of the thesis have to be interpreted with care. Particular attention should be paid to the fact that:

- Neither the data bases used for the underlying inventory nor the impact assessment method applied to calculate the environmental impact scores explicitly distinguish the chemical state of all elements, e.g. all metal species[313]. Impacts are assigned to metals regardless whether a certain metal species can be environmentally dangerous or not. This in turn can lead to possibly biased impact assessment results.
- Background concentrations of naturally existing elements, such as metals are not taken into account in present impact assessment methods.
- The database used for the inventory of materials in the production site and the impact assessment method used to calculate the impact scores consider long term effects of emissions with a time horizon of 60.000 years[314]. The uncertainty of such prognoses is indisputably high (Hellweg 2000). It is also debateable whether the inclusion of so-called long term effects is reasonable, firstly in context with the LCA method as such (which is a non-spatial and non-temporal method), and secondly from a scientific point of view in general. So far, the modelling of the long term effects (in particular related to landfill sites) considers the release of (mostly all) matter from an initial storage to one second storage. There the matter accumulates again and at a certain point of time leads to significant releases. In this point the present modelling of long term effects clearly disregards the principle of dilution.
- Finally, though applying one of the most extensive inventory databases, a significant number of data sets were missing and needed to be approximated. In particular data sets on the production of rare metals were missing.

8.2. *Outlook and Perspectives for Future Studies*

The above briefly outlined limitations of the presented thesis require further endeavours in the field of environmental studies of communication networks. In general, the methodology, here LCA, needs improvement with respect to a more specific assignment of impacts scores to metal species. A planned research project in particular aims at the determination of characterisation factors for metal species in order to more exactly allot the impact score to metal species. In this context, the reasonable modelling of long term effects from landfill sites shall be addressed. Further research is needed with respect to the environmental performance of electronic scrap in thermal EOL treatment processes. Initial steps with respect to the experimental analysis of non-organic substances and the development of appropriate experimental methodologies have been undertaken but improvement is vitally needed. Little or nothing has been done with respect to the experimental analysis of organic compounds of electronic scrap. Future studies in particular should concentrate on the environmental performance of organics, such as flame retardants, contained in electronic scrap. Finally, the data basis on the inventory needed to efficiently perform LCA studies for mobile phone networks, or any other communication network that relies on electronic components, needs to be expanded and improved.

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[313] There are no data bases or impact assessment methods known to the author that distinguish between all metal species.

[314] At that time the next ice age is expected.

8.3. ***References***

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Appendices

A: Network Component Study

A1: Typical technical specifications of a GSM 900 BTS rack.

	GSM 900 Base Transceiver Station rack (BTS rack)	Sources
Rack specifications		
Weight [kg]	220.59	
Size (w x h x d) [mm]	600 x 1800 x 450	
Power consumption [kW]	1.85	
Rack device specifications		
sANTENNA CONNECTOR UNITS		(SiemensAG, 2000)
Number	4	
Weight [kg] each	1.7696	
Sub components	Housing, Screws, PWBA, Cable	
Size (w x h x d) [mm]	50 x 300 x 200	
TRANSCEIVER UNIT		(SiemensAG, 2000)
Number	12	
Weight [kg]	2.31	
Sub components	Housing, Screws, PWBA, Cable	
Size (w x h x d) [mm]	50 x 300 x 400	
AMPLIFIER		(SiemensAG, 2000)
Number	2	
Weight [kg]	2.1	
Sub components	Housing, Screws, PWBA, Cable	
Size (w x h x d) [mm]	50 x 300 x 400	
CORE BASIC MODULES		(SiemensAG, 2000)
Number	4	
Weight [kg]	2.0605	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	50 x 300 x 200	
CABLES		
Length [m]	20	
Mass [kg]	1.4	
Typical material	PVC, Copper wire	
RACK HOUSING		
Weight [kg]	170	
Typical material	Steel, Aluminium	
Size (w x h x d) [mm]	see rack specifications above	

A2: Transfer coefficients applied to rack landfill processes.

The assumption of complete metal leaching (TC = 1) was adopted from ecoinvent (Doka, 2003) for nearly all metals. In some special cases reduced TCs were applied. Those reduced TCs were applied either as literature suggests the application of those values or as otherwise unreasonable results were obtained. All transfer coefficients equal to one (TC = 1) were subject to sensitivity analysis. The original values were replaced by 0.5 and 0.1 respectively. The reduced values did not change the results of the impact assessment.

Chemical element	Overall transfer coefficient (TC) for the landfill site
Ag	1
Al	1
As	0.5
Au	1
Be	1
Bi	1
Br	1
Cd	1
Cl	1
Co	1
Cr	0.9
Cr VI+	0.1
Cu	1
Eu	1
Fe	1
Ga	1
Ge	1
Hg	1
In	1
Mn	1
Na	1
Ni	1
Pb	1
Pd	1
Pt	1
Ru	1
Sb	1
Se	1
Si	1
Sn	1
Th	1
Zn	1

A3: Transfer fractions applied to rack landfill processes.

Emission path (to air, soil and water)	Fraction	Comments/ References
Ag_air	0.05	estimated value;
Ag_soil	0.3	estimated value;
Ag_wat	0.65	estimated value;
Al_air	0.05	estimated value; small transfer to air
Al_soil	0.3	based on (Lumsdon, 1996)
Al_wat	0.25	based on (Lumsdon, 1996)
As_air	0.1	estimated value;
As_soil	0.3	based on (Hartley et al., 2004)
As_wat	0.6	based on (Hartley et al., 2004)
Au_air	0.01	estimated value;
Au_soil	0.24	estimated value;
Au_wat	0.75	estimated value;
Be_air	0.05	estimated value;
Be_soil	0.4	estimated value;
Be_wat	0.55	estimated value;
Bi_air	0.01	estimated value;
Bi_soil	0.44	estimated value;
Bi_wat	0.55	estimated value;
Br_air	0.1	estimated value;
Br_soil	0.2	estimated value;
Br_wat	0.7	estimated value;
Cd_air	0.05	estimated value; small transfer to air
Cd_soil	0.45	based on (Lumsdon, 1996)
Cd_wat	0.35	based on (Lumsdon, 1996)
Cl_air	0.24	estimated value;
Cl_soil	0.3	estimated value;
Cl_wat	0.46	estimated value;
Co_air	0.01	estimated value;
Co_soil	0.24	estimated value;
Co_wat	0.75	estimated value;
Cr_air	0.05	estimated value; small transfer to air
Cr_soil	0.35	based on (Rinehart et al., 1997)
Cr_wat	0.25	based on (Rinehart et al., 1997)
Cr_VI_air	0.005	estimated value; small transfer to air
Cr_VI_soil	0.25	based on (Rinehart et al., 1997)
Cr_VI_wat	0.7	based on (Rinehart et al., 1997)
Cu_air	0.05	estimated value; small transfer to air
Cu_soil	0.45	based on (Hartley et al., 2004)
Cu_wat	0.35	based on (Hartley et al., 2004)
Eu_air	0.1	estimated value;
Eu_soil	0.3	estimated value;
Eu_wat	0.6	estimated value;
Fe_air	0.01	estimated value;
Fe_soil	0.14	estimated value;
Fe_wat	0.85	estimated value;

A3: continued.

Emission path (to air, soil and water)	Fraction	Comments/ References
Ga_wat	0.7	estimated value;
Ge_air	0.01	estimated value;
Ge_soil	0.65	estimated value;
Ge_wat	0.34	estimated value;
Hg_air	0.12	estimated value; partly transfer to air
Hg_soil	0.55	based on (Biester et al., 2002)
Hg_wat	0.33	based on (Biester et al., 2002)
In_air	0.01	estimated value;
In_soil	0.65	estimated value;
In_wat	0.34	estimated value;
Mn_air	0.05	estimated value;
Mn_soil	0.35	estimated value;
Mn_wat	0.6	estimated value;
Na_air	0.3	estimated value;
Na_soil	0.1	estimated value;
Na_wat	0.6	estimated value;
Ni_air	0.01	estimated value; small transfer to air
Ni_soil	0.55	based on (Chirenje et al., 2002)
Ni_wat	0.14	based on (Chirenje et al., 2002)
Pb_air	0.01	estimated value; small transfer to air
Pb_soil	0.34	based on (Hartley et al., 2004, Hellweg et al., 2004)
Pb_wat	0.2	based on (Hartley et al., 2004, Hellweg et al., 2004)
Pd_air	0.04	estimated value;
Pd_soil	0.36	estimated value;
Pd_wat	0.6	estimated value;
Pt_air	0.01	estimated value;
Pt_soil	0.34	estimated value;
Pt_wat	0.65	estimated value;
Ru_air	0.05	estimated value;
Ru_soil	0.35	estimated value;
Ru_wat	0.6	estimated value;
Sb_air	0.05	estimated value; small transfer to air
Sb_soil	0.75	based on (Wilson et al., 2004)
Sb_wat	0.2	based on (Wilson et al., 2004)
Se_air	0.05	estimated value; small transfer to air
Se_soil	0.65	based on (Wang and Chen, 2003)
Se_wat	0.3	based on (Wang and Chen, 2003)
Si_air	0.05	estimated value;
Si_soil	0.85	estimated value;
Si_wat	0.1	estimated value;
Sn_air	0.01	estimated value;
Sn_soil	0.34	estimated value;
Sn_wat	0.65	estimated value;
Th_air	0.01	estimated value;
Th_soil	0.29	estimated value;
Th_wat	0.7	estimated value;
Zn_air	0.01	estimated value; small transfer to air
Zn_soil	0.65	based on (Hellweg et al., 2004, Martínez and Motto, 2000)
Zn_wat	0.24	based on (Hellweg et al., 2004, Martínez and Motto, 2000)

A4: Transfer coefficients applied to rack incineration processes.

It was assumed that high quality filter technique was applied to retain metals posing critical environmental impacts. Larger transfer coefficients indicate that the respective elements are highly volatile and are only partly retained by the filter technique applied. All other elements were assumed to be retained in the slag transferred finally to the landfill site.

Chemical element	Overall transfer coefficient (TC) for the incineration site	Comments
Ag	0.01	assumed to be retained;
Al	0.2	some aluminium particles leave the incinerator;
As	0.3	volatile;
Au	0.01	assumed to be retained;
Be	0.75	volatile;
Bi	0.01	assumed to be retained;
Br	0.75	volatile;
Cd	0.5	volatile;
Cl	0.75	volatile;
Co	0.01	assumed to be retained;
Cr	0.01	assumed to be retained;
Cr VI+	0.1	volatile;
Cu	0.1	some copper particles leave the incinerator;
Eu	0.01	assumed to be retained;
Fe	0.01	assumed to be retained;
Ga	0.2	some gallium particles leave the incinerator;
Ge	0.01	assumed to be retained;
Hg	0.75	volatile;
In	0.01	assumed to be retained;
Mn	0.1	some manganese particles leave the incinerator;
Na	0.5	volatile;
Ni	0.1	some nickel particles leave the incinerator;
Pb	0.2	some lead particles leave the incinerator;
Pd	0.01	assumed to be retained;
Pt	0.01	assumed to be retained;
Ru	0.01	assumed to be retained;
Sb	0.2	some antimony particles leave the incinerator;
Se	0.01	assumed to be retained;
Si	0.2	some silicon particles leave the incinerator;
Sn	0.01	assumed to be retained;
Th	0.01	assumed to be retained;
Zn	0.01	assumed to be retained;

A5: Transfer fractions applied to rack incineration processes.

Beneath, the transfer fractions applied to the overall emissions released during the rack incineration process are compiled. The fractions were multiplied with the above given transfer coefficients and the respective emissions inventoried. As no information was found on the fractionation of the emissions released during the rack incineration process, all values were estimated based on general physico-chemical element properties and of the environmental conditions prevailing in a municipal waste incineration oven. The values compiled represent average data.

Emission path	Fraction	Comments
Ag_air	0.9	estimated value;
Ag_soil	0.05	estimated value;
Ag_wat	0.05	estimated value;
Al_air	0.95	estimated value;
Al_soil	0.025	estimated value;
Al_wat	0.025	estimated value;
As_air	0.99	estimated value;
As_soil	0.005	estimated value;
As_wat	0.005	estimated value;
Au_air	0.4	estimated value;
Au_soil	0.4	estimated value;
Au_wat	0.2	estimated value;
Be_air	0.9	estimated value;
Be_soil	0.05	estimated value;
Be_wat	0.05	estimated value;
Bi_air	0.1	estimated value;
Bi_soil	0.8	estimated value;
Bi_wat	0.1	estimated value;
Br_air	0.9	estimated value;
Br_soil	0.05	estimated value;
Br_wat	0.05	estimated value;
Cd_air	0.8	estimated value;
Cd_soil	0.15	estimated value;
Cd_wat	0.05	estimated value;
Cl_air	0.5	estimated value;
Cl_soil	0.1	estimated value;
Cl_wat	0.4	estimated value;
Co_air	0.1	estimated value;
Co_soil	0.6	estimated value;
Co_wat	0.3	estimated value;
Cr_air	0.2	estimated value;
Cr_soil	0.7	estimated value;
Cr_VI_air	0.6	estimated value;
Cr_VI_soil	0.3	estimated value;
Cr_VI_wat	0.1	estimated value;
Cr_wat	0.1	estimated value;
Cu_air	0.1	estimated value;
Cu_soil	0.8	estimated value;
Cu_wat	0.1	estimated value;
Eu_air	0.1	estimated value;
Eu_soil	0.7	estimated value;
Eu_wat	0.2	estimated value;

A5: continued.

Emission path	Fraction	Comments
Fe_air	0.1	estimated value;
Fe_soil	0.6	estimated value;
Fe_wat	0.3	estimated value;
Ga_air	0.2	estimated value;
Ga_soil	0.4	estimated value;
Ga_wat	0.4	estimated value;
Ge_air	0.1	estimated value;
Ge_soil	0.7	estimated value;
Ge_wat	0.2	estimated value;
Hg_air	0.99	estimated value;
Hg_soil	0.005	estimated value;
Hg_wat	0.005	estimated value;
In_air	0.1	estimated value;
In_soil	0.6	estimated value;
In_wat	0.3	estimated value;
Mn_air	0.1	estimated value;
Mn_soil	0.6	estimated value;
Mn_wat	0.3	estimated value;
Na_air	0.4	estimated value;
Na_soil	0.1	estimated value;
Na_wat	0.5	estimated value;
Ni_air	0.1	estimated value;
Ni_soil	0.6	estimated value;
Ni_wat	0.3	estimated value;
Pb_air	0.1	estimated value;
Pb_soil	0.6	estimated value;
Pb_wat	0.3	estimated value;
Pd_air	0.1	estimated value;
Pd_soil	0.6	estimated value;
Pd_wat	0.3	estimated value;
Pt_air	0.1	estimated value;
Pt_soil	0.7	estimated value;
Pt_wat	0.2	estimated value;
Ru_air	0.1	estimated value;
Ru_soil	0.6	estimated value;
Ru_wat	0.3	estimated value;
Sb_air	0.2	estimated value;
Sb_soil	0.6	estimated value;
Sb_wat	0.2	estimated value;
Se_air	0.1	estimated value;
Se_soil	0.7	estimated value;
Se_wat	0.2	estimated value;
Si_air	0.3	estimated value;
Si_soil	0.4	estimated value;
Si_wat	0.3	estimated value;
Sn_air	0.1	estimated value;
Sn_soil	0.6	estimated value;
Sn_wat	0.3	estimated value;
Th_air	0.1	estimated value;
Th_soil	0.6	estimated value;
Th_wat	0.3	estimated value;
Zn_air	0.1	estimated value;
Zn_soil	0.7	estimated value;
Zn_wat	0.2	estimated value;

B: Network Study I

B1: Typical architecture of a GSM 900 mobile phone network.

Network generation		**2G**
Network standard		GSM (Phase 2)
Data transmission mode(s)		CS[315]
Data transfer rates [kbit/s]	Voice transmission (maximum)	14.4
	Data (uplink) (maximum)	7.2
	Data (downlink) (maximum)	14.4
Access methods		FDD/TDD
Modulation		FDMA/TDMA
Network configuration/ Network elements	Mobile Subsystem	Mobile Station (MS) incl. Subscriber Identity Module card (SIM-card)
	Base Station Subsystem	Base Transceiver Station (BTS) BTS racks (2-3) Back-up batteries (< 17) Air conditioner (~1-2) Cabling (indoor, outdoor) (~20-40 m) Mast (site depending) Antennae (~ 6)
		Base Station Controller (BSC) BSC racks (3-4) Air conditioner (~1-2) Cabling (indoor, outdoor) (~20-40 m)
	Network Switching Subsystem	Mobile Switching Centre (MSC) MSC racks (4-6) Air conditioner (~1-2) Cabling (~20-40 m)

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[315] Circuit Switched.

B2: Configuration of the modelled GSM 900 mobile phone network.

		Characteristics	References
Network generation		2G	
Network standards		GSM	
Data transmission services/ Access methods		FDD/TDD	
Data transfer rates [kbit/s]	Voice Transmission	9.6	(ETSI, 1996)
	Data Transmission	9.6	(ETSI, 1996)
Network configurations	Mobile Station (MS)	6188793	(BAKOM, 2004)
	Base Transceiver Station (BTS)	6800	(Rothus, 2002)
	BTS racks[316]	2	(Swisscom, 2003)
	Back-up batteries[1]	17	(Swisscom, 2003)
	Subscriber capacity[317]	96	(Swisscom, 2003) (Duque-Antón, 2002) (Eberspächer et al., 2001)
	Air conditioner[1]	1	(Swisscom, 2003)
	Cabling (outdoor)[1]	40	(Swisscom, 2003)
	Mast (site depending)[1]	1	(Swisscom, 2003)
	Antennae[1]	6	(Swisscom, 2003)
	Base Station Controller (BSC)	50	calculated based on (ERICSSON, 2002a, SiemensAG, 1999)
	BSC racks[318]	4	(Duschl, 2003)
	Air conditioner[3]	2	(Duschl, 2003)
	Cabling (outdoor)[3]	20	(Duschl, 2003)
	Mobile Switching Centre (MSC)	34	calculated based on (LucentTechnologies, 2001a) (Nokia, 2002)
	MSC racks (4-6)[319]	4	(Duschl, 2003)
	Air conditioner[4]	8	(Duschl, 2003)
	Cabling[4]	40	(Duschl, 2003)

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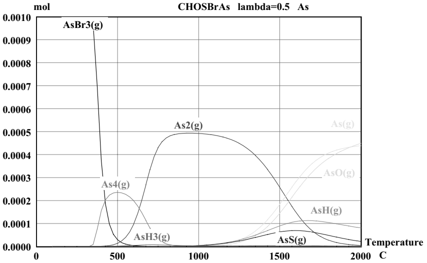
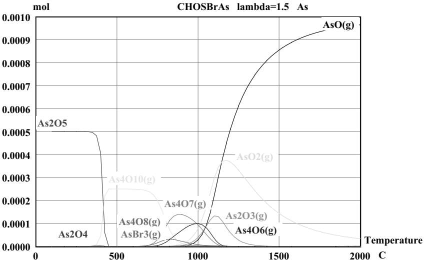
[316] Per antenna station.
[317] Per rack.
[318] Per BSC.
[319] Per MSC.

C: Network Component Experiment

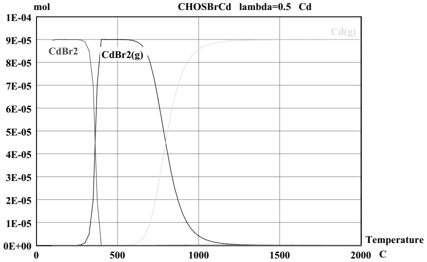
C1: Results of the thermodynamic equilibrium calculations.

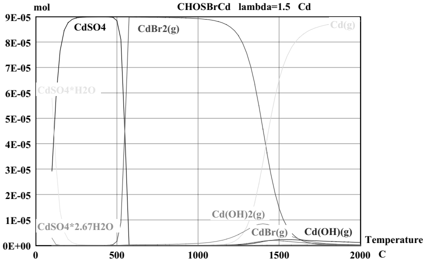
Element: **Arsenic**
Mol-fraction of PWBA [mol]: 0.001
Conditions: reducing oxidising



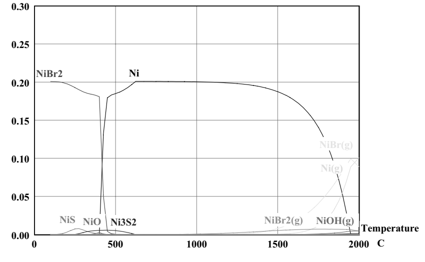


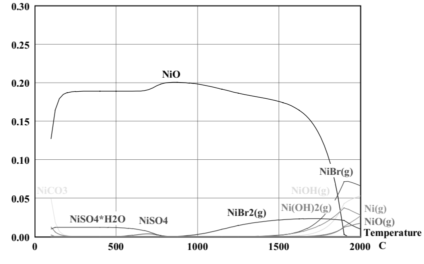
Element: **Cadmium**
Mol-fraction of PWBA [mol]: 0.00009
Conditions: reducing oxidising



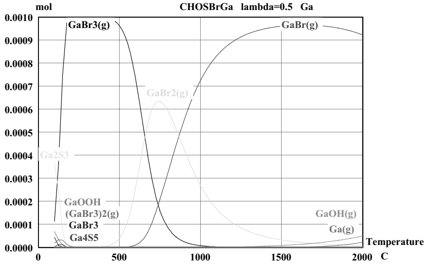


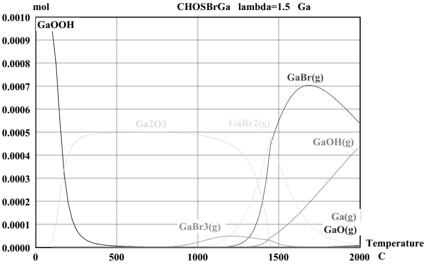
Element: **Nickel**
Mol-fraction of PWBA [mol]: 0.201
Conditions: reducing oxidising



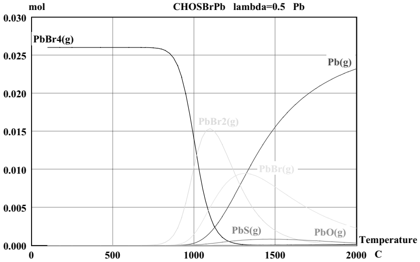


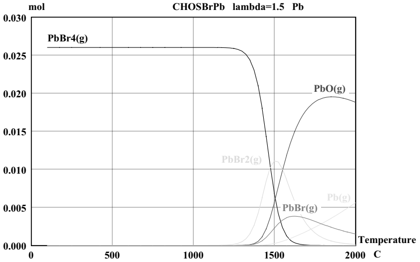
Element: **Gallium**
Mol-fraction of PWBA [mol]: 0.001
Conditions: reducing oxidising



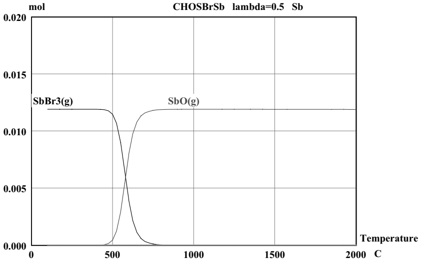


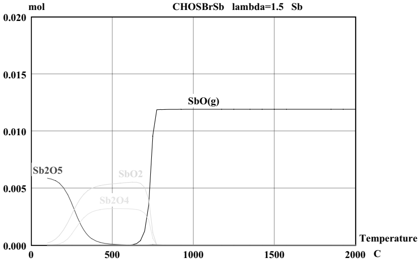
Element: **Lead**
Mol-fraction of PWBA [mol]: 0.026
Conditions: reducing oxidising





Element: **Antimony**
Mol-fraction of PWBA [mol]: 0.0119
Conditions: reducing oxidising

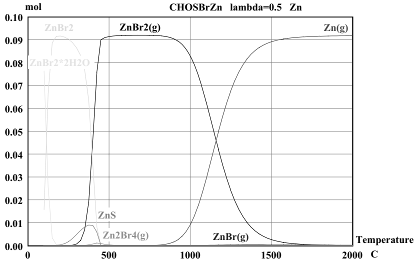


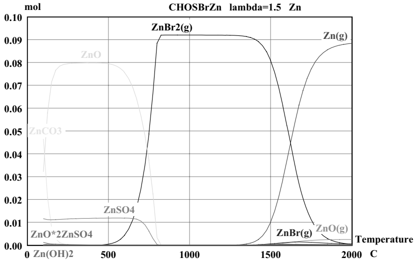


Element: **Zinc**

Mol-fraction of PWBA [mol]: 0.092

Conditions: reducing oxidising





D: Network Study II

D1: Typical technical specifications of a GSM BTS rack.

Same configuration as given in Appendix A1.

D2: Typical technical specifications of a GSM BSC rack.

	GSM Base Station Controller (BSC) rack	Sources
Rack specifications		
Weight [kg]	273.2	
Size (w x h x d) [mm]	600 x 1800 x 400	
Power consumption [kW][320]	0.60	
Rack device specifications		
APZ 21233C		(Enderin et al., 2001, ERICSSON, 2004)
Number	21	
Weight [kg] each	0.64	
Sub components	Housing, Screws, PWBA, Cable	
Size (w x h x d) [mm]	20 x 115 x 175	
RPG-3		(Enderin et al., 2001, ERICSSON, 2004)
Number	24	
Weight [kg] each	0.23	
Sub components	Housing, Screws, PWBA, Cable	
Size (w x h x d) [mm]	20 x 115 x 175	
RPP		(Enderin et al., 2001, ERICSSON, 2004)
Number	24	
Weight [kg]	0.23	
Sub components	Housing, Screws, PWBA, Cable	
Size (w x h x d) [mm]	20 x 115 x 175	
GDM Subrack		(Enderin et al., 2001, ERICSSON, 2004)
Number	2	
Weight [kg]	8.0	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	450 x 150 x 200	
GEM Subrack		(Enderin et al., 2001, ERICSSON, 2004)
Number	2	
Weight [kg]	16.0	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	450 x 200 x 200	
IRB		(ERICSSON, 2004)
Number	4	
Weight [kg]	0.64	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	20 x 115 x 175	
SCB		(Enderin et al., 2001, ERICSSON, 2004)
Number	4	
Weight [kg]	0.64	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	30 x 115 x 175	
CGB		(Enderin et al., 2001, ERICSSON, 2004)
Number	4	
Weight [kg]	0.71	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	20 x 115 x 175	
DLEB		(Enderin et al., 2001, ERICSSON, 2004)
Number	24	
Weight [kg]	0.43	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	20 x 115 x 175	

---

[320] Maximal value.

D2: continued.

	GSM Base Station Controller (BSC) rack	Sources
Rack device specifications		
ET155-1		(Enderin et al., 2001, ERICSSON, 2004)
Number	8	
Weight [kg]	0.41	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	20 x 115 x 175	
XDB		(Enderin et al., 2001, ERICSSON, 2004)
Number	4	
Weight [kg]	0.68	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	20 x 115 x 175	
CABLES		
Length [m]	10	
Mass [kg]	1.4	
Typical material	PVC, Copper wire	
RACK HOUSING		
Weight [kg]	175	
Typical material	Steel, Aluminium	
Size (w x h x d) [mm]	see rack specifications above	

D3: Typical technical specifications of a GSM MSC rack[321].

	GSM Mobile Switching Centre (MSC) rack	Sources
Rack specifications		
Weight [kg]	285.7	
Size (w x h x d) [mm]	600 x 2200 x 600	
Power consumption [kW][322]	4.00	
Rack device specifications		
Fan		(ProKomp, 2004)
Number	3	
Weight [kg] each	3.24	
Sub components	Housing, Screws, PWBA, Cable	
Size (w x h x d) [mm]	483 x 32 x 208	
UNIVERSAL GATEWAY		(LucentTechnologies, 2001a)
Number	1	
Weight [kg]	3.8	
Sub components	Housing, Screws, PWBA, Cable	
Size (w x h x d) [mm]	483 x 150 x350	
SIGNAL PROCESSING UNIT		(LucentTechnologies, 2001a)
Number	2	
Weight [kg]	3.8	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	183 x 130 x 350	
SERVER SUN NETRA T1400/05		(SUNmicrosystems, 1996, 1999)
Number	2	
Weight [kg]	36.7	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	432 x 264 x 505	
ISDN CARDS		(LucentTechnologies, 2001a, Steffen, 2004)
Number	36	
Weight [kg]	0.15	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	20 x 240 x 165	
CABLES		
Length [m]	10	
Mass [kg]	0.71	
Typical material	PVC, Copper wire	
RACK HOUSING		
Weight [kg]	185.0	
Typical material	Steel, Aluminium	
Size (w x h x d) [mm]	see rack specifications above	

---

[321] Data based on Lucent Flexent™ Feature Server.

[322] Maximal value.

D4: Typical technical specifications of a UMTS NodeB rack.

	UMTS NodeB rack	Sources
Rack specifications		
Weight [kg]	240.36	
Size (w x h x d) [mm]	600 x 1880 x 600	
Power consumption [kW][323]	6.70	
Rack device specifications		
Fan		(ProKomp, 2004)
Number	1	
Weight [kg] each	3.24	
Sub components	Housing, Screws, PWBA, Cable	
Size (w x h x d) [mm]	483 x 32 x 208	
Antenna Filter units		(Jarkadie, 2005, LucentTechnologies, 2002)
Number	3	
Weight [kg] each	4.04	
Sub components	Housing, Screws, PWBA, Cable	
Size (w x h x d) [mm]	220 x 350 x 80	
Transceiver unit		
Number	3	
Weight [kg]	2.9	
Sub components	Housing, Screws, PWBA, Cable	
Size (w x h x d) [mm]	430 x 80 x 220	
Amplifier Unit		(Jarkadie, 2005, LucentTechnologies, 2002)
Number	3	
Weight [kg]	10.4	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	99 x 355 x 450	
Exchange Terminal (E1/T1)		(LucentTechnologies, 2002)
Number	10	
Weight [kg]	0.52	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	20 x 260 x 165	
Cables		
Length [m]	10	
Mass [kg]	0.71	
Typical material	PVC, Copper wire	
Rack housing		
Weight [kg]	180	
Typical material	Steel, Aluminium	
Size (w x h x d) [mm]	see rack specifications above	

---

[323] Maximal value.

D5: Typical technical specifications of a UMTS RNC rack.

	UMTS Radio Network Controller (RNC) rack	Sources
Rack specifications		
Weight [kg]	230.70	
Size (w x h x d) [mm]	600 x 1800 x 600	
Power consumption [kW][324]	2.50	
Rack device specifications		
Fan		(ProKomp, 2004)
Number	4	
Weight [kg] each	3.24	
Sub components	Housing, Screws, PWBA, Cable	
Size (w x h x d) [mm]	483 x 32 x 208	
TIMING UNIT BOARD		(Gestner and Persson, 2002, Reinius, 1999)
Number	2	
Weight [kg] each	0.96	
Sub components	Housing, Screws, PWBA, Cable	
Size (w x h x d) [mm]	20 x 260 x 165	
EXCHANGE TERMINAL (ET4-1)		(ERICSSON, 2002b, 2004)
Number	9	
Weight [kg]	0.67	
Sub components	Housing, Screws, PWBA, Cable	
Size (w x h x d) [mm]	20 x 260 x 165	
GENERAL PURPOSE PROCESSOR BOARD		(ERICSSON, 2004, Gestner and Persson, 2002)
Number	6	
Weight [kg]	0.90	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	20 x 260 x 165	
SPECIAL PURPOSE PROCESSOR BOARD		(Gestner and Persson, 2002)
Number	9	
Weight [kg]	0.75	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	20 x 260 x 165	
SWITCH EXTENSION BOARD		(Gestner and Persson, 2002)
Number	2	
Weight [kg]	0.42	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	20 x 260 x 165	
SWITCH CORE BOARD		(Gestner and Persson, 2002)
Number	6	
Weight [kg]	0.48	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	20 x 260 x 165	
CABLES		
Length [m]	20	
Mass [kg]	1.42	
Typical material	PVC, Copper wire	
EXCHANGE MAGAZINE		
Number	3	
Mass [kg]	7.5	
RACK HOUSING		
Weight [kg]	170.0	
Typical material	Steel, Aluminium	
Size (w x h x d) [mm]	see rack specifications above	

---

[324] Maximal value.

D6: Typical technical specifications of a GPRS SGSN rack.

	GPRS Serving GPRS Support Node (SGSN) rack	Sources
Rack specifications		
Weight [kg]	378.00	
Size (w x h x d) [mm]	600 x 2200 x 600	
Power consumption [kW][325]	10.50	
Rack device specifications		
Fan		(ProKomp, 2004)
Number	3	
Weight [kg] each	3.24	
Sub components	Housing, Screws, PWBA, Cable	
Size (w x h x d) [mm]	483 x 32 x 208	
SWITCH UNIT		(CiscoSystems, 2005, Coleman, 2004a)
Number	1	
Weight [kg] each	2.7	
Sub components	Housing, Screws, PWBA, Cable	
Size (w x h x d) [mm]	438 x 45 x 419	
ISDN CARDS		(Coleman, 2004a)
Number	24	
Weight [kg]	0.22	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	20 x 260 x 175	
SERVER SUN NETRA CT400		(Coleman, 2004a, SUNmicrosystems, 2001)
Number	8	
Weight [kg]	18.10	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	445 x 534 x 400	
CHASSIS SERVER SUN NETRA CT400		(Coleman, 2004a, SUNmicrosystems, 2001)
Number	1	
Weight [kg]	22.2	
Typical material	Steel, Aluminium	
ROUTER UNIT		(CiscoSystems, 2004a, Coleman, 2004a)
Number	2	
Weight [kg]	6.27	
Sub components	Housing, PWBA, Cable	
Size (w x h x d) [mm]	445 x 437 x 419	
CABLES		
Length [m]	10	
Mass [kg]	0.71	
Typical material	PVC, Copper wire	
RACK HOUSING		
Weight [kg]	180	
Typical material	Steel, Aluminium	
Size (w x h x d) [mm]	see rack specifications above	

---

[325] Maximal value.

D7: Typical technical specifications of a GPRS GGSN rack.

	GPRS Gateway GPRS Support Node (GGSN) rack	Sources
Rack specifications		
Weight [kg]	292.9	
Size (w x h x d) [mm]	430 x 1800 x 530	
Power consumption [kW][326]	4.00	
Rack device specifications		
Fan		(ProKomp, 2004)
Number	3	
Weight [kg] each	3.24	
Sub components	Housing, Screws, PWBA, Cable	
Size (w x h x d) [mm]	483 x 32 x 208	
ROUTER CISCO 7809		(CiscoSystems, 2004b, Coleman, 2004b)
Number	1	
Weight [kg] each	102.6	
Sub components	Housing, Screws, PWBA, Cable	
Size (w x h x d) [mm]	431 x 933 x 533	
CABLES		
Length [m]	10	
Mass [kg]	0.71	
Typical material	PVC, Copper wire	
RACK HOUSING		
Weight [kg]	180.0	
Typical material	Steel, Aluminium	
Size (w x h x d) [mm]	see rack specifications above	

---

[326] Maximal value.

D8: Typical architecture of the investigated 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[327]	CS/PS[328]	CS/PS	CS/PS	CS/PS	PS[329]
Data transmission services			GPRS	EDGE			
Data transfer rates [kbit/s]	Voice transmission	14.4	14.4	14.4	12.2	12.2	64.0
	Data (uplink)	7.2	31.2	192.0	64.0	960.0	< 5800.0
	Data (downlink)	14.4	62.4	384.0	384.0	1920.0	< 20000.0
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. *S*ubscriber *I*dentity *M*odule card (SIM-card)			*U*ser *e*quipment (Ue) incl. *U*ser *S*pecific *I*dentity *M*odule card (USIM-card)		
	Base Station Subsystem/ Radio Network Subsystem	*B*ase *T*ransceiver *S*tation (BTS) BTS racks (2-3) Back-up batteries (< 17) Air conditioner Cabling (indoor, outdoor) Mast (site depending) Antennae (~ 6)			NodeB NodeB racks (2-3) Back-up batteries (< 17) Air conditioner Cabling (indoor, outdoor) Mast (site depending) Antennae (~ 6)		
		*B*ase *S*tation *C*ontroller (BSC) BSC racks (3-4) Air conditioner Cabling (indoor, outdoor)			*R*adio *N*etwork *C*ontroller (RNC) RNC racks (3-4) Air conditioner Cabling (indoor, outdoor)		
	Switching system - Circuit Switched Domain (CSD)	*M*obile *S*witching *C*entre (MSC) MSC racks (4-6) Air conditioner Cabling					

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[327] Circuit Switched.

[328] Packed Switched.

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

D8: continued.

Network generation Network standards		2G GSM (Phase 2)	2.5G (Phase 2+)	2.5G (Phase 2+)	3G UMTS (3GPP R'99)	3G UMTS (3GPP R'04)	3G UMTS (3GPP R'06)
	Packet Switched Domain (PSD)				*S*erving *G*PRS *S*upport *N*ode (SGSN) SGSN racks (1-2) Cabling		
					*G*ateway *G*PRS *S*upport *N*ode (GGSN) GGSN racks (1-2) Cabling		

D9: Configuration adopted to model the mobile phone 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	HSDPA, HSUPA
Data transfer rates [kbit/s]	Voice Transmission	9.6	-	-	12.2	-	-
	Data Transmission	9.6	62.4	384.0	384.0	1920.0	12000.0
Network configurations	*M*obile *S*tation (MS)/ *M*obile *E*quip. (ME)		6188793		70000	1050660	1459250
	*B*ase *T*ransceiver *S*tation (BTS)/ NodeB		6800			3465[330]	
	BTS racks/ NodeB racks[331]		2			1	
	Back-up batteries[1]		17			15	
	Subscriber capacity[332]	192	192	192	198	396	324[333]
	Air conditioner[1]		1			1	
	Cabling (outdoor)[1]		40			40	
	Mast (site depending)[1]		1			1	
	Antennae[1]		6			3	
	*B*ase *S*tation *C*ontroller (BSC)/ *R*adio *N*etwork *C*ontroller (RNC)		50			23	
	BSC racks/ RNC racks[334]		4			4	
	Air conditioner[3]		2			2	
	Cabling (outdoor)[3]		20			40	
	*M*obile *S*witching *C*entre (MSC)		34		15		-
	MSC racks (4-6)[335]			4			-
	Air conditioner[4]			8			-
	Cabling[4]			40			-
	*S*erving *G*PRS *S*upport *N*ode (SGSN)	-	50			23	
	SGSN racks[336]	-	1			1	
	Cabling[5]	-	35			35	

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[330] 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. (2004): WCDMA for UMTS: Radio Access for Third Generation Mobile Communications *0-470-87096-6*. John Wiley & Sons Ltd.: Chichester..

[331] Per antenna station.

[332] Per rack.

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

[334] Per BSC/RNC.

[335] Per MSC.

[336] Per SGSN.

D9: continued.

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	HSDPA, HSUPA
Network configurations	*G*ateway *G*PRS *S*upport *N*ode (GGSN)	-	50		23		
	GGSN racks[337]	-	1		1		
	Cabling[1]	-	35		35		

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[337] Per GGSN.

D10: Data sources for the modelling of the network components.

Network	Component	Subcomponent	Sources
GSM 900 (basic)	MS		(ERICSSON, 1999, Nokia, 2005a, 2005b)
	BTS	Antenna	(Conquadrat, 2003, Doradus, 2003a, 2003b)
		Mast	(ITF, 2005)
		Cable (outdoor)	(SuperiorCables, 2003)
		Rack	(LucentTechnologies, 2000, SiemensAG, 2000)
		Backup battery	
	BSC	Rack	(Enderin et al., 2001, ERICSSON, 2002a, 2004)
	MSC	Rack	(LucentTechnologies, 2001a, 2003a, 2003b, 2003c, 2005, NSI, 2005, SUNmicrosystems, 1999)
GSM 900 (GPRS/EDGE)	SGSN	Rack	(Lucent, 2004a)
	GGSN	Rack	(CiscoSystems, 2004b, Lucent, 2004b)
UMTS	ME		(Anonymous, 2005, 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)
		Backup battery	see in GSM 900 (basic): backup 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

D11: Transfer coefficients and fractions adopted for incineration processes.

Element	Transfer coefficient	Emission path	Transfer fraction [%]
Ag_tot	0.01	Ag_air	0.9
		Ag_soil	0.05
		Ag_wat	0.05
Al_tot	0.144	Al_air	0.95
		Al_soil	0.025
		Al_wat	0.025
As_tot	1	As_air	0.99
		As_soil	0.005
		As_wat	0.005
Au_tot	0.01	Au_air	0.4
		Au_soil	0.4
		Au_wat	0.2
Be_tot	0.01	Be_air	0.9
		Be_soil	0.05
		Be_wat	0.05
Bi_tot	0.01	Bi_air	0.1
		Bi_soil	0.8
		Bi_wat	0.1
Br_tot	1	Br_air	0.9
		Br_soil	0.05
		Br_wat	0.05
Cd_tot	1	Cd_air	0.8
		Cd_soil	0.15
		Cd_wat	0.05
Cl_tot	0.75	Cl_air	0.5
		Cl_soil	0.1
		Cl_wat	0.4
Co_tot	0.2	Co_air	0.1
		Co_soil	0.6
		Co_wat	0.3
Cr_tot	0.01	Cr_air	0.2
		Cr_soil	0.7
		Cr_wat	0.1
Cr_VI_tot	0.1	Cr_VI_air	0.3
		Cr_VI_soil	0.25
		Cr_VI_wat	0.1
Cu_tot	0.01	Cu_air	0.1
		Cu_soil	0.8
		Cu_wat	0.1
Eu_tot	0.01	Eu_air	0.1
		Eu_soil	0.7
		Eu_wat	0.2
Fe_tot	0.041	Fe_air	0.1
		Fe_soil	0.6
		Fe_wat	0.3
Ga_tot	0.01	Ga_air	0.2
		Ga_soil	0.4
		Ga_wat	0.4

D11: continued.

Element	Transfer coefficient	Emission path	Transfer fraction [%]
Ge_tot	0.01	Ge_air	0.1
		Ge_soil	0.7
		Ge_wat	0.2
Hg_tot	0.75	Hg_air	0.99
		Hg_soil	0.005
		Hg_wat	0.005
In_tot	0.01	In_air	0.1
		In_soil	0.6
		In_wat	0.3
Mn_tot	0.1	Mn_air	0.1
		Mn_soil	0.6
		Mn_wat	0.3
Na_tot	0.5	Na_air	0.4
		Na_soil	0.1
		Na_wat	0.5
Ni_tot	0.01	Ni_air	0.1
		Ni_soil	0.6
		Ni_wat	0.3
Pb_tot	0.271	Pb_air	0.1
		Pb_soil	0.6
		Pb_wat	0.3
Pd_tot	0.01	Pd_air	0.1
		Pd_soil	0.6
		Pd_wat	0.3
Pt_tot	0.01	Pt_air	0.1
		Pt_soil	0.7
		Pt_wat	0.2
Ru_tot	0.01	Ru_air	0.1
		Ru_soil	0.6
		Ru_wat	0.3
Sb_tot	0.361	Sb_air	0.2
		Sb_soil	0.6
		Sb_wat	0.2
Se_tot	0.01	Se_air	0.1
		Se_soil	0.7
		Se_wat	0.2
Si_tot	0.2	Si_air	0.05
		Si_soil	0.4
		Si_wat	0.3
Sn_tot	0.01	Sn_air	0.1
		Sn_soil	0.6
		Sn_wat	0.3
Th_tot	0.01	Th_air	0.1
		Th_soil	0.6
		Th_wat	0.3
Zn_tot	0.356	Zn_air	0.1
		Zn_soil	0.7
		Zn_wat	0.2

D12: Transfer coefficients and fractions adopted for landfill processes.

Element	Transfer coefficient	Emission path	Transfer fraction [%]
Ag_tot	1	Ag_air	0.05
		Ag_soil	0.3
		Ag_wat	0.65
Al_tot	1	Al_air	0.05
		Al_soil	0.3
		Al_wat	0.25
As_tot	1	As_air	0.1
		As_soil	0.3
		As_wat	0.6
Au_tot	1	Au_air	0.01
		Au_soil	0.24
		Au_wat	0.75
Be_tot	1	Be_air	0.05
		Be_soil	0.4
		Be_wat	0.55
Bi_tot	1	Bi_air	0.01
		Bi_soil	0.44
		Bi_wat	0.55
Br_tot	1	Br_air	0.1
		Br_soil	0.2
		Br_wat	0.7
Cd_tot	1	Cd_air	0.05
		Cd_soil	0.45
		Cd_wat	0.35
Cl_tot	1	Cl_air	0.24
		Cl_soil	0.3
		Cl_wat	0.46
Co_tot	1	Co_air	0.01
		Co_soil	0.24
		Co_wat	0.75
Cr_tot	0.25	Cr_air	0.05
		Cr_soil	0.35
		Cr_wat	0.25
Cr_VI_tot	0.25	Cr_VI_air	0.05
		Cr_VI_soil	0.25
		Cr_VI_wat	0.7
Cu_tot	1	Cu_air	0.05
		Cu_soil	0.45
		Cu_wat	0.35
Eu_tot	1	Eu_air	0.1
		Eu_soil	0.3
		Eu_wat	0.6
Fe_tot	1	Fe_air	0.01
		Fe_soil	0.14
		Fe_wat	0.85
Ga_tot	1	Ga_air	0.05
		Ga_soil	0.25
		Ga_wat	0.7

D13: continued.

Element	Transfer coefficient	Emission path	Transfer fraction [%]
Ge_tot	1	Ge_air	0.01
		Ge_soil	0.65
		Ge_wat	0.34
Hg_tot	1	Hg_air	0.22
		Hg_soil	0.55
		Hg_wat	0.33
In_tot	1	In_air	0.01
		In_soil	0.65
		In_wat	0.34
Mn_tot	1	Mn_air	0.05
		Mn_soil	0.35
		Mn_wat	0.6
Na_tot	1	Na_air	0.3
		Na_soil	0.1
		Na_wat	0.6
Ni_tot	1	Ni_air	0.01
		Ni_soil	0.55
		Ni_wat	0.14
Pb_tot	1	Pb_air	0.05
		Pb_soil	0.34
		Pb_wat	0.2
Pd_tot	1	Pd_air	0.04
		Pd_soil	0.36
		Pd_wat	0.6
Pt_tot	1	Pt_air	0.01
		Pt_soil	0.34
		Pt_wat	0.65
Ru_tot	1	Ru_air	0.05
		Ru_soil	0.35
		Ru_wat	0.6
Sb_tot	1	Sb_air	0.05
		Sb_soil	0.75
		Sb_wat	0.2
Se_tot	1	Se_air	0.05
		Se_soil	0.65
		Se_wat	0.3
Si_tot	1	Si_air	0.05
		Si_soil	0.85
		Si_wat	0.1
Sn_tot	1	Sn_air	0.01
		Sn_soil	0.34
		Sn_wat	0.65
Th_tot	1	Th_air	0.01
		Th_soil	0.29
		Th_wat	0.7
Zn_tot	1	Zn_air	0.01
		Zn_soil	0.65
		Zn_wat	0.24

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Curriculum Vitae

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Nationality: German
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Professional Experience

2002 – present	Swiss Federal Laboratories for Materials Testing and Research (EMPA), Scientific Collaborator (Candidate for PhD).
2001 – 2002	Swiss Federal Institute of Technology Zurich, Scientific Collaborator, KTI Research Project “Neues Orthogonales Wärmeübergangs Anemometer” (Testing an Anemometer Prototype under Field and under Laboratory Conditions).
2000 – 2001	Dresden Technical University, Scientific Collaborator, Run-off Water Modelling.
1996 – 1999	Dresden Technical University, Student Assistant.

Other Professional Activities

2003 – present	Reviewer for the International Journal of Life Cycle Assessment, the Journal of Cleaner Production, the Journal of Hazardous Materials.

Education

2002 – present	Swiss Federal Institute of Technology Lausanne, PhD research project “Life-Cycle Assessment of Mobile Telephone Networks with Focus on the Environmental Relevance of the End-of-Life Phase”.
2003	Swiss Federal Institute of Technology Zurich, Graduate course “Mobile Telephony”.
2002	Swiss Federal Institute of Technology Zurich, Graduate course “Interactive Data Language”.
1999 – 2000	Uppsala University, Studies of Hydrology and Meteorology, Graduation as M. Sc.; Diploma in “Sustainable Water Management in the Baltic Region”.
1996 – 1999	Dresden Technical University, Studies of Hydrology and Meteorology.
1992 – 1995	“Justus v. Liebig” Agrartechnisches Gymnasium Altroßthal, General qualification for university entrance (Abitur).

Civil Service

1995 – 1996	Grüne Liga Sachsen e.V.

Special Skills

Languages	German, English, Swedish, Russian (advanced level).
Informatics	GaBi (LCA-software) since version 4.0, Interactive Data Language (IDL) since version 5.4, JAVA, R, Microsoft Office Tools
Experimental	Handling of wind tunnels and quartz tube reactors; establishing experimental set ups for field and for laboratory conditions.

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