# EXPLORING THE RESOURCE POTENTIALS OF MINING WASTE AND LANDFILL MINING IN AUSTRIA

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## A STUDY ON COPPER, ZINC AND LEAD

DIPLOMA THESIS BY MANUEL FRANZ SUDEN MATRICULATION NUMBER 778941

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# Landfill Mining: Resource Potentials of Mining Waste and Municipal Solid Waste Landfills in Austria

-A study on copper, zinc and lead-

Diploma Thesis

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*For my family and friends*

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# Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared

sources that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

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# Abstract

Copper, lead and zinc are constituencies of technical materials, which are required in modern industries. Higher-grade mineral deposits are considered to be limited and the increasing primary production of metal is highly energy consumptive and connected to environmental burdens. For this reason, the secondary resource potential of Mining Residues was investigated in this thesis.

Substance-Flow-Analysis (SFA) for three non-ferrous metals were carried out for mining tailings (Mineral Processing Residues), using the software STAN. Transfer coefficients for input flows of metals to the stock of tailings have been calculated annually to estimate its resource potential in Austria and compared to the stock of MSW landfills. Data from the literature was used as empirical values for the modeling process.

Results for copper and zinc indicated similar patterns when comparing tailings to MSW-landfills. For copper a theoretical resource potential of about 2,600t stored in tailings could be calculated for 1919-1976, compared to Min/Max of 39,000t / 149,000t potentially stored in MSW-landfills until 2009. Contrary to copper and zinc, lead showed a higher resource potential in tailings. Further results recovered unexpected wide ranges between the resource potentials calculated for tailings (SFA), estimated from historical references and "secured" potentials documented in company´s own bookkeeping or recent analysis. In summary, the present study discovered uncertainties about former pathways of disposal that might limit the today's resource potential. Nevertheless, the results for tailings could contribute to maximizing the recovery of valuable materials such as non-ferrous metals.

# Content

# List of Tables

# List of Figures

# 1 Introduction

## 1.1 Background

“Since World War Second globally more resources and particularly metals have consumed like in the whole history of human life before”.
This statement, as put by Günter Tiess from the Montan University Leoben, Austria during a discussion on resource politics, indicates significant raise in resource consumption (ORF 2011). Nowadays metals at the same time are highly valuable materials to serve the demand of our modern societies as they are “finite” resources. This leads to resource bottlenecks that can be seen as a function of per capita consumption, population, the rate of exploration and in the long run the amount of natural and secondary resources in stock.

Today´s earth´s population of about 7 billion of people is constantly growing and will, by a middle projection scenario, count 10,6 billion humans by the year of 2050 (United Nations 2011). Next to population growth particularly the changing consumption patterns in densely populated emerging countries like China, Brazil or India resulted in higher demand especially of metal resources.
Furthermore asset bubbles in commodity markets lead to price fluctuations and rises.
Because of a high correlation between the industrialization and the demand e.g. for copper, a decrease in the demand for copper could not be expected in the medium term and its probable that the long term demand growth remains robust (Lucas, Bleischwitz et al. 2008).
Triggered resource conflicts and the depletion of resources without a sustainable development of the local societies could even result in war like in Congo, owning the largest secured reserves of highly demanded coltan (Economist 2010). Moreover it’s questioned how Europe for example can secure the supply of non-ferrous metals in terms of their 'ethically sound' use to run a competitive economy, while these resources partly come from authoritarian regimes like Congo or China.

*Material Flows of a Resource System*

Generally, the increased consumption of resources directly or delayed resulted in increased material flows. This accounts for Metallic Raw Material Cycles (Figure 1) including Mining Waste at the very beginning of the production-cycle as well as for Municipal Solid Waste (MSW) at the end of the life-cycle.

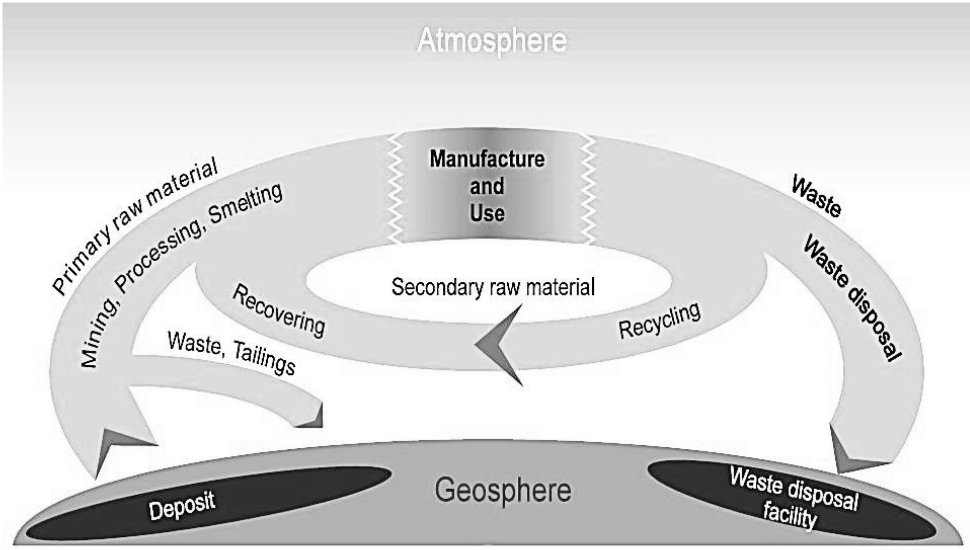


*Figure 1: The Metallic Raw Material Cycle (Cöppicus and Bauer 2002)*

Mining Waste can be defined as waste from excavation and processing of mineral resources such as metal ore. After being excavated the metal´s fate contained in mineral ores could end up in different pathways. Like other resources, metals could be either:

- disposed (stored in gangue or tailings);
- diluted (if dumped in rivers/ponds);
- burned (concentrated in metallurgical processes);
- entering Production- and Life-Cycles;
- entering Waste-Management-Systems (including Recycling).

Due to indelible character of metals, they tend to stay in the stock of life-cycles and waste facilities for an undefined time. An orientation of the material flows connected to mining and primary production of non-ferrous metals (here shown for copper, Figure 2) shows the process steps where mining wastes occur.

After being excavated the metal bearing ore gets separated from the material of less value, the so-called gangue rock. Thus gangue rock is the first waste stream in mining of mineral ores. Then the separated ore, of a specific metal concentration, the so-called ore grade, runs through several steps of mineral processing (milling, sorting, grain-sizing) that are upstream process steps to the actual separation of the metal particles (process of flotation). Flotation leads to the second mining waste stream, the tailings.

Tailings are left over from the process of separating the values from the invaluable gangue rock. They are of very fine dimension of approx. 0.2mm and bear non-ferrous metal fractions that could not been separated.

For the separation of metals flotation several reagents (water, lime and chemicals) need to be added. Off flotation parts of the material, in form of concentrates of app. 30% Cu flow to further metallurgical processing. Simultaneously a big fraction of residues is separated of as tailings. Because the process of flotation is the major process investigated in this study, further details were given in chapter 1.4.1.

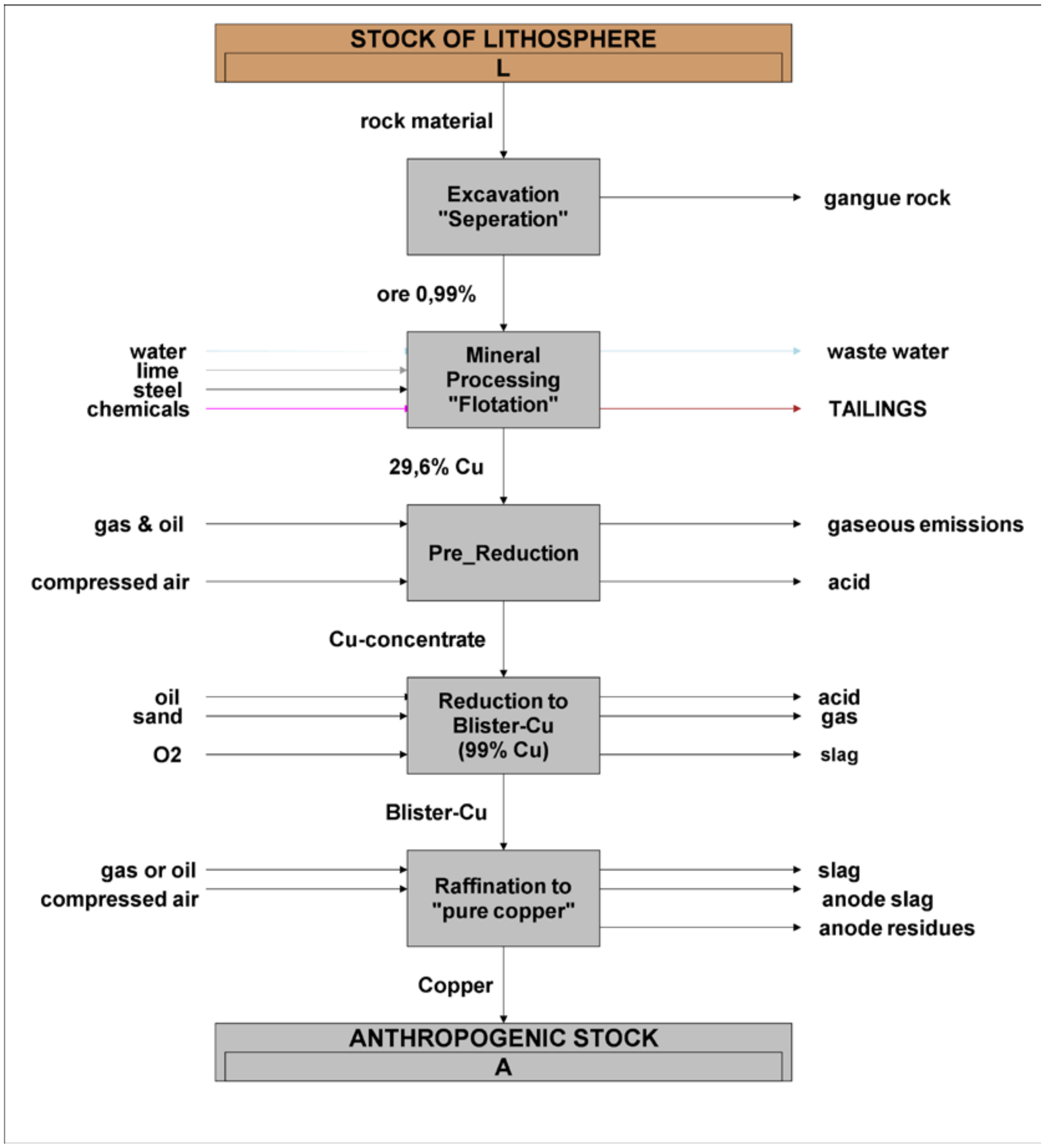


*Figure 2: Material flows in the primary production of copper showing the origin of tailings (Modified after Krauß and Wagner et al., BGR)*

During the metallurgical processes from Pre-Reduction (roasting) over the Reduction to Blister-Cu (99% Cu) and the final Refinery to “pure copper” different materials are added or remain as residues, before the metal gets added to Production- and Life Cycles, the Anthropogenic Stock. In summary copper mainly remains in tailings, slags, anode slags and anode residues. Metallurgical slags get recycled inside the metallurgical processing; though do not accumulate in stocks. Anode residues today get exported and are not investigated in this study.

*Environmental Issues*

Waste streams and facilities together relate to a broad range of environmental burdens. Landfill emissions such as $CH_4$, $NH_4$, salts and organic emissions occur over long periods of time. Not only wastes directly connected to daily life and consumption, like MSW, relate to environmental problems.

Also Mining wastes can trigger environmental risks. Mining is highly water- and energy consumptive as well as connected to intensive land-use by excavation and the deposition of residues. Many mining waste facilities are left in conditions that pose grave dangers e.g. of copper production. Before and after its entry in the economic cycle, much copper is lost due to dissipation, partly leading to dilute contamination of soils. This process was further described by (Reijnders 2003).

Like MSW landfills some mining waste dumps heave to be closed/sealed, after-cared and monitored to prevent future environmental hazards. For this reason the EU Commission issued the EU-Mining Waste Directive (BRGM 2001) to improve the Management of Mining- and Ore-Processing Waste.

High off-flows of mining activities have increased the need for sinks.

To recover landfilled resources, including the energetic use of plastics in MSW, can reduce the need for final sinks, but not completely eliminate it. Thus, future planning of resource recoveries have to control such off flows to appropriate final sinks (Brunner, Kellner et al. 2012). Same accounts for tailings where re-worked fractions need to be disposed, if not being used for backfilling.

## 1.2 Potential of Secondary Resources

The use of secondary resources has the potential to significantly reduce negative consequences of primary production. It for example decreases the dependence on land and energy consumptive excavation. Moreover, the processing of secondary resources significantly reduces the energy consumption and relates to lower harms to the environment as compared to the primary production of copper from sulfide ores (Ayres R. U., Ayres L. W. et al. 2002)

Thus secondary resources are nowadays regarded to be a clean and more sustainable alternative that brings back resources into active-cycles. Recent studies in the field of “Urban Mining” often regard landfills as the future resource deposits. Hence, the resource potential of metals in landfills already has been investigated by different studies (Kapur and Graedel 2006; Gillner 2010; Gäth and Nispel 2011). Remarkably the metal concentrations of landfills, e.g. of app. 1% of Cu, exceed the concentrations of ores that are currently excavated (Alvarado, Maldonado et al. 1999; Bertram, Graedel et al. 2002).

From a resource perspective, also Mining Waste that is regarded to be one of the biggest waste streams in the European Union (BRGM 2001), is considered to be a material of interest. Mining of mineral ores is connected to high material and waste flows like “Gangue” and “Tailings” that could consist of relative amounts of resources (*Figure* 3).

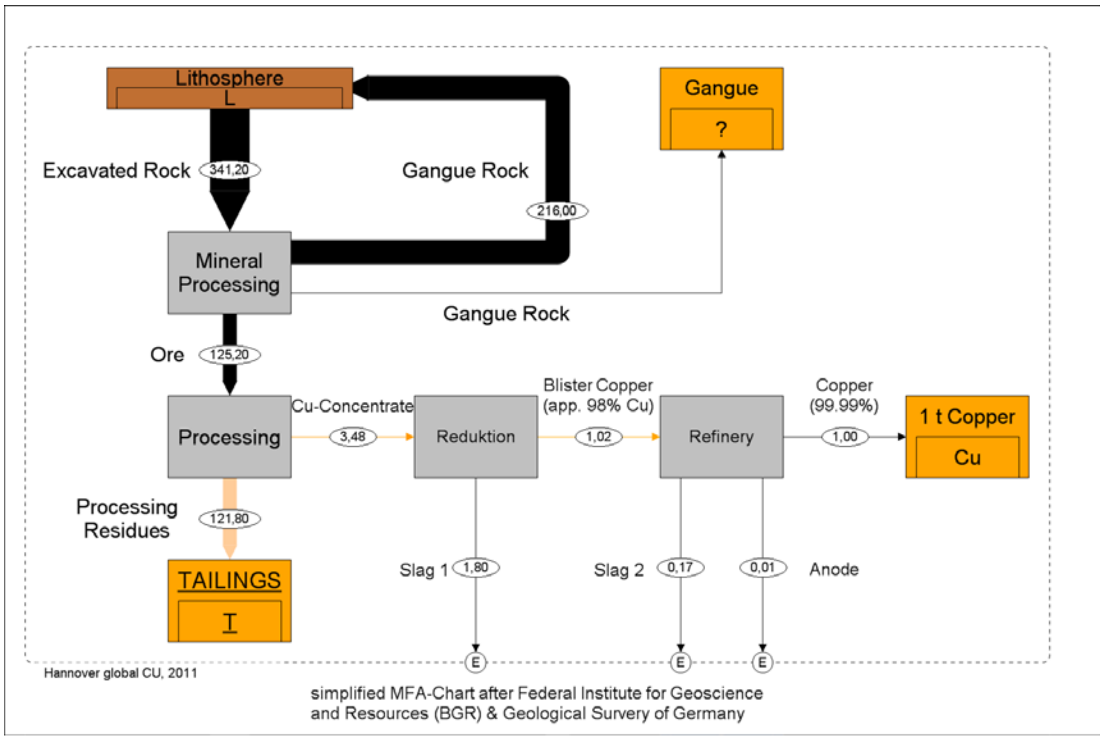


*Figure 3: Material Flows connected to the Primary Production of 1 ton of copper; flows mineral production and metallurgical processes reduced to copper bearing outflows (Modified after Krauß and Wagner et al.(1999)).*

Since the metal concentrations of the ore mined decreased, the material flows had to increase over time to be able to recover the same amount of metal. For example, if two copper ore have respective contents of 7% and 0.7%. For one ton of produced copper, the first one will produce 11.5 tons of waste while the second will produce 164.4 tons (EU Mining Waste Directive, Final Report 2006).

Because of their leading role in recycling techniques both, landfills and mining waste facilities could be earlier assessable for Western European countries compared to others. By all means, this suggests that the mental model of resource stocks must be considered much more broadly. Austria´s metal cycle is dominated by imports and exports, thus more important to secondary resources in the future.

*Research Overview*

The “Landfill Mining” of secondary resources has risen in popularity not only in the scientific world. While this tendency has triggered an increasing number of investigations on the anthropogenic flows of base-, precious- and rare metals, currently, several studies address landfills, regarded as stocks for selected metals (Mocker and Faulstich 2010; Bockreis and Knapp 2011; Gäth and Nispel 2011).

Another line of research was initiated at the Technical University of Vienna in Austria. Here analyses of residues derived from incineration ashes (Morf, Brunner et al. 2005; Mitterbauer, Skutan et al. 2009) or Mechanical-Biological-Treatment (Skutan and Brunner 2006) have been used to calculate substance concentrations of the MSW inputs.

Residues derived from mining have been hardly analyzed**,** mostly because of data constraints and a few studies tailings or mining residues (Krauß, Wagner et al. 1999; Cöppicus and Bauer 2002; Gordon 2002). Investigating U.S. Mining Wastes Gordon (2002) found copper concentration in mill tailings from 0.75 (early 20$^{th}$ century) to 0.9% (state of art).

Investigations made in Austria are restricted to the works of Scherer (1979); Jedlicka (1983); Montanwerke Brixlegg AG (1983) and Schedl, Mauracher et al. (2001). Scherer and Jedlicka focused on Mining Waste Facilities of the Pb/Zn mining area in Bad Bleiberg, Carinthia. Herein the authors mention ranges of metal concentrations and further calculated the estimated resource potential. The company´s own report of the Montanwerke Brixlegg AG is the only investigation found on copper tailings, whereas the “Mining Area/Dump Register” ÜLG-40 Project of Schedl, Mauracher et al. (2001) mainly focused on environmental risk assessment.

## 1.3 Goals and Research Questions

### 1.3.1 Goals

*Scope of this Thesis*

To answer the question: *Where are the resource potentials?* it was asked whether the higher resource potential is :

a) in Mining Residues;
b) in the Anthropogenic Stock or
c) in MSW landfills.

The scope of this study was to investigate resources in Mining Residues, because they have not been investigated on the national level before. Stock c) was chosen to relate the results for a) to an already well-investigated stock. This study neglects the anthropogenic stock b), thus focuses on the estimation of the seldom investigated stock a) compared to the well-studied stock c).

At the beginning of this thesis it was questioned which Mining Residues bear metal concentrations of interest for resource recovery. It is not documented in literature, gangue material to be of recoverable metal concentrations. Gangue, in this thesis is assumed not to bear metal concentrations of interest.
This study focuses on the resource potential of tailings, that related to large material flows of recoverable metal concentrations (Scherer 1979; Jedlicka 1983), but haven´t been investigated on the national level of Austria before.

*Goals of this thesis*

In order to determine the resource potential of MSW landfills and mining waste facilities the aims of this thesis are to:

- quantify the Theoretical Resource Potential of tailings
  and MSW landfills for Cu,Zn and Pb on the national level for Austria
- estimate the Real Resource Potential of tailings considering:
  - recovery technology
  - factors that are limiting the availability of resources
- compare the Theoretical Resource Potential of tailings
  with the potential of MSW landfills
- assess the importance of the resource potentials of the investigated stocks in relation to other secondary resource stocks

### 1.3.2 Research questions

To assess the resource potential of tailing, the research questions of this thesis are:

- can the MFA approach determine the amount of disposed tailings?
- how can metal concentrations in Austrian tailings be assessed?
- how much non-ferrous metal there is in tailings and will it be available?
- how can the total amount landfilled in Austrian MSW landfills be determined ?
- how can the concentration of  a non-ferrous metal in MSW can be assessed?
- how much non-ferrous metal there is in MSW landfills and
- how can resource stocks of tailings and MSW landfills be compared to each other and to other secondary resource stocks?

In order to answer the research question, the subquestions are:

- how reliable is the calculated resource potential of tailings
- can historical reference data reflect the volume of recent mining waste facilities;
- which factors affect the recoverability of metals from tailings;
- how reliable are the calculated volumes and non-ferrous metal concentrations in MSW landfills

## 1.4 Fundamentals of Non-Ferrous Metal Resources

### 1.4.1 Copper

The use of copper goes back to some of the oldest civilizations on record, going back at least 10.000 yrs. It is the most important functional metal of mankind, due to the metals´ outstanding material performance. Its thermal and electrical conductivity, as well as its anti-microbial effect and high corrosion resistance are favoring copper for a wide field of applications. Therefore copper was and still is strongly demanded on global raw material markets. Moreover, copper can be refined unlimited times without any drop in quality, thus its regarded as the metal with the highest potential for a sustainable development.

*Primary Deposits of Copper*

The global main excavation countries of copper ore are in North- and South American. The Austrian deposits are in the Northern Greywacke Zone, with major ore deposits in the area Schwaz-Brixlegg (for metallogenetic map of Austria see: http://www.geologie.ac.at/de/ GEOMARKT/ uebersichtskarten.html). These ore lodes are situated in dolomite from lower and middle Devonian. The second large deposits of nationwide importance are Chalcopyrite (Copper Pyrite) ores in the area of Mitterberg, Salzburg. More information regarding the mining area of Schwaz-Brixlegg is given in chapter 4.3.2.

*Extraction and Processing of Copper Ore*

Today copper is generated from ores containing 0.1-1% copper. After excavation the ore gets treated in different steps of mineral processing illustrated in Figure 4. After the separation of the values (3) and drying (4) the ore then gets prepared for flotation by milling. Crushing and grinding to particle size was required to allow contact with flotation chemicals. Today´s tailings are mostly of <0.2mm dimension (Krauß, Wagner et al. 1999).

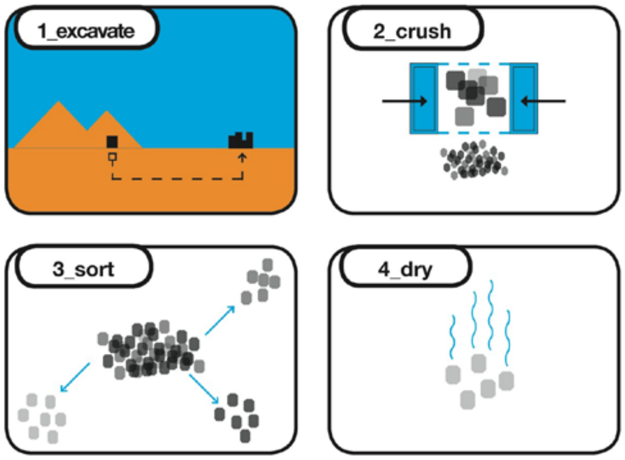


*Figure 4: Process steps of mining and mineral processing prior to flotation (own illustration)*

*Fundamentals of Flotation*

From its invention in1869 until today it is the main technique to recover metals from ores, used for concentration of 90% of all copper, zinc and lead ores processed today. Due to flotation is the process where tailings occur and it is also used to recover zinc and lead it is described in more detail in the following. Flotation requires the reduction of particle size of the ore by milling and grinding to particle size of app <0.2mm. These fines than get mixed up with different reagents and water to a pulp. This floatable pulp has fractions of solids between 20-40% (Krauß, Wagner et al. 1999). To this pulp, air is injected in order to produce air bubbles that rise through the column.

The principle of flotation then is described by physics. A particle that is to be held in this mineralized pulp must be so fine that its downward pull of gravity is smaller than its adhesion to an air-water interface (illustrated in Figure 5). Herby the adhesion of particles to comparatively large air bubbles allows for example Cu sulfides to rise through the column while gangue rock particles sink to the bottom.

The reason for this lies in slightly changes of the surface characteristics of metal bearing particles. Thus the challenge of flotation is to find conditions (pH, solid-liquid ratio, particle size etc.) where minerals of value get modified, while others remain indifferent and can be separated.

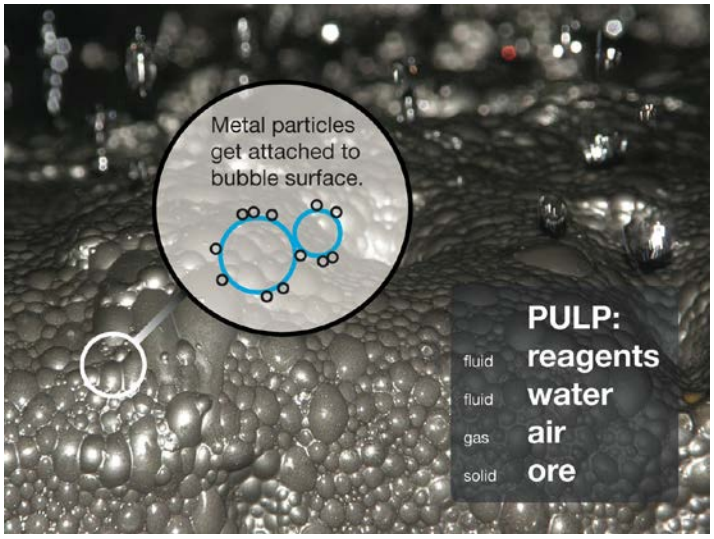


*Figure 5: Frothed up pulp from a flotation cell. Tiny metal particles are adhering to air bubbles (own illustration).*

If the temporal buoyant combinations of mineral particle and air bubbles form froth at the surface, the process is known as Froth-Flotation. The recovery efficiencies of metals ranges from 85-93% for (Cu)-Chalcopyrite (Prior 1965), and up to 93% for Zn and 76% for Pb (Jedlicka 1983).

*Primary Production and Secondary Production of Copper*

Copper ores can be either refined by pyro-metallurgical or hydro-metallurgical processes. In pyro metallurgical refining of copper low grade ores are getting concentrated to produce pure cathode copper and precious metals. While smelting, oxygen is induced by either getting inflated or blown into the smelter to oxidize and refine copper-bearing material. The smelt then is getting further cleaned and concentrated in the anode furnace. Coming out of the anode furnace the smelt is concentrated to 99% copper. In pyro metallurgical processes ending at this stage a fraction of copper remains in the slag. Further refining is done by hydrometallurgical processes that are also used to extract copper form low grade ores. Hydrometallurgical techniques are also used to recover copper primarily. This process is known as In-Situ Leaching (ISL). The Hydrometallurgical technique is generally applied to low grade ores or to oxide ores that occur in sulfide ore deposit. For this reason it can be used in the same way to recover non-ferrous from low grade ore bodies like tailing dumps. Some 10% of the global primary productions of copper have been generated by making use of hydrometallurgical processes (Krauß, Wagner et al. 1999).

Copper as a secondary resource mainly derives from the construction-, electrical/electronical– and transport sector. Relating to its metal concentrations, copper waste either gets directly into metallurgical processing or need to be pre-treated (e.g. digestion of circuit boards).

An approach to recover copper from residues of primary production like tailings is to float these residues for another time. Here, dump material basically gets treated in the same manner like fresh ore. The second approach to recover copper from dump sites uses hydrometallurgical techniques. This recovery process is known as dump- or heap leaching (see chapter 3.4.1).

*Environmental Issues related to Copper*

Within primary copper production energy consumption is one of the main burdens to the environment. Moreover, mining (North and South America) and processing and recycling of copper (Western World) is spatially divided, though adding additional energy cost for logistics.

Whereas mining of aluminum ores for example is seldom documented to relate to chemical threads, numerous side-elements (nickel, lead) in copper ores are of a potential environmental risk. Deposited mining and processing residues can generate acidic leachate can threaten surface and ground waters. Furthermore the generation of fly dust and the occurrence of mining related subsidence can change ecosystems that surround mining areas. For further studies of the copper system, a list of publications by the Collaborative Research Center 525 of the RWTH Aachen can be recommended for the interested reader.

### 1.4.2 Zinc

Zinc is represented in the earth´s crust at a high concentration of 70 (ppm) compared to zinc and lead. After USGS (2011) the identified world resources of zinc are about 1.9 billion metric tons. Furthermore high amounts of zinc are estimated to hibernate in the anthropogenic stock (mainly infrastructure, buildings, landfills etc.). Zinc has a wide field of applications, but mainly is used as anticorrosive agent, roof material and in production of alloys, such as brass and nickel silver.

*Primary Deposits*

Globally the most important zinc deposits are of the magmatic type. Based on a commercially available database of reserves and resources and excluding Australia and China the (USGS 2011) reports 250,000kt of identified world zinc reserves. The most important Austrian deposits are the Zn/Pb deposits in the Northern Chalk Alps, those in the Cenral Alps Paleozoic, those of the area of Graz and the deposits of the Gailtaler Alps.

*Primary Production and Secondary Production*

The extraction and primary production in general follow the basic principles as for copper or lead. Further metal specific details are provided in technical handbooks (Prior 1965; Habashi 2009)

Secondary production of zinc today is almost entirely done be re-smelting of scrap material. A secondary production of zinc with approximately 490 kt/a accounts for 20% of the European annual production (Metallgesellschaft Metallgesellschaft 1994). In Austria the large zinc manufacturer VOEST, producing app. 25 % of the annual national consumption (Daxbeck, Schönbauer et al. 1997), is considered to be also engaged in secondary zinc production (however, no specific information on this question is available).

In Austria, few is documented about the secondary production of zinc from mining residues. Jedlicka (1983) reported that close to 1900kt Pb/Zn mining wastes with a content of 50,000t $Zn_s$ have been reworked until 1982.

*Environmental Issues*

Zinc emissions for example can lead to contaminations of drinking water, but this needs far higher concentrations than emissions of e.g. copper. Nevertheless water ecosystems are sensible to zinc emissions. Furthermore, high zinc concentrations have negative affects to the functions of soils. It is phytotoxic from concentrations higher than 200mg/kg and can decrease the activity of micro-organisms. Thus it relates to declines of nutrient intakes and degradation of harmful substances.

### 1.4.3 Lead

Lead is represented in Earth´s crust at concentrations around 14 (ppm). In their annual Commodity Summaries the USGS (2011) stats the world resources of lead to be of 1.5 billion of tons. Lead is mainly used in lead-acid batteries, as radiation shield and as alloying agent for copper, zinc, tin and antimony.

*Primary Deposits*

The identified world reserves of lead are reported to be of 80,000kt (USGS 2011). The biggest European primary deposits are in Poland and Sweden. Austrian deposits mostly meet the deposits stated in this thesis for zinc (see 1.4.2 Fundamentals of Zinc).

*Primary Production and Secondary Production*

The primary production of lead in Austria ended in 1992. Like in Germany lead is Austria either gets imported or secondary recovered. Large amounts of secondary lead are recycled from old car batteries. In the U.S. in 2010 about 82% of the reported domestic lead consumption was recovered from old scrap. In Austria, few is documented about the secondary production of lead from mining residues. Jedlicka (1983) reported that close to 1900kt Pb/Zn mining wastes with a content of 9300t Pb have been reworked until 1982.

*Environmental Issues*

Lead is a common environmental pollutant. The heavy metal can be deposited from atmosphere to soil, ground and surface water. Especially the anthropogenic sources, including mining, use of sewage sludge as soil conditioner, paint and leaded gasoline are important inputs. These factors for example could result in higher lead concentrations in urban soils. Higher lead concentrations in soil or ground and surface waters can also result from dispersed mining waste, which compounds tend to be more mobile after milling.

# 2 Methods

## 2.1 Material Flow Analysis

The Material Flow Analysis methodology (MFA) is a tool that was introduced by Baccini and Brunner (1991) to model material flows or fluxes between compartments (processes, stocks & flows) of a spatial-temporal defined system. Since, the MFA-methodology was successfully applied to widespread case studies, especially in the Waste Management sector.

Though, MFA is often applied to rather complex systems. Although we are highly educated, as pointed out by Ford (1999), due to higher levels of complexity, our mental models seem inadequate to the task of assessing serious problems of environmental systems. The MFA-methodology allows to simplify complex systems in order to develop a clear approximation of a system´s material- and substance flows. Setting up the model we can also improve our understanding of the trajectories of waste systems.

MFA is based on the premise of the conservation of mass, meaning that within a given system, matter can neither be created nor destroyed. This means that the total inputs into a process and the total outputs from it need to be equal or lead to a change of a stock. The results of a MFA are simple mass balances of a system, described by:

$$\textit{Input} - \textit{Output} = \textit{Change of Stock } (+/-)$$

The first step when setting up a MFA is to define a process oriented system in space and time. Then the structure of the model was built in form of a MFA diagram (Figure 6). To build these MFA diagrams, the graphic structure of MFA models, the software STAN2 was used. STAN2 is an open source software developed at the Institute of Water Quality, Resource and Waste Management of the Vienna University of Technology in Austria.

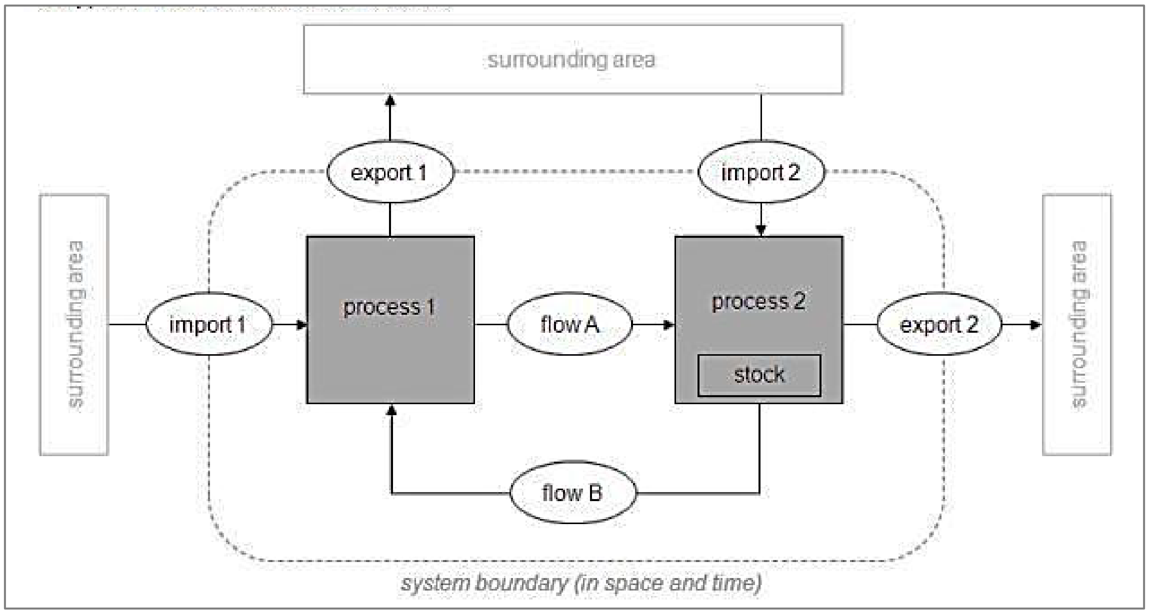


*Figure 6: A simple MFA diagram illustrating the main symbols used in a MFA model (From STAN 2.0, help menu)*

Starting with the investigated processes (box) the model is structured by connecting processes through relating substance flows (arrows). MFA methodology´s language distinguishes between (for definitions of terms see Glossary):

- “processes”
- “flows”
- “flux”
- “stocks”

It further has to be distinguished between a Material Flow Analysis, assessing materials, named goods and a Substance Flow Analysis (SFA) to assess flows on the substance level. In MFA terminology (see Glossary):

- “good”
- “substance”

### 2.1.2 Selection of System Boundaries

The spatial boundary of the system is set to the political borders of Austria and the inside situated waste facilities. The time frame addressed of this MFA-approach follows the availability of reference data. Thus the MFA-model is set for copper (1919-1976) and for zinc and lead (1918-1992). Technical details and a further description of the application of the MFA-model can be found in chapter 3.1.

### 2.1.3 Selection of Investigated Substances

Substances selected in this thesis have been chosen because of their abundance in mining tailings deriving from Austrian´s history in non-ferrous metal production.

For tailings (good), a high tonnage processed over the investigated period together with scarce reference data on former secondary recovery, raised the interest to investigate possible resource potentials. It was furthermore motivated by today´s high economic values of non-ferrous and the possibly connected environmental risk potential (e.g. Acid-Mine-Drainage of Copper).

Moreover, all selected substances are well documented in investigations addressing their concentrations in MSW, thus a good availability of reference data allows the comparison to the resource potential estimated for tailings.

## 2.2 Methodology to assess the Resource Potential of MSW Landfills

In assessing the resource potential it was distinguished between the calculation of the theoretical and the real resource potential of a particular metal.

The theoretical potential of a metal was determined by its total mass resting in a landfill, where the practical or real resource potential is determined by different factors. They could only be calculated considering the following:

- market situation/price,
- price and local asses to energy resources, logistics and nearby customers of by-products,
- specific financial situation of deposit operator (aftercare costs,
- and state of art recovery technology for a specific momentum.

To assess the resource potential of MSW landfills, this study restricts to estimate the theoretical resource potential in Austria.

In this study, to assess this potential, first the total amount of waste disposed at MSW landfills was calculated from various reference data. Estimates for years with any waste volume documented, were assessed by linear integration between recorded years. Then statistics derived from literature have been used to estimate the recycling paths for each year to determine the amounts that were disposed at MSW landfills. A detailed description of the application of this methodology is given in chapter 3.2.

# 3 Systems Definitions and Data Acquisition

## 3.1 Application of Material Flow Analysis

### 3.1.1 Determination of Key Processes, Flows and Stocks

Due to tailings derived from the process of flotation, flotation was the key process of the MFA model. It determined the inflow to the stock of “Tailings” for all metals investigated in this thesis.

Flotation has most often been a combination of a few cascadeus oriented washing devices, but was regarded in this MFA model as a single process to not increase the level of complexity. The investigation of all downstream installed processes and their relating losses of metals over the investigated period was not the scope of this work. The key flows studied were the in- and outflows of the investigated stock of tailings (see Figure 7).

### 3.1.2 Model Building and Structure

The model was simplified by neglecting inflows of reagents and alike to the process of “Flotation”. Keeping the model as simple as possible the flows to and off Flotation were limited to the inflows of “dry ores” and “reworked tails” and the outflows of “tails” and “valuable material”.

In the following, the developing steps of the conducted MFA study are described. For the convenience of the reader this description follows the MFA diagram presented in Figure 7.

*Material Flow Analysis*

By applying MFA on a time series base, literature data has been taken to either calculate or estimate the model´s input parameters. Information about mass flows was mostly taken or calculated by the Montan-Yearbooks of Austria (MHB). All data or data imports to the model were conducted through Microsoft Excel.

First, the material flow into the system was derived by the annual amount of excavated ore in Austria (MHB). The first process “Dewatering”, not even necessary to model the substance flows of metal in the SFA, was added to use the software to calculate the water loss of “dry ores” for years where only the wet weight of ore was documented. An average loss in mass by “Dewatering” of 6% for copper and 3% for zinc-lead ores was calculated from literature and assumed for other years.

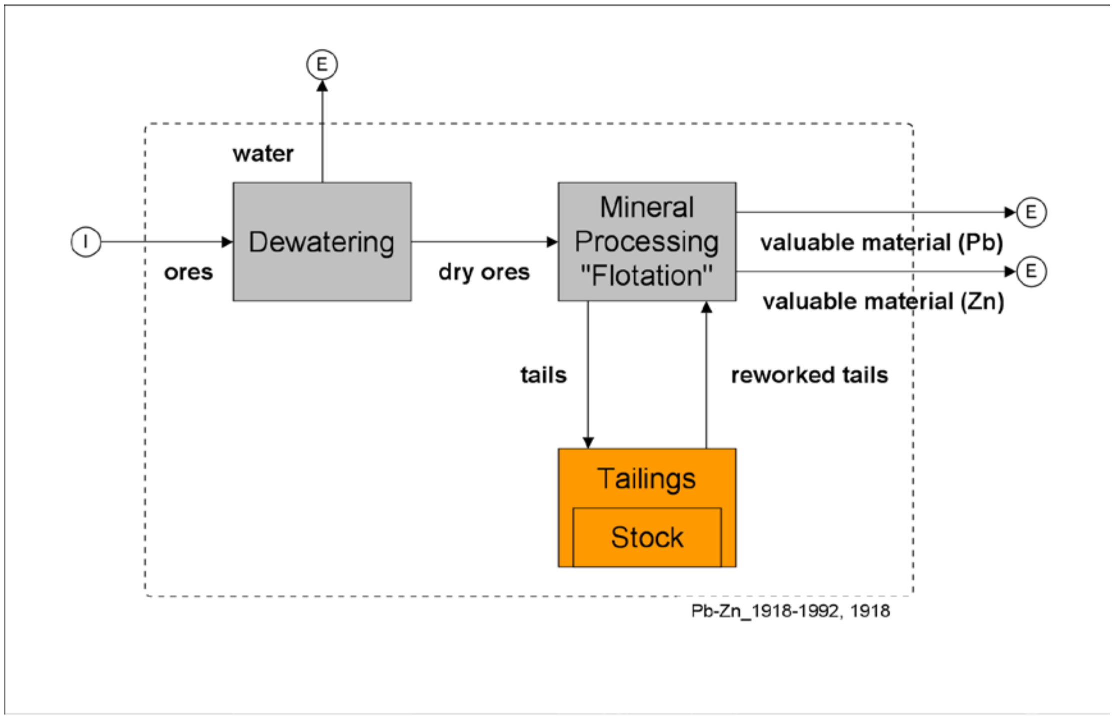


*Figure 7: MFA diagram for the Processing of Zinc and Lead*

Transfer coefficients (TC) have been used to model the material flows from the process “Flotation”. Transfer coefficients determined the partitioning of a good or substance by a process into different products. They are defined as

$$c_{m,i} = \frac{X_{m,i}}{X_{E,i}}$$

| | | |
|---|---|---|
| $c_{m,i}$ | = | transfer coefficient of good/substance *i* in product *m* |
| $X_{m,i}$ | = | flow of good/substance *i* in product *m* |
| $X_{E,i}$ | = | amount of good/substance *i* in educt *E*. |

Transfer coefficients have been estimated from literature data collected in Microsoft Excel sheets (*see Annex*). For example, for copper a TC of 0.97 from “Flotation” to “Tailings”, meaning 97% of the educts material flow remain in “Tailings”, was derived from Krauß, Wagner et al. (1999), see Figure *3*. The same value was assumed for the flow of “Reworked tailings” to “Tailings”, resulting in a material flow of 3% to “valuable materials” in case of copper. For zinc and lead values have been either calculated or assumed in the same way.

*Substance Flow Analysis*

On the substance level the flows of each metal has been modeled annually via constant substance flows or transfer coefficients. Again parameter values mostly have been calculated from Montan-Handbooks of Austria. The first process “Dewatering” was neglected regarding metal losses due to dilution or alike. Thus the inflow of metals to “Flotation” was set to 100%.

To model the metal flow to tailings, first a “Recovery Efficiency” in % (equal to TC * 100) has been calculated by dividing the “metal content after extraction” by the “amount of metal recovered” (*see Annex*). So the “Recovery Efficiency” equals the percentage of metal recovered to “valuable materials”.

For those years where it was not possible to calculate this recovery efficiency from production data, missing values have been taken from either technical handbooks (Prior 1965; Jedlicka 1983) or historical literature (Günther 1993). For years with no reference data, input parameters were estimated by linear integration in Excel worksheets.

On the substance level an annually determination of TCs was necessary because of ranging recovery efficiencies (*E*) and ore grades. Values for *E* ranged from (Cu) 93 to 98%; (Zn) 65 to 90% and (Pb) 68 to 94%. Moreover the ore grade of reworked tailings ranged from 0.49 to 2.3% for Cu, 1.95 to 4.67% for Zn and 0.30 to 0.89% for Pb. For each year the substance flows have been calculated using the TCs. *Figure* 8 and *Figure* 9 show this calculation exemplary for Zn and Pb in 1952. 1952 was chosen exemplary because all imports to the system were about of the same level and allow a rough comparison between flows of zinc and lead. In purpose of clearness, values were rounded to two digits. Investigating the whole period, values have been calculated in exact tons and later rounded to two digits.

For years where an amount of reworked tailings has been documented the TCs of first step of flotation were assumed. Transfer coefficients for the outflow of “valuable material” (metal in concentrates) were calculated as differences to the second outflow to tailings. To assess how metals accumulate in the stock of tailings, the annual changes of the stock were balanced (see 4.1 Results).

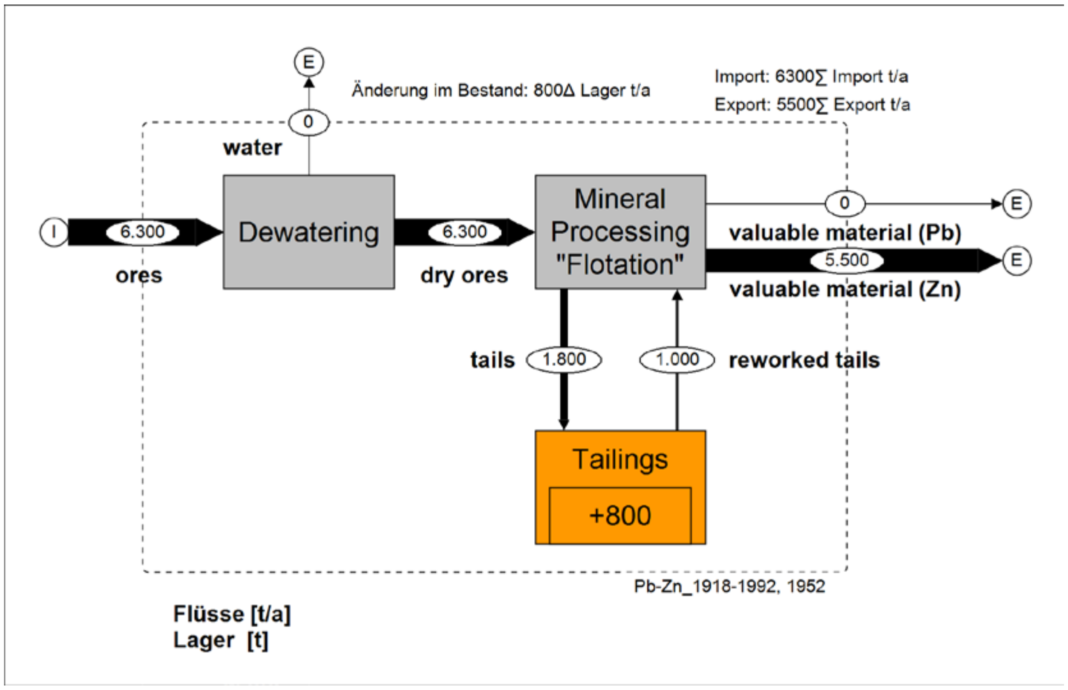


*Figure 8: Substance flows of zinc in 1952*

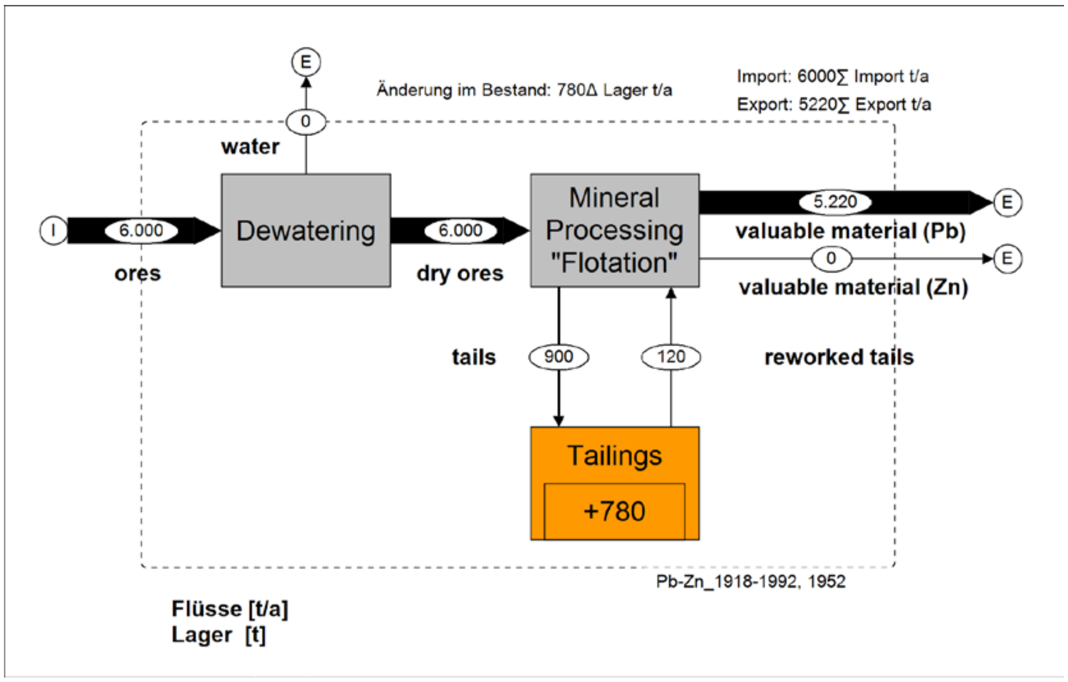


*Figure 9: Substance flows of lead in 1952*

## 3.2 Assessment of the Resource Potential of MSW landfills

*Calculation of total amount deposited at MSW landfills*

A complete existing database of material flows and storage data is currently not available for MSW-landfills in Austria. Requesting DI M. Danzer (BMUJF) for EDM-data on landfilled MSW was no success. Therefore, the calculation of the landfilled waste volume is based on the work of Lunzer and Domening et al. (1998) who estimated the total waste volume deposited on Austrian landfills in 1998. This amount than was added by the annual waste generation volumes that were published in the Federal Waste Management Plans (BAWP) until 2009. For years where no data was available, linear integration was performed in Microsoft, Excel to estimate the annually generated amounts of MSW and Household Waste (HW). Table 1 shows the integrated values between the two years of BAWP reports 1998 and 1999.

To address the amount deposited at MSW landfills again data from the BAWP was used. Parts of the data were derived from BAWP-Material Flow Sheets that represented the recycling paths as shown in Annex 1. For years without BAWP documentation, the fractions deposited wastes were calculated. Therefore the in the BAWP published recycling paths graphics have been studied (see Annex 2)

To estimate values for 1998, the recycling paths of the preceding year were assumed (see Table 1). According to BAWP (Annex 2) changes in the recycling paths were neglected for period of 1999 to 2003. Thus the recycling path fractions of 1999 have been used to calculate the amount gone to landfills. For years where no previous year could be taken into account, the recycling paths have been estimated graphically from Annex 2.

*Table 1: Linear integrated amounts of MSW and Household Waste in 1998 and the amounts landfilled per waste category; see Annex 3 for values from integration for other years.*

| Year | Waste Categories | Waste in t |
|---|---|---|
| **until 1997** | *(43,3 mio m3)* | |
| **Lunzer et al. (1998)** | *(assumed density 0,9 t/m3)* | **38,970,000** |
| | | |
| **1997** (BAWP 1998) | MSW (Inc. Res., Bulky Waste, MBW) | 2,780,000 |
| | Household Waste (HW) | 1,290,000 |
| landfilled | HW (directly deposited) | **666,000** |
| | Incineration Residues | **125,000** |
| | Bulky Waste | **221,000** |
| | MBW Residues | **145,000** |
| | | **1,157,000** |
| | | |
| **1998** (estimated) | MSW (Inc. Res., Bulky Waste, MBW) | 2,940,000 |
| | Household Waste (HW) | 1,302,500 |
| landfilled | HW (directly deposited) | **704,331** |
| | Incineration Residues | **132,194** |
| | Bulky Waste | **233,719** |
| | MBW Residues | **153,345** |
| | | **1,223,590** |
| | | |
| **1999** (BAWP 2001) | MSW (Inc. Res., Bulky Waste, MBW) | 3,100,000 |
| | Household Waste (HW) | 1,315,000 |
| landfilled | HW (directly deposited) | **665,000** |
| | Incineration Residues | **123,000** |
| | Bulky Waste | **219,000** |
| | MBW Residues | **139,000** |
| | | **1,146,000** |

| **Recycling paths in % of MSW (1997)** |
|---|
| 23.96 |
| 4.50 |
| 7.95 |
| 5.22 |

*Assessment of metal concentrations in MSW*

To assess the substance concentrations of metals different data from various studies ((Daxbeck, Schönbauer et al. 1997; Morf, Brunner et al. 2005; Skutan and Brunner 2006) and (Gillner 2010; Gäth and Nispel 2011) was studied to estimate lower and upper boundaries of concentrations.

According to studied literature, approaches of sampling residues of incineration slags were regarded to be the best method available when assessing metal concentrations in MSW for several reasons. First in general, the sampling of incineration ashes enables to investigate very high sampling volumes. In the project CHARO, Mitterbauer and Skutan et al. (2009) sampled 18t slag at an incineration plant. High sample volumes are regarded to deliver analysis of a high representativity for heterogeneous input material, such as MSW. Moreover, within a waste incineration plant it is possible to analyze all outflows of the system (slags; filter ash; gaseous & waste water) though to gather the input concentrations. The second source of data was derived from a similar approach by Morf (2006) who investigated incineration residues at Thurgau, Switzerland. The results both studies are assumed to be belong to the most reliable approaches, due to the comprehensive sampling and process control of the analysis made. For this reason this data was used in this study to calculate the amounts of metals in landfilled MSW.

## 3.3 Fundamentals of Secondary Resource Sites

The investigated secondary resource sites, tailings and MSW landfills, are significantly different. In the following resource contents and deposit characteristics, such as: Stratigraphy, Segmentation, Spatial diversion, Hydrogeology, risk environmental hazards, dissipation of substances or location to infrastructure are described for both sites.

### 3.3.1 Tailing Waste Facilities

Tailings are left over from the process of separating the values and invaluable gangue rock (Process of Flotation). Flotation requires the reduction of the particle size of ore by milling and grinding. For this reason tailings are of fine dimensions. Most tailings in the 1920s have been around 0.25mm maximum dimension (Nash 2003). Today´s tailings are reported to be <0.2mm (Krauß, Wagner et al. 1999).

Each ore deposit has its specific characteristics and properties all its own and so do tailings. Thus, the dump´s heterogeneity directly reflects the mining history. Depending excavation, processing and tipping conditions (water content) over time, tailings can be defined as disperse tipped material with sporadically visible stratigraphy.

Juridical, tailings by definition belong to Mining Waste. After the European Court of Justice´s the definition of waste relies on the question if the holder discards or intends or is required to discard a material (ECJ-C-129/96 1996). The "intention to discard" is given for Mining Residues which are not being proven to be used for backfilling.

In Austria too few information is documented on the chemical composition of tailings. They consists of milled rock material and effluents from mineral processing including water, ore and reagents (see Figure 5). Metal resources in tailings are not only found in chemically pure form and differ to a high extent. In general tailings consist of different sulfide, oxide ore compounds (different degree of oxidation) and gangue rock material. The ratios of sulfide and oxide compounds are requisite to estimate the amount of metal that is secondary recoverable via flotation. Scherer (1979) showed wide ranges in the ratios of total Zn-content and sulfide compounds for zinc (1.8 Zn total: 1 $Zn_s$ to 9 Zn total: 1 $Zn_s$) that indicate another uncertainty when estimating resource potentials.

Tailings and their metal concentration differ in relation to the ore and corresponding mineral processing technique.

*Production and Properties of Tailings*

The production of tailings directly relates to the amount of processed ore. The more ore gets processed, the more tailings have to be produced. How much needs to be processed to recover a particular amount of metal depends on the ore grade. Figure 10 shows the increase in the amount of processed ore with a declining in ore grade. Another relationship between the excavation of ore and tailing dumps, cycles of exploration and excavation which are typical in mining. Periods of advanced explorations for example correspond to large quantities of gangue rock deposited at dumps. Thus, more gangue could have been disposed with tailings.

The spatial diversion of resources inside the tailing material is considered to be relatively homogenous for short periods of process conditions, but changes periodically in relation flotation conditions. The metal recovery by flotation depends on different parameters. One important factor is the particle size of the milled ore. How it relates to copper concentrations in tailings and the recovery grade of copper in concentrates is illustrated in Figure 11.

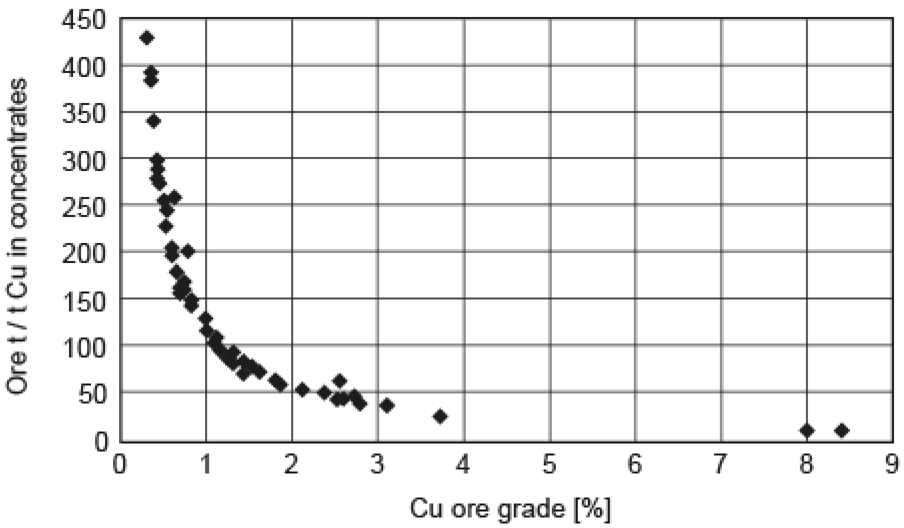


*Figure 10: Relation of Cu ore grade to the tonnage or ore excavated per ton of Cu in produced concentrates (From Krauß, Wagner et al. (1999) p.77).*

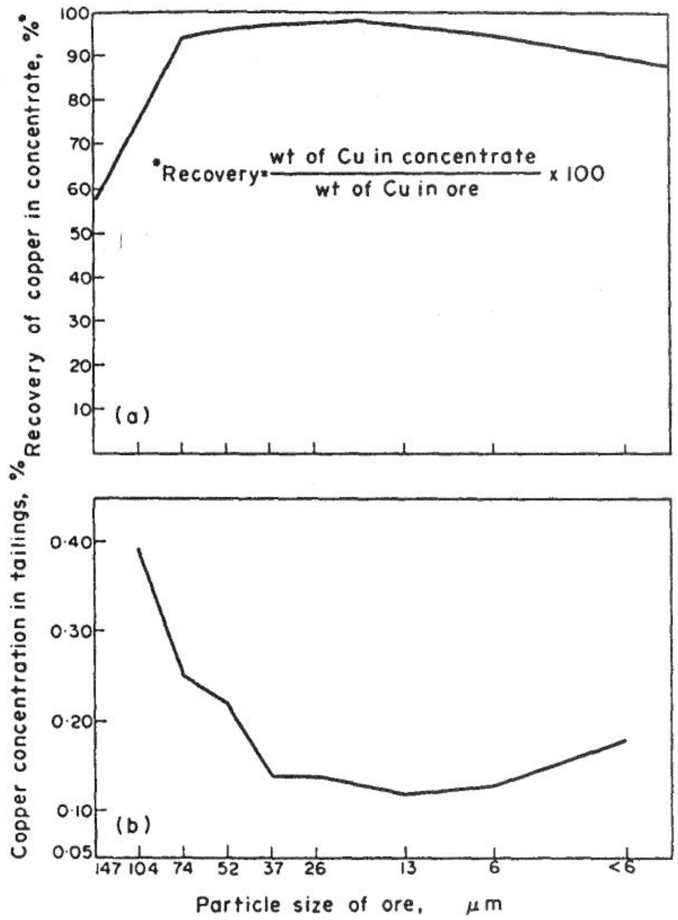


*Figure 11: Effect of milling (with decreasing particle size)on a) the recovery efficiency of copper and b) the copper concentrations in tailings (From Biswas and Davenport 1994, Extractive Metallurgy of Copper - Third Edition)*

*Environmental Risks*

Tailings are potential sources of contamination to the environment. After extraction and subsequent mineral processing, metals and metal compounds tend to become chemically more available. This may result in the formation of acid or alkaline drainage, making the management of tailings an intrinsically risky activity. an As an additional thread the flotation process involves residual processing chemicals. In general, surface waters and mine drainage which flow through tailings can decrease water quality and the quality of local ecosystems. “Because the tailings were generally placed in lowlands, commonly within flood plains of streams and ephemeral creeks, these mine-related materials are more likely to interact with surface waters than is mine-dump waste”(Nash 2003). In fact this especially accounts for Austria, where in mountain regions, mining localities are mostly situated close to local river systems.

### 3.3.2 MSW Landfills

Accounting the number of substances deposited and their distribution inside the deposit landfills are more heterogenic than tailing dumps. Like in other European countries the Austrian Ordinance governing landfills of referring to European community law in DeponieVO (2008), distinguished landfills in a specific classification, differing technical requirements to the landfill and the quality of approved wastes deposited. Landfill types assigned were:

- Excavated Soil Landfills
- Inert Material (Bulky Waste) Landfills
- Non Environmental Dangerous Material Landfills
  - Bulky Waste Landfills
  - Mass Landfills
  - Residual Waste Landfills
    (high organic fraction)
- Environmental Dangerous Material Landfills

This study focuses on the type of mass landfills or landfill classes mainly consisting of residual waste such as MSW landfills. But one has to consider that this classification does not properly define a landfills composition. Especially older landfill types consist of mixtures of waste fractions being eponymous for the landfill types or classes.

*Stratigraphy and Landfill Body*

The diverse characteristics of landfills relate to former working practices, site-differing sealing constructions and execution of internal layers. Furthermore landfills consist of a spatial internal structure of sectors differing in their waste composition, sometimes relating to former practical guided decisions.

Recent structures inside the landfill body are governed by the concept of "Multiple Security" described in DeponieVO (1996). It firstly describes the obligation of a basis- and surface sealing as well as the capture of landfill leachate and landfill gases (Exogenous Security), and secondly the segmentation of wastes of equal characteristics inside the landfill (Endogenous Security), in order to minimize chemical reactions between different waste lots though leading to the segmentation structure of modern landfills. Different constructions and consumption patterns led to different spatial deposition characteristics of waste.

Further descriptions of landfill characteristics mainly derived from "MSW landfills in Austria" by Lunzer, Domening et al. (1998).

*Subsoil Conditions at Landfills*

Based on a survey of all MSW landfills in Austria, they investigated current landfill- technology and management, including aftercare period and site-specific geological features. It was reported that 34 of the 60 landfills operating in 1998, in case of failure on landfill sealing, would show ground characteristics, such as sandy or gravely subsoil, giving an advantage to the dispersion of pollutants.

26 landfills were situated on high permeable underground with kf-values >$10^{-5}$ m/s. “This conditions merely account for older landfills, where information on the geological and hydrological conditions hasn´t been taken into account when establishing landfill sites (Lunzer, Domening et al. 1998)”. It was further noted, that 12 landfills did not even have a bottom sealing and were only surrounded by sheet pilings. Nowadays information on relating environmental risks, especially for concepts of preventive groundwater protection, influence decision on Landfill Mining.

*Landfill Life Stages and Environmental Risks*

Baccini (1989) defines life states for landfill, distinguishing most of recent landfills between their stage of the operating phase and their aftercare phase where, fluxes that are dangerous for environment appear and force operators to monitoring and preventive maintenance. Landfill monitoring consists of measurements to provide information on groundwater likely to be affected by the discharging of waste, with at least one measuring point in the groundwater inflow region and two in the outflow region.

As described earlier, landfills differ in their technical construction. The way this construction relates to the specific locality and its environmental conditions determines possible threads to nature and humans.

Threats firstly associated to landfills are pollution or contamination of both, surface- and groundwater. Investigating potential contaminations in an area of 2km downstream the groundwater flow, Lunzer, Domening et al. (1998) show that landfill leachate at 25 sites can threat private- and at 6 landfills in cases can prejudice municipal wells.

While for Austria the guidelines for the deposition of waste by the Federal ministry of Youth, Economy and Family (1990), advise a distance to settlement structures of at least 300m. Lunzer, Domening et al. (1998) published that 14 Austrian landfills only kept 200m of distance and 5 landfills just even keep distances between 50 to 100m. As (Lunzer, Domening et al. 1998) put it: “Form a emissions perspective these distances are far too low”. Landfill emissions are mostly related to contamination of groundwater, and can lead to the need of the sanitation of a landfill. Surveying Austrian landfills Lunzer, Domening et al. (1998) found that 28 operators do not have any financial reserves for closure or aftercare. Most often (22 landfills) fixed bank guaranties e.g. from 28,000 to round 9,000,000 EUR are deposited.

## 3.4 Resource Recovery Technology

The deposits own characteristic, described in the previous chapter have to be considered when investigating resource recovery techniques. When excavating a landfill or re-processing mining wastes it has to be figured out which is the most advantageous scenario from an environmental and resource-, as well as from economical perspective. Due to studying secondary resource recovery of metal requires a differentiation by deposits. This chapter consists of a part on recovery possibilities from tailings and a part on MSW landfills. It furthermore has to be addressed which is the most effective and cost efficient processing equipment etc. which are further described in this chapter. Together, petrographic, geological and the excavation and processing parameters determine the secondary resource potential of a specific metal.

### 3.4.1 Tailings

Generally the efficiency of how a metal tends to be technically recyclable is determined by waste and deposit characteristics. Investigating mining residues, these are:

- Petrography (mineral content, ore grade)
- Chemical and physical properties of rocks and ores (e.g. oxides or sulfides)
- Deposit Characteristics (dispersion of values; volume, locality).

Tailings from dumps can rarely be smelted directly. Metals can be extracted from mining wastes either by physical mineral processing or by using chemical techniques. To decide the way of recovery it is mandatory to get information on the materials chemical composition. Principally it is of interest to know the amounts of oxides and sulfide compounds, because these directly relate to the floatability.

*Physical recovery techniques*

To physical recover metals form tailings cold requisite steps of milling and grinding. Then, tailings usually get floated in basically the same way as primary ores. An introduction to the flotation process is given in chapter 1.4.1. Based on this introduction, Figure 12 illustrates the conditioning process to prepare the mineral particles in a way to maximize their selective attraction to air bubbles. Recovery rates of secondary flotation were reported by Gordon (2002) as 60% for copper sulfide, from 35 to 76% for total lead and from 92 to 95% for Zn sulfides.

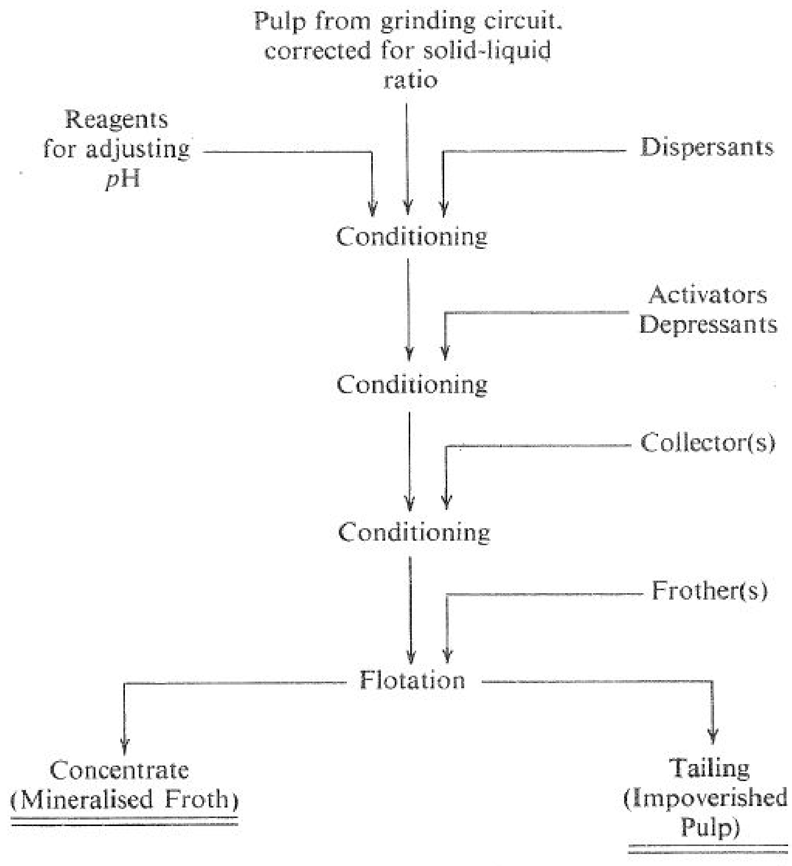


*Figure 12:Flotation Flow-sheet, illustrating the conditioning of particle surfaces for selective attraction of mineral particles (From Prior (1965) Mineral Processing, p.459).*

*Chemical Recovery Techniques*

If higher oxide fractions are abundant, like in many zinc ores, chemical extraction techniques are favorable. Gordon (2002) states about 75% of the copper in tailings at mine Morenci to be in copper-oxide minerals, thus were not effectively to be recovered by froth-flotation. Chemical techniques are available in form of hydrometallurgical extraction and dump leaching.
Hydrometallurgical processes allow recovering metals from very poor ores (Cut-off-grade), as well as the secondary recovering of copper from low grade by-products like tailings (1.4.1 Fundamentals of Copper).

Dump leaching can be described as leaching with sulfuric acid ($H_2SO_4$) and purification. In practice tailing deposits are sprinkled with highly diluted solutions of sulfuric acid (2-10g/l $H_2SO_4$) that slowly percolates through the tailing pile. Dump leachate is applied for periods of several weeks. The copper enriched solution (2-5g/l Cu) then is constantly pumped to the surface for further processing by solvent extraction (Krauß, Wagner et al. 1999).

The Solvent extraction principle (Fluid-Fluid-Extraction) is based on differences in solubility of the dissolved fractions. By adding a tuned solvent, dissolved substances like copper sulfides are selectively extracted in a solvent extraction plant (Figure 13). The fluid then is further processed in a so called electrowinning device for the separation and extraction of metals in solution by electrolysis. This thesis is too static to go in to technical details on such matters, which are richly provided in the current technical press. Compared to flotation, the loss of metal per ton of ore is generally higher with leaching. Authors like Krauß, Wagner et al. (1999) posed a mean copper recovery rate of 70%, whereas Gordon (2002) anticipated that new proprietary leaching techniques could recover 90% of this copper.

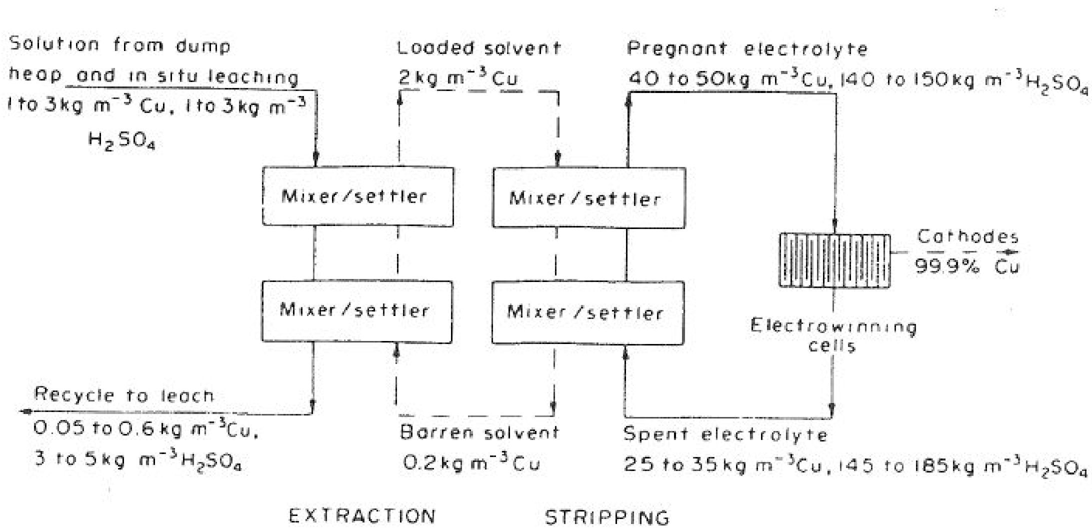


*Figure 13: Flow sheet of the process of solvent extraction (From Krauß amd Wagner et al. 1999)*

But since Austrian mining waste deposits are localized near river systems or aquifers such as sediments or molasses of the Alps, chemical extraction techniques are not favorable because of possible environmental risks for surface and ground waters.

### 3.4.2 MSW Landfills

As mentioned earlier the different waste substances are generally heterogenic distributed inside the landfill. The steps needed to recover non-ferrous metals from MSW can be explained through looking at their relevant waste fractions.

Non-ferrous or heavy metals are mainly included in WEEE (waste electrical and electronic equipment), metal scrap, mineral fractions and in potentially harmful substances (Morf and Taverna 2006).

The fact that these fractions just relate to a relative small mass of the total waste volume (WEEE 0.75%, potentially harmful substances 0.75%, metal scrap 3% and mineral fraction 12.5%) makes clear that recovering resources requires a great sorting efforts. This includes expenses for energy, logistics and the implementation of the sorting plants. Implementing state-of-art sorting technology starts with the in-situ development of a functioning and effective constellation of sorting equipment which is then further optimized while operating.

*Description of Recovery Plants*

Here a feasible constellation of a mobile plant is described in general terms. It can consist of four processes: star screen; air classifier; magnets over conveyor belts and an Eddy Current Separator (ECS). At landfills, the excavated material is firstly dumped through a coarse screen into a star screen in order to separate soil and organics which also include most of hazardous material and therefore is regarded to be non-recyclable.

Further screening produces separated material categories that need to be re-deposited: Containing heavy degraded waste and cover material, the "fines" Containing hazardous material.

Air classification separates out combustibles such as paper, plastic or textiles while magnets positioned over the conveyor belts separate the ferrous. The ECS then separates non-ferrous metals (copper, brass, etc.) from inert materials (concrete, mineral wastes, glass, wood, plastic, etc.) and removes the smallest parts left after magnetic separation. Separated metals are downloaded directly into separate containers.

Stationary plants are often used because of their higher sorting efficiency. Depending on market requirements recovered metals have to be cleaned prior to been sold e.g. in a stationary washing plant. For this reason, general sophisticated knowledge of the market and quality demands for secondary materials could be necessary when planning a recovery project.

## 3.5 Data Acquisition

Currently, a complete existing database of material flows and storage data is not available for mining waste facilities or MSW landfills in Austria. Therefore, information and reference data was collected from two different sources:

- Secondary Data: processed raw data, such as statistics, information from publications, governmental and non-governmental reports and the Internet and spatial data in GIS formats
- Tertiary Data: informal data, such as estimation, expert interviews and non-published data

Most of the data used in this thesis derived from Secondary Data of various sources. Since there was no financial budget released for this thesis, the use of national statistics, company´s own bookkeeping and scientific publications was essential. In a this thesis own GIS-based approach spatial data was used to assess volumes of mining waste facilities.

Tertiary Data in form of educated guess was used to estimate missing input values to the model that could not be calculated. In order to obtain input to the investigation, several experts were consulted (GBA, Montanwerke Brixlegg, Federal Mining Ministry). No Tertiary Data in form of expert interviews was used to model parameters.

### 3.5.1 Data on Tailings

Additionally, Montanwerke Brixlegg AG´s own archive at the head office in Brixlegg, Tirol have been searched. In order to discover quantitative data on the production of tailings the company´s bookkeeping of 20th century was studied. Finding only annotations on tailings minimized the outcome of this effort. Later, Dr. Schedl (GBA) kindly provided the only traceable analysis of Cu in tailings conducted at Brixlegg in 1985. Together with the works of Scherer (1979) and Jedlicka (1983), with their investigation of Zn and Pb in tailings at BBU in Bad Bleiberg it was the only comprehensive analytical data found.

For Austria, within the scope of a nationwide research project ("Mining Area/Dump Register") 4486 mining localities (recent and old mining areas for ores, industrial minerals and energy resources) have been investigated and recorded in a GIS-based documentation system by Schedl and Mauracher et al. 2001. The study focused on the environmental risk of mining waste in order to fulfill the requirements of the EU´s mining waste directive. Trying to asses environmental risk assessment issues the analysis made focused oxide compounds. Oxide compounds tend to become chemically more available, which can result in Acid Mine Drainage (AMD), the genesis of acid or alkaline drainage.

To assess the environmental risk potential, spatial data on mining sites and corresponding waste facilities has been raised. The study as well includes limited analysis of tailings in form of indication samples. Hence, risks of either over- or underestimating the potential of a resource are to be considered.

Samples taken have been vertically distributed slit samples at larger dumps or just visually taken by hand from the peak to the slope foot at smaller sites.

In total 32 samples of 15-30kg have been analyzed by X-ray fluorescence spectroscopy (XRF) and Inductively Coupled Plasma-Mass Spectrometry (ICP). The authors stated to abstain from large extent sampling and wide geochemical analysis like conducted by Scherer (1979) because of the high workload needed to obtain reliable measurements. They further state that samples taken are not representative for a dump body and suggest excavator samples to depth of at least 0.5 to 1m to minimize weathering induced material changes at the surface. This should be to considered for future sampling.

### 3.5.2 Data on MSW Landfills

In Austria by the law of „*Abfallwirtschaftsgesetz*” (AWG) the annual generated waste volumes have to be documented latest every six years. To calculate generated volumes, waste data is collected by local state governments and further processed relating to the Waste Management Plants and Materials Database of the Federal Environment Agency, information on industry-specific concepts and opinions of experts.

The volumes landfilled that have been used in the calculations in *Chapter 5* refer to a comprehensive investigation of landfills in Austria of the Federal Ministry for Environment, Youth and Family (Lunzer, Domening et al. 1998). According to their work, in 1997 a waste volume of 43.3 Mio m3 was landfilled at 60 operating Austrian sites.

Recent Data on national waste generation volumes was mainly related to records from landfill operators, who by law have to deliver that data to the Federal Ministry of Agriculture, Forestry, Environment and Water Management. In comparison to the Federal Waste Management Plan of 2001 (reference year 1999) the generated waste volume increased by 5 million tons to annual 54 million tons in 2004 including 22 Mio.t of bulky waste. In general this annual waste volume not only consists of primarily generated waste but included secondary waste like by-products of processed primary waste such as slag and ashes from incineration or animal meal and – fat. To accumulate data on the fraction of the generated waste volume that ends up at landfills, statistics on the recycling pathways derived from BAWPs, like shown in Annex 1 have been studied. (For further information on data acquisition on MSW landfills see also chapter 3.2).

### 3.5.3 GIS-based Approach

Using a GIS approach, Schedl and Mauracher et al. (2001) have linked wastes from excavative industries to environmental risks. In their ÜLG-40 they investigated mining residues on a national wide level and registered over 4400 mining localities in Austria. The idea of this thesis´s GIS-based approach was to combine data derived from ÜLG-40 with ALS data to assess volumes of disposed mining waste.

Spatial data provided by ÜLG-40, also known as “Mining Area/Dump Register” consisted of 2-D GIS-data (polygons of registered dumps) for two mining regions (Brixlegg/Carinthia & Bad Bleiberg/Tirol) Dr. Schedl, project leader of the ÜLG-40, considered these two case study areas to be roughly representative on a nationwide level for Austria.

Whereas other investigations used 2-data, mostly to address questions related to Environmental Risk Assessment, the present study is presenting an approach that uses GIS modeling to investigate resource potentials. In this approach a determination of volume of mining waste dumps is addressed by using Aerial Laser Scan-data (ALS). The calculation of the theoretical resource potential then is assessed by multiplication of a certain metal concentration of a dump at its determined volume.

The calculation of dump volume is considered in this thesis to be an equation of the dump´s surface area and change in elevation ($\Delta h$), where $\Delta h$ is the difference of a secondary Digital Elevation Model (DEM) calculated from the ALS-data (actual surface) to the Digital Height Model (DHM) of the surface area at the moment pre to the disposal of residues (former surface).

$$\text{Dump volume} = \text{surface area} \times \Delta h,$$

$$\Delta h \text{ to be} = \text{recent DEM} - \text{historical DHM}$$

$$\text{Dump volume} = \text{surface area} \times (\text{recent DEM} - \text{historical DHM})$$

For the surface area, 2D-data in form of shape-files (polygons of dumps >10,000m$^2$, provided limited for two case study areas by the Geological Survey of Austria, have been taken as reference data. In this thesis an academic-version of the GIS software TNTlite by Microimages, Inc. has been used to visualize and process the GIS-data provided.

The scope of the GIS approach of this study was to search a cost-effective tool to determine volumes of a high number of dumps. By this it was planned to estimate today´s possible secondary resources deposited for an assumed range of concentrations. Moreover, the results should have been used to verify the top-down results derived from the SFA-approach. Because of uncertainties of in situ deposited volumes and the heterogenetic structure of cubatures, it was obvious that only high-resolution data is feasible to calculate volumes. For this reason federal and state governments have been requested for Aerial-Laser-Scan-Data (ALS), with a resolution of data points between 2-10cm.

For the Bad Bleiberg in Carinthia ALS-data, which is point-data, was converted to an interpolated raster height-model. Due to less working experience in the GIS software it consumed unexpected amounts of time just to convert the data to this model and to visualize it for geo-referencing. The produced raster model then was geo-referenced with maps derived from Google Earth, calibrated by characteristic points in both data sets.

To get an idea of where dumps are located in the diverse area of a mountain region, the elevation height model was visualized by rendering the landforms by means of a shaded relief function of the software (Figure 14).

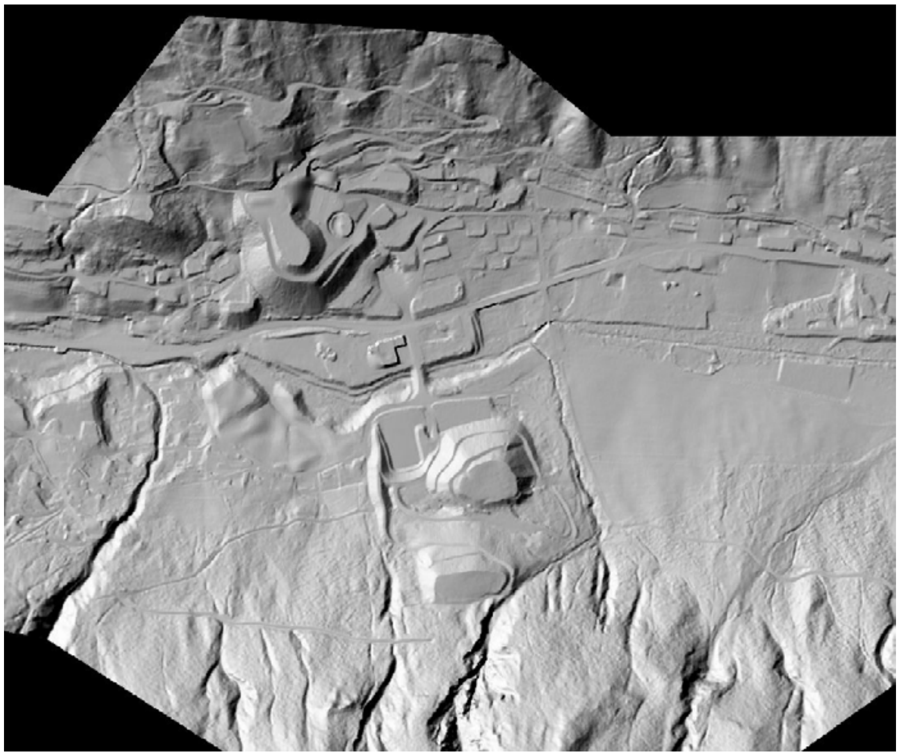

*Figure 14: Shaded relief showing Mining Waste dumps in the area of Bad Bleiberg, Carinthia*

To calculate a DHM of the former surface, it was planned to digitalize analog topographic cards in the way to digitalize isohypes to vectors with height as attribute values of the isolines.

Austrian topographic cards of the investigated in the best case are of a scale of 1:20,000. This relates to relatively high distances between the isolines and thus decreases the accuracy of the calculation of the ground surface model. Considering a big fraction of dumps seldom to exceed heights of 5m, the calculation error was considered to have a weighting effect on the determination of volume. To realize this 3D-model and to estimate the modeling error, GIS´s expert knowledge would have been necessary. Due to this reason the GIS-approach was neglected in this study and did not exceed work of the conceptual state.

Nevertheless, the in this study presented Laserscan-based GIS approach is regarded to have the potential to be feasible method for volume determination of a high number of dumps. By using volume measurements from Scherer (1979) it would be possible to roughly test the applicability of the GIS approach, without the need of re-measurements. For this, the test sites need to be checked in situ to be flat based as well not being partly reworked since the last measurement. For best results a tachometric determination of the volume of reference dumps is recommended to verify the GIS approach.

# 4 Results

The results are presented in the way that first the outcome of the MFA for tailings is given, followed by the SFA results for each metal. Then, the results for the calculated total amount of MSW deposited in Austria and the calculated minimum and maximum contents of resource are given.

## 4.1 The Resource Potential of Tailings

### 4.1.1 Copper

The material flows of copper tailings calculated in the MFA-model showed annual values ranging from approx. 5000t in 1945 to approx. 180,000t in 1972. Figure 15 shows the fraction of reworked tailings of the production of tailings from 1918-1976. Note, that the production of tailings directly related to production capacity of metal, though followed the production trend. The accruing amount of tailings was around 20,000t/a at the beginning of the investigated period, followed by high production in the 1920s around 120,000t/a and a sharp decrease in 1939/31 to approx. 8000t. Production then stayed at relatively low level < 20,000t/a before it raised to amounts between 120,000t/a and 180,000t/a after World War Second. The amount of reworked Cu-tailings ranged from 7152t

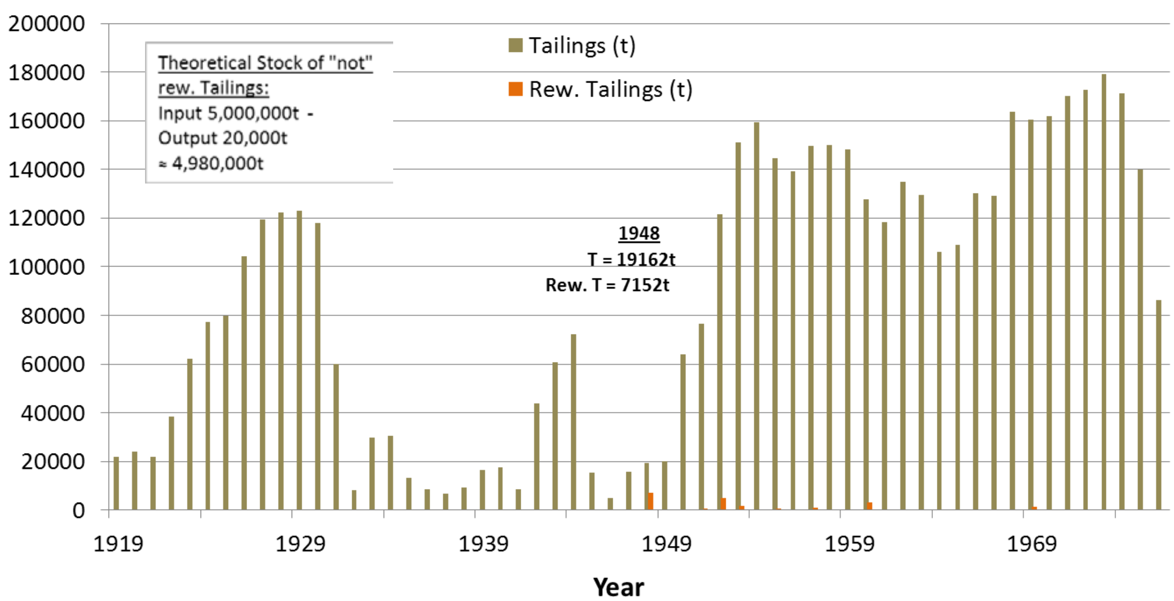


*Figure 15: Fraction of reworked tailing in Cu-tailings (1919-1976)*

to 69t (1948/1954). The primary production of copper in Austria ended in 1976, thus there haven´t been any inflows to tailings later than this date. In total, about 5 MT of tailings have been produced, of which only about 20,000t have been reworked. Thus, an approximate amount of 4,980,000t of tailings that have not already been reworked was calculated.

The results of the SFA for copper showed the inflows and outflows to the stock of tailings on the substance level (Figure 16). Moreover, the outflow of Cu from tailings represented the contribution of reworked tailings to the production of copper. The substance flows basically followed the data calculated for production of tailings. After WWII the Cu-Inflow raised again to annual amounts around 50t, then peaks with flows close to 120t in 1954/55 and then fluctuated between 36 and 74t/a until 1970. From 1970 on the production, and therby the Cu-Inflow to tailings decreased until the end of mining activity in 1976.
Notably, the flow of Cu recovered from tailings was higher represented in the data than its corresponding material flow as shown in Figure 15. For example in 1948 roughly 30% of the processed ore was derived from tailings. In the same year 69t of Cu that has been recovered from tailings compare to only 9t Cu going to flotation residues.  In 1951 the Cu-Inflow nearly equaled the stock´s outflow. Over the investigated period of 56yrs the Cu-Inflow to tailings summed up to about 2700t whereas the Cu-Outflow from tailings accounted app. 130t. By balancing in-and outflows of the investigated period, a theoretical stock of approx. 2570 t of Cu in tailings was calculated.

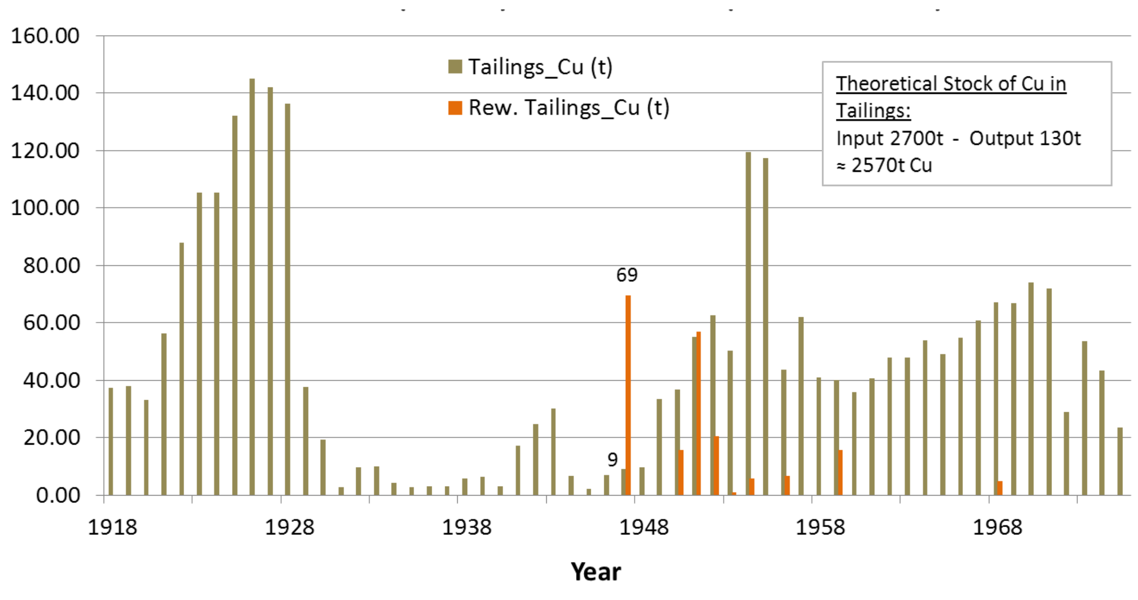


*Figure 16: Relation of Cu-inflow to tailings to. Cu-outflow via reworked tailings*

### 4.1.2 Zinc

The material flows of Pb- and Zn tailings had to be calculated together due to both metals getting recovered from the same ore. Figure 17 shows the fraction of reworked Tailings in Zn/Pb tailings. Production values for tailings and the fraction of “Reworked” both showed a different trend compared to the production of copper.
A period of relatively constant production activity in the first 50 years was followed by a increase in production that peaked in 1982 with an annual production of about 730,000t. Close to 8.5 million tons, represented over half of the tailings produced in the investigated period, have been produced in the last 20 years of production. The data showed three periods where tailings have been reworked. In total, from about 15 million tons of tailings, about 2.7 million tons have been reworked. Thus, a theoretical amount of approximately 12.7 million tons of not reworked tailings could be estimated.

The resulting substance flows are given in Figure 18. Output-Flows leaving the Zn-Stock of tailings, summed up to about 53,000t of zinc. Considering a calculated Input-Flow of 100,000t Zn to tailings a theoretical stock of 47,000t of zinc remained Pb/Zn tailings.

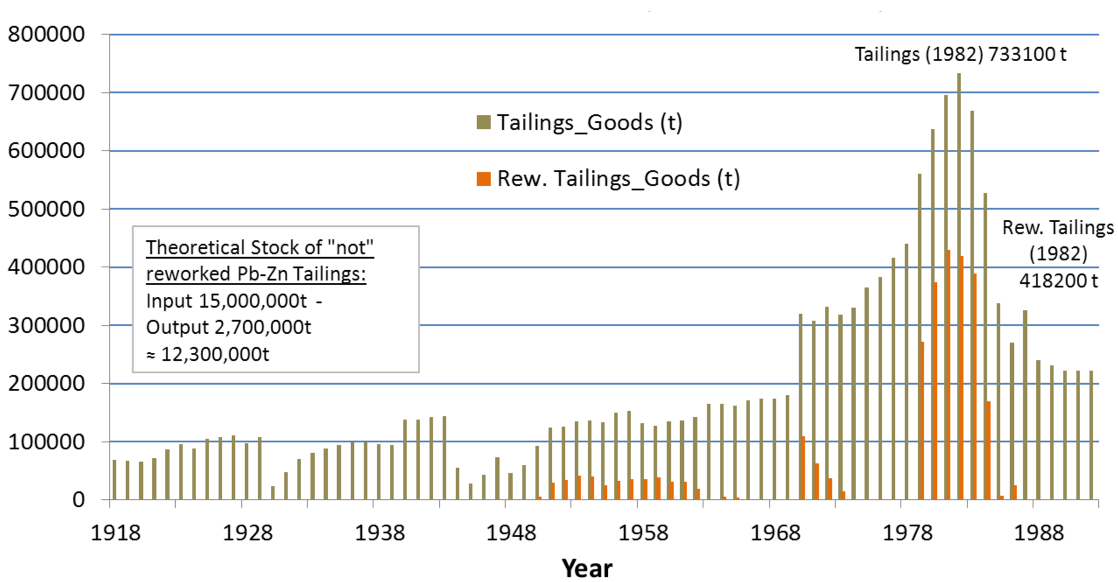


*Figure 17: Fraction of reworked tailings in Pb/Zn tailings; upper box shows the theoretical stock of “not” reworked Pb-Zn tailings after balancing in- and outflows.*

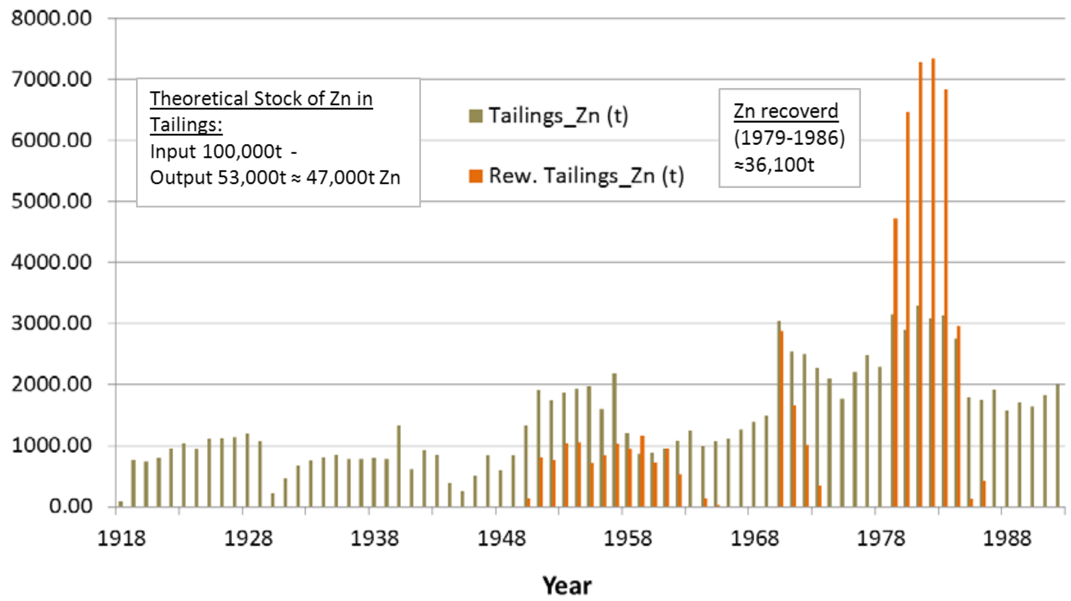


*Figure 18: Relation of Zn-inflow to tailings to Zn-outflow via reworked tailings*

### 4.1.3 Lead

The substance flows of lead were directly connected to the values stated for zinc. This did not only account for the Primary Production, but also for the recovery from tailings. Flows of lead were represented in an Input-Flow to tailings of rounded 91,000t and Output-Flow via “Reworked Tailings” of app. 9,000t. The relatively high Input in the period 1918-1944 corresponded to ore grades of around 6% Pb. By balancing in- and outflows a theoretical stock volume of lead in tailings of 82,000t was calculated.

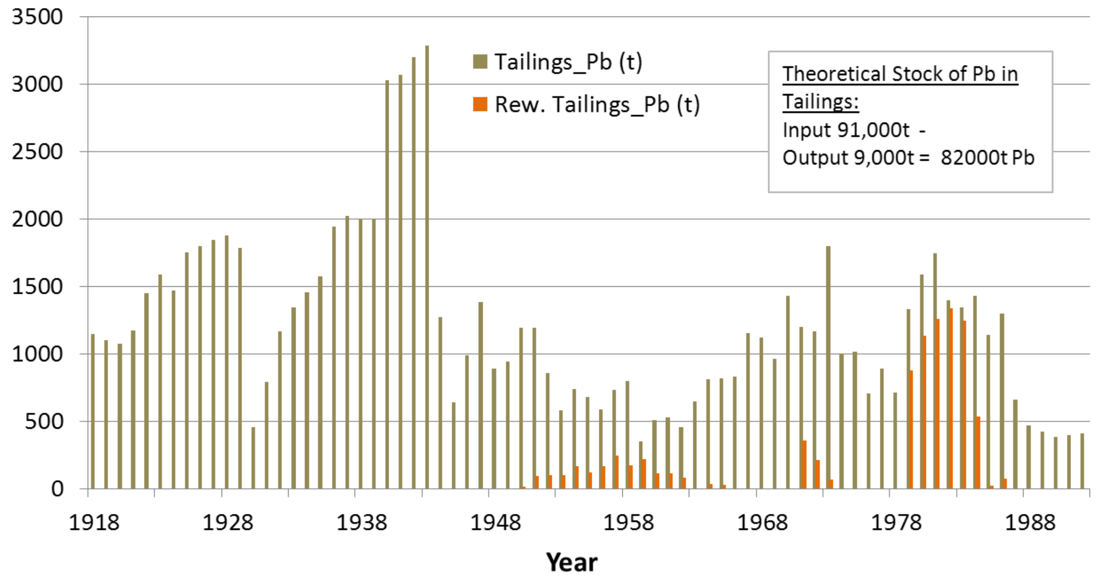


*Figure 19: Relation of Pb-inflow to tailings to the Pb-outflow via reworked tailings*

## 4.2 The Resource Potential of MSW Landfills

Considering the amounts that have been calculated to be annually added to MSW landfills, in total approximately 51 million tons were estimated to be landfilled by the end of 2009 (see Table 2, 1997-2009).

*Table 2: Annual amount of waste landfilled (1997-2009) derived from Federal Waste Management Plans (BAWP) or estimated (*see 2.2 Methods*) and the calculated total amount of landfilled MSW.*

| **Until 1997** | Landfilled Waste (t) | **38,970,000** |
|---|---|---|
| **1997** (estimated) | | **1,157,000** |
| **1998** (estimated) | | **1,223,000** |
| **1999** (BAWP 2001) | | **1,146,000** |
| **2000** (estimated) | | **1,171,000** |
| **2001** (estimated) | | **1,190,000** |
| **2002** (estimated) | | **1,210,000** |
| **2003** (estimated) | | **1,231,000** |
| **2004** (BAWP 2005) | | **814,000** |
| **2005** (estimated) | | **794,000** |
| **2006** (estimated) | | **653,000** |
| **2007** (estimated) | | **472,000** |
| **2008** (estimated) | | **532,000** |
| **2009** (BAWP 2011) | excl. 18000 t metals recovered from inc. slag | **519,000** |
| **Sum landfilled by end of year 2009** | | **51,110,000 ≈ 51 Mio. t** |

Considering the range of metal concentrations in MSW as reported by Morf (2006) for the estimated total amount of 51 million tons that are landfilled results in the values given in Table 3. For copper a theoretical resource potential of 39,000t to 54,000t of Cu, 51,000t to 61,000t Zn and 18,000t to 22,000t Pb (rounded amounts). The results of the second study CHARO (2009) led to 137,000t to 149,000t of copper, 44,000t to 49,000t of zinc and 6,900t to 8400t of lead that were estimated to hibernate in Austrian MSW landfills.

*Table 3: Results of the calculated resource potential of non-ferrous metals in MSW landfills. Metal concentrations were derived from Morf (2006): "Chemische Zusammensetzung verbrannter Siedlungsabfälle…KVA-Thurgau (2003)" and Charo (2009), FS = wet weight of waste.*

| | Analysis at KVA-Thurgau (2003) | | CHARO (2009) | |
|---|---|---|---|---|
| | average assay (mg/kg FS) | rel. error (%) | average assay (mg/kg FS) | rel error (%) |
| CU | 910 | 11.5 | 2800 | 3.9 |
| ZN | 1100 | 9.5 | 910 | 5.2 |
| PB | 400 | 10.7 | 150 | 10.7 |
| | range of assay (mg/kg FS) | Metal in MSW landfills (51 Mt) | average assay (mg/kg FS) | Metal in MSW landfills (51 Mt) |
| CU | 770-1050 | 39,000 - 54,000t | 2680-2920 | 137,000 - 149,000t |
| ZN | 1000-1200 | 51,000 - 61,000t | 860-960 | 44,000 - 49,000t |
| PB | 360-440 | 18,000 - 22,000t | 135-165 | 6,900 - 8,400t |

## 4.3 Case Studies of Austrian Mining Areas

### 4.3.1 Bad Bleiberg, Carinthia

*Historical investigations at Bad Bleiberg*

Comprehensive literature study showed that investigations of tailings as a secondary resource is not a completely new field.

As early as in 1941 the Austrian mining company Bleiberger Bergwerksunion AG (BBU) detected the importance of an economical use of a maximum fraction of the exploration output and invested in processing of mining residues. By processing 33685t of residues (incl. tailings) with concentrations of 0,69% Pb and 4,49% Zn, secondary resources accounted for 20% of the annual performance in 1941 (Jedlicka 1983).

Before Jedlicka assessed dump mining in 1983, mining waste dumps at BBU have been investigated by Scherer (1979) how also presented data of Schroll from 1951. Even when their work was made way back in the late 1970´s to early 1980´s, Scherer and Jedlicka conducted two of the few investigations in this field, possibly the most import ones conducted in Austria. For this reason, they were getting further described here and partly used as reference data. Scherer investigated concentrations and the resource potential of mining waste dumped at BBU. His work is the most comprehensive study found for the study area (Bad Bleiberg) and on Austrian tailings. For this reason it is described here in more detail.

Scherer measured 17 dumps and analyzed their lead- and zinc concentrations. To calculate dump volumes Scherer divided the cubature into sheets with height difference steps of 2 to 5 m. Then the arithmetic average of two neighbored areas was calculated and multiplied with the sheet height.

Scherer didn´t investigated the chemical weathering (mainly oxidation) of mining waste but reported comprehensive analysis of concentrations of metal compounds that could be of interest when investigating future recovery planning. He reported average concentrations from 0.049% to 0.397% for lead sulfides and 0.092% to 0.484% for zinc sulfides. He further found lead oxide concentrations being 3.5 times higher and zinc oxide concentrations being 4 times higher, compared to sulfides. For reasons of different floatability of sulfide and oxide, this relation is of importance for future recovery.

*An overview of measurements by different investigation in Table 4 lists ore grades and mining waste grades for corresponding volumes Table 4: Overview of investigation made at BBU, Bad Bleiberg. Ore grades derived or calculated from MHB, concentrations given as Zns = Zinc sulfide and Pbt = Lead total due to limitted floatability of oxides (see text), (a) = estimated total stock, (b) = additional sampling and analysis, (c) = tails processed per a; Schroll (Internal Company Report), Scherer (Company supervised diploma thesis), Jedlicka (Journal Article at Berg-und Hüttenmännische Montanhefte).*

| **Publication** | **Reference year** | **Ore grade (%)** | | **Mining Waste grade (%)** | | **Mining Waste Volume (t)** |
|---|---|---|---|---|---|---|
| | | *Pb* | *Zn* | *$Zn_s$* | *$Pb_t$* | |
| Jedlicka (1983) | 1938 | • 7.50 | 2.97 | 4.74 | 0.70 | 1220000 (a) |
| Jedlicka (1983) | 1941 | • 6.81 | 3.36 | 4.49 | 0.69 | 33685 (c) |
| Schroll (1951) in Scherer (1979) | 1950 | • 4.75 | 4.51 | 3.51 | 0.63 | ---- |
| Scherer (1979) | 1978 | • 1.07 | 4.67 | 0.21 | 0.52 | 360000 (b) |
| Jedlicka (1983) | 1982 | • 0.67 | 2.63 | 1.97 | 0.41 | 859990 (a) |
| Weighted mean | --- | • --- | --- | 3.64 | 0.65 | • |

The study also included results of Schroll (1951) see Table 4. Schroll investigated 125, 000t dump material and measured a weighted average concentration of 0.24% molybdenum. Assuming a recovery ratio of 55% he stated the theoretical resource potential to be between 110 and 170 t of molybdenum.

In Scherer´s work comprehensive evaluation of data including profound planning of sample-taking, correlation between numbers of samples with confidence limits and interpretation of dispersion bands for both compounds was conducted.

Scherer statistically analyzed zinc oxides by relating total zinc to sulfide compounds and found ranges from 1.8:1 to 9:1 (Zn tot/Zns) with a mean of about 3.5:1.

Additionally Scherer didn´t found correlations between the totals of lead and zinc at the dumps studied. This indicates that it can´t be concluded from high zinc to high lead contents. Also this information, if proven, could be of interest for future recovery planning.

### 4.3.2 Brixlegg, Tirol

*Historical background*

Mining activity has a prehistorical history around Northern Tyrolean Brixlegg/Schwaz, going back until the late Bronze Age (Goldenberg and Rieser 2004). The rich copper deposit of the "Schwazer Dolomit" were the basis for mining at Brixlegg and allowed the locality to become one of the most important European mining localities in Early Modern Age.

*Production at Brixlegg*

Big parts of the primary production of copper proceeded from the end of the $19^{th}$ century to a finite "end" in 1930[1]. Between WWI and WW2 only five mining sites remained in Austria. Brixlegg have been of the two largest mining areas, together with the mining area of Mitterberg, Hochkönig (MHB).

This period is characterized by processing big parts of copper bearing fahlores, the ores mainly excavated in the early $20^{th}$ century; correspond to large amounts of tailings. The development of the amount of ore excavated from 1918 is shown in Figure 16. The excavation of ore at Brixlegg declined in the 1970´s until the end of excavation in 1976.

When visiting the headquarters in August 2011, it was questioned if deposits of copper bearing metallurgical slags exist and are to include in the investigation of this study. Stibich noted that all deposits of copper bearing slags have been already recycled. Nowadays, refinery residues are recycled in situ and the coupled products

[1] Expert interview of Robert Stibich (COO, Montanwerke Brixlegg AG), at $23^{rd}$ of August 2011

(sandblast slag and anode residues) are sold to export, there is no more deposition of wastes connected to metallurgical processing today. Wastes from metallurgical production processes have not been investigated at both study areas but are well described for copper (BGR 2006).

## 4.4 Economics of Secondary Resources

In this chapter the factors influencing economics of recovery actions are described in general terms. The calculation of profitability is determined by balancing recovery costs against the market values of saleable products at a specific momentum. Influencing factors can include: costs for exploration, such as for deforestation or the removal of landfill cover, operational costs, transport and processing costs, values of by-products and cost associate to remediation and aftercare costs.

### 4.4.1 Tailings

Depending on their mineral composition, tailing dumps are polymetallic deposits. Therefore, at least one metal need to be abundant at recoverable concentrations. Whether the values of by-products at local markets are often substantial for an economic recovery, in the long run mining waste economics are linked global rates of exploration and excavation. The fractions of a resource that can be recovered is illustrated in Figure 21. It is depending on recovery costs and resource sales prices, that define the Cost-Effective Potential; the state-of-the-art of recovery technology, defining the Practical Resource Potential and the total content of a resource that defines the Theoretical Potential

*Monetary value of the theoretical resource potential of tailings*

Non-ferrous metals have been priced at the London Metal Exchange (LME) at around 7500$/t copper, 1900$/t zinc and 2000$/t lead in November 2011. Assuming these values and the SFA results of this study, metal worth about $19 million (copper), $94 million (zinc) and $115 million (lead) are residing in tailings in Austria.

*Economic and cost savings potential*

Recovering metals from tailings show cost savings potential compared to the mining of ore deposits. Mining and processing of mineral ore is highly energy consumptive. Figure 20 shows that as much as 30% of copper production cost are mining related costs. This indicates cost savings of a third part of total costs of metal production when mining secondary deposits like tailings.

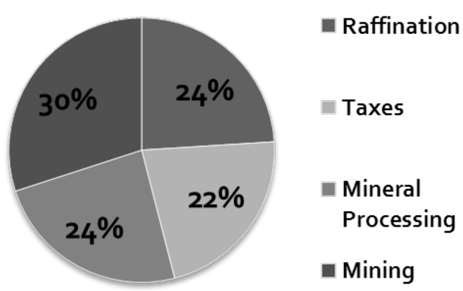


*Figure 20: Overview of cost related to primary copper production. (Modified after Krauß, Wagner et al. (1999)).*

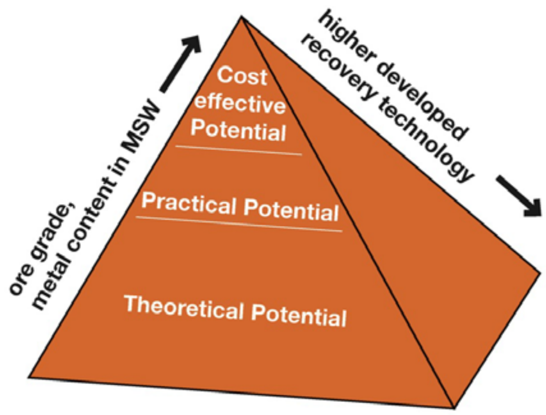


*Figure 21: Overview over the relations between the resource concentrations in a deposit (ore grade, metal content in MSW), the level of recovery technology and resulting potentials (own illustration).*

Cost before recovery

Before been able to rework material from old dumps different cost can come up. If no reliable data on the materials metal concentrations is abundant sampling programs are requisite. Sampling dumps can relate to deforestation costs like described in Scherer (1979). Furthermore, land use conflicts are likely to occur with agriculture or nearby settlements and can cause compensatory payments.

*Recovery related costs*

Tailings can be graded according to their size of grain and their grain size distribution. From practical experience of recovery processing factors like water content and the fraction of binders e.g. clay could have a significant influence on processing costs. After recovery, costs for transport and the safe disposal of leftovers have to be considered. These costs may include constructions of waste facilities or the backfilling into excavation voids. For industrial minerals, the cost of Mining Waste Management seldom if ever exceeds 2% of the sales value of the mineral being sold (EU Comission 2009).

Sometimes costs can be balance by subsidies for aftercare in order to prevent contamination. Modern day mines, particularly in well-developed countries that are operated by responsible mining companies, incorporate the rehabilitation and safe disposal of tailings in the mining costs. In particular activities of early mining operations, which did not take adequate steps to make tailings areas environmentally safe after closure, can create needs of aftercare in the future. A development of the juridical basis, towards higher environmental standards for mining waste facilities, thus could reinforce future recovery.

### 4.4.2 Landfills

*Monetary Value of the Theoretical Resource Potential in MSW Landfills*

Non-ferrous metals have been priced at the **London Metal Exchange (LME)** at around **7500$/t copper, 1900$/t zinc and 2000$/t lead in** November 2011. Assuming these values, metal worth about $1 billion (copper), $92 million (zinc) and $14 million (lead) are residing in Austrian MSW-landfills.

*Economic and cost Savings Potential*

Often the resource and energy potential of landfills alone doesn´t relate to economic recovery, thus most of the recent Landfill Mining projects have been connected to subsidies for preventive ground water protection.

Mining of landfills is connected to various economic factors. Lucrative factors that are balancing recovery and remediation costs are: Waste-to-Energy capacities, remediation of space (e.g. building land in urban areas), and conservation of landfill cover and shortening of landfill aftercare.

# 5 Discussion

Aim of the present study was to assess the theoretical resource potentials in tailings and MSW landfill on the national level of Austria. Furthermore the results of the SFA study which was conducted for tailings should be compared to those found for MSW landfills. The third aim of the thesis then was to assess factors that could limit the availability of the resource potentials found. Considering the discovered limitations the importance of the investigated stocks should be related to other secondary stocks.

The discussion consists of 4 parts which follow the goals defined at the beginning of this thesis. In the first part the goal to assess the *theoretical resource potentials of tailings* is discussed in combination with relating research questions. In the same way, the second part provides a discussion of the *real resource potentials of tailings*. The third part focuses on the *theoretical resource potentials of MSW landfills*, followed by an a *comparison of both investigated stocks*. In the last part also the *importance of the resource potentials of tailings and MSW landfills* is discussed in relation to other stocks of secondary resources.

## *Assessment of Theoretical Resource Potentials of Tailings*

Given the goal to assess theoretical resource potential of tailings, it was first to be questioned, if the MFA model of this thesis is feasible to determine the material flows of tailings. Due to the national scope of the project, analytical sampling was ruled out considering a number of mining waste facilities of >4000 sites. Instead of sampling programs or in situ measurements of dumps volumes or metal concentrations an MFA approach was used, because its, rough estimates could be regarded as sufficient enough to determine resource potentials on a national level. The results of the MFA showed balanced theoretical stocks of approx. 5 Mt of Cu tailings and approx. 12 Mt of Pb/Zn tailings that have not yet been reworked. Due to the used data on the annual amounts of excavated ore derived from relatively reliable sources like MHB and the fact that the off-flows of the flotation process were well described in literature (see 3.1), the model was regarded to represent material flows at sufficient accuracy.

### *How to assess metal concentrations in tailings?*

After addressing the material flows, the question of how to assess metal concentrations in tailings was addressed. Krauß and Wagner et al. (1999) argued that: “ The far out most important factor for the material balance of a mining business is the ores resource grade”. This also applies when investigating the resource potentials of tailings where the main challenge is to gather data about concentrations.

During data acquisition it was evident that the available data varied in accuracy. Data quality varied form reliable to vague and uncertain. Data formats ranged from annual time series to single historical records. Data on concentrations such as ore and tailing grades were regarded to be of limited reliability since they were calculated from a low number of samples, like 10 to 53 samples/site at Brixlegg, see Annex 4). In the work of Jedlicka (1983) not even any numbers of samples were documented. Therefore it was preferred to use data derived from the same source (MHB) as the corresponding amounts of excavated ore. By deriving concentrations from the calculated recovery efficiency ("metal content recovered from ore" to "metal content after extraction" ratio) it was tried to avoid the use of data from local analysis on the national level. By this, substance flows or concentrations of tailings were calculated and successfully used as input parameters to the model.

But when interpreting the results of the model, it shows some discrepancies in the source of MHB and therefore sometimes large differences between the calculated metal concentrations of tailings and those derived from MHB. While assessing metal concentrations of the stock of tailings it has to be considered that the fraction of "not" reworked tailings is a theoretical value, since reworked tailings were mixed with not reworked tailings in the same stock. Therefore, although the theoretical stock of e.g. Pb/Zn tailings is the product of the same process of flotation, it may already include two processing steps.

This mixture of tailings with reworked tailings of lower concentrations led to a decrease in concentrations of the stock. For example low metal concentrations of reworked tailings (1960: Pb 0.4%; Zn 2.8%) compared to ore grades of 4.8% Pb and 5:0% Zn led to decreased concentrations of the resulting tailings.

Investigating zinc, substance flows of 53,000t of Zn left the stock of tailings via substance flows to reworked tailings (Figure 18). This accounts for over half of the Zn-Inflow to tailings and explains a low average concentration of 0.38% Zn. The same holds for copper tailings.

But contrary to the calculations made for Pb and Zn, the results of the model could not explain the high concentrations in reworked tailings documented in MHB. Tailings reworked in 1951/1954 showed concentrations of 2.4% and 1.5% Cu, while the ore excavated in these years was around the same concentrations (approx. 2% Cu). Due to recovery efficiencies of beyond 90% which have been calculated (from MHB data) in this study, the results of the SFA could not verify these high concentrations.

To explain these high concentrations the residues either had to include dumped ore material or to consist of processing residues of far higher ore grades before processing. Even assuming ore grade of 5% Cu at a Processing Efficiency of 70% would not result into concentrations that high. It was therefore assumed that separated ore of higher value had been dumped together with tailings, but this could not be verified by literature.

*How much metal there is tailings?*

How much metal there is in tailings was tried to answer by SFA modeling. The results of the SFA conducted for non-ferrous metals indicated high resource potentials in tailings. With the exception of copper tailings approximately containing 2,600t Cu, the results showed relatively high potentials of 82,000t Pb and 47,000t Zn to reside in tailings.

Moreover the results could show the impact of former reworking of tailings. During the investigated period, 130t Cu, 53,000t of Zn and 9,000t of Pb have been recovered from waste facilities. The increase of reworking activity was most evident in case of for Pb/Zn tailings. The reason for this behavior shown in (Figure 17) could not be clarified by this study. Relating the rough trend of the annual consumption of zinc to its production data, it could be shown that reworking activities occurred in a period of a decreased consumption shown in Figure 22. Two explanations are hypothesized by this work. Because, the BBU was the only zinc mining company since the 1970´s it is possible that reworking was concentrated in periods of exploration works. By that, the mining company might have bridged the lowered excavation of primary ore. As a second explanation the increase in reworking could be interpreted as a respond to market signals, due to reworking can be less energy or cost intensive.

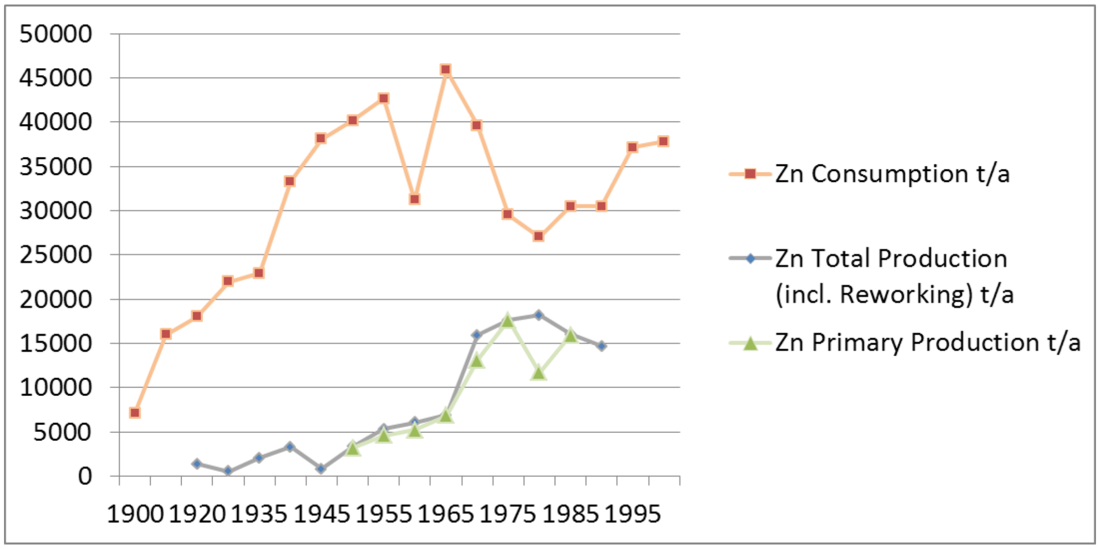


*Figure 22: Rough estimate of the relation between the annual primary production, total production and consumption of zinc in Austria. Note: Consumption data was estimated from USGS (2010) and calculated by assuming the U.S. per capita consumption for the Austrian population derived by ÖSTAT (2011). Production data was estimated from MHB.*

When interpreting the amounts calculated for copper it has to be taken into account that the data derived from the Austrian MHB resulted in rather conservative copper recovery efficiencies.

Other authors like Bertram and Graedel et al. (2002) assumed recovery efficiencies to be approximately 13% lower than the values used in this thesis, which would result into higher losses to tailings and higher resource potentials. Those discrepancies in estimating of the resource potentials of tailings show the uncertainty of contents. But those uncertainties are only one part in the estimation of the potentials of tailings. The differences in concentrations of ore and in tailings could explain the development of stock volumes. Comparing concentrations of Cu- ore of 2.3% in 1919 to concentrations of tailings of 0.15% Cu in 1920, Günther (1993) can explain the low theoretical resource potentials found for copper.

The high theoretical stock of Pb in tailings that was found in this thesis was mainly due to high substance flows in the period 1918-1944. Here, Pb concentrations of approx. 6% were on average twice as high as concentrations of Zn.

*Are the resources available?*

Regardless of the resource potentials that have been calculated, it still has to be questioned, if these resources are available. Today´s concentrations and especially the volumes of tailings or other residues that currently exist at dumps are highly uncertain. Resource potentials analyzed by investigations on local level, though of their national importance, show large differences to this study SFA´s results. Focusing on potential copper recoveries from processing residues, the report of the Montanwerke Brixlegg AG (Austria Metall 1987), with 133t states an about 20 magnitudes lower resource potential hibernating in dumps than it was calculated in the SFA.

For zinc the SFA results were compared to the results of Jedlicka (1983) who investigated resource potentials by balancing dump stocks at Bad Bleiberg/Kreuth. Jedlicka states a stock of app. 17,000t $Zn_{s.}$ This is about three magnitudes lower than the stock calculated in the SFA, which might be explained by missing documentation of former reworking periods in the MHBs. Like nowadays obligation to report for landfill operators, the data of the sources is based on uncertainties on surveying of companies.

Furthermore it has to be considered that mining residues have been mixed with hill slide debris. Since historical mineral processing techniques were often dependent on supply of water energy, some dumps are located in or nearby mountain slopes (Figure 23). Due to their possibly high impurity and their impractical location they cannot be considered to be recoverable.

Another factor discovered in the literature review of this work was regarded to have led to high uncertainties: historically, tailings were disposed however it was convenient, such as in downstream running water or down drains (BKBB 2011). Günther (1993) reported Cu tailings to be dumped into local rivers at Mühlbach, Austria in 1925 (Figure 23). For this reason, an inherent uncertainty has to be considered regarding calculations made in this study that could neither consider, nor quantify losses of tailings via disposal to rivers.

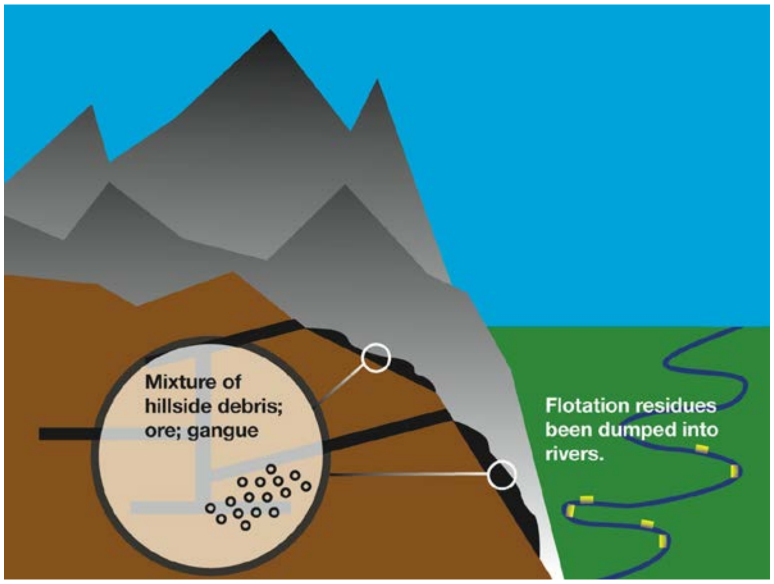


*Figure 23: Disposal pathways of excavation and flotation related to former mining activities (own illustration)*

It cannot be ruled out and rather is hypothesized, that same disposal pathways have also been used in other mining areas. Furthermore there is hardly any other documentation of disposal pathways in literature. For this reason the uncertainty of the pathways of disposal is regarded to be over magnitudes higher than the uncertainty being inherent in the SFA model. This is one major explanation for the differences between expected and actual stock volumes. For the same reason historical data from prior to 20$^{th}$ century like Apelt (1899) was not included into the SFA of this thesis. In summary, knowledge about recent local positioning, volume and the composition of tailings (or other residues) is required to estimate theoretical resource potentials.

Apart from its input parameters, the MFA model showed a high level of uncertainty on a national wide scale. Calculated substance flows and stocks have therefore to be regarded as the "most probable" allowing some range. Uncertainties of disposal pathways in rework history were considered to be of magnitudes higher than those of transfer rates in mineral processing. Disregarding these uncertainties, the SFA results were regarded to hold as rough estimates of former substance flows of non-ferrous metals to tailings, but not to be reliable in representing today's secondary resource stocks.

### *Estimation of Real Resource Potentials of Tailings*

Due to this discovered uncertainties, it could not be realized to estimate the real resource potential of tailings in this thesis. Nevertheless the work presented general terms on recovery technologies that connect to the question of the availability of secondary resources. Technically the recovery of metals from tailings is possible at high efficiencies and well described in literature (Jedlicka 1983; Gordon 2002; Espiari, Rashchi et al. 2006).

Jedlicka (1983) reported Zn-recovery efficiencies of 84% for Pb/Zn tailings. These are close to the highest level of primary processing documented in this study (89% in 1989). Other studies report technical Zn-recovery efficiencies of 88% by leaching with 2 M sulfuric acid (1h/60°) and close to 98% under optimal conditions (Espiari, Rashchi et al. 2006). Even assuming high recovery rates of up to 70% for copper, like reported by Gordon (2002), heap leaching is not favorable because of high environmental risks for surface and ground waters. But in general, recovery is possible to a high degree, either by flotation for sulfide residues or by leaching for residues of higher oxide fractions.

A positive factor regarding the recoverability of Austrian tailings could be that large fractions of the total amount deposited, have been dumped rather recently (Pb/Zn-tailings in the 1980´s; see Figure 17). Compared to copper tailings where large amounts have been dumped in the 1920´s, 1950´s and 1960´s, Pb/Zn residues are relatively young. This short time of deposition could result into a lower amount of oxide and therefore a higher recoverability of existing deposits by flotation processes.

## *Assessment of Theoretical Resource Potentials of MSW landfills*

To achieve the goal of assessing the theoretical resource potential of MSW landfills, first the total amount of landfilled MSW has been calculated to 51 Mt. This thesis´s approach to determine the total amount of landfilled MSW is, in the scope of this thesis regarded to be the best approach compared to others. It combined the findings of Lunzer und Domening (1998) who referred to a database of the UBA and surveyed all Austrian landfills with recent data from BAWPs. Other works, like Faulstich and Franke (2010) estimated higher landfill volumes of 158 Mt by considering the waste generation per capita since 1950. Compared to the approach of this study, their work included illegal dumping sites etc. of unknown compositions which complicates the assessment of future resource potentials.

### *How to determine non-ferrous metal concentrations of MSW?*

The question of how to determine the metal concentrations of MSW have been addressed by different studies before. It is reported that in general, they can range to a large extent between different landfills. Gäth and Nispel (2011) conducted sorting analysis at two MSW landfills in Germany and reported non-ferrous contents to range from 0.38 to 0.57% at one landfill and from 0.95 to 1.64% at another.

Other authors like Döberl and Fehringer et al. (2004), who roughly estimated single metal contents and found 0,05 to 0,1% of zinc in  their project RALLES.

To assess non-ferrous metal concentrations in MSW, this thesis favored the use of results that are based on the analysis of incineration residues, due to their high sampling volumes. With sample volumes of >15,000t like within CHARO, such approaches were regarded to deliver more representative results on substance concentrations of heterogeneous waste. Accounting the average metal of CHARO (2008), a theoretical resource potential of 146,000t Cu was calculated, which relates to Austria´s annual consumption with a factor of 1.35. Rettenberger (2009) reported similar potentials of Landfill Mining in Germany by estimating landfilled copper of 1.42 times the annual consumption. So the results of this thesis partly met the results of other authors like (Rettenberger 2009). This showed that using the results of a recent analysis concept like CHARO (2008) holds to calculate rough estimates of resource potentials for copper in MSW landfills. Similar applicability, could not been proven but for other non-ferrous metals. Comparing the findings of CHARO with the results of Morf (2006) showed about equal estimates for zinc, but about three magnitudes higher concentrations for copper in the CHARO results, whereas Morf (2006) found one magnitude higher lead concentrations. For the reason of this range in the values, the upper and lower borders of both studies have been used in this work. Regarding the composition of MSW, large changes during the 1960´s and 1980´s have to be considered. Baccini, Brunner et al. (1985) reported increasing fractions of copper, zinc and lead in MSW in Switzerland. Nowadays the share of metals getting landfilled is still relatively small due to high separation efficiencies. The average content of copper in landfilled waste in Europe for example might not exceed 0.1% (Bertram, Graedel et al. 2002). It was hypothesized that today's higher metal separation efficiencies prior to landfilling (Separate Waste Collection, Sorting or Separation from Incineration Ash) are partly balancing the lower metal concentrations of the 1960´s or 1970´s. This could be partly shown for copper, where the rough estimate equaled the calculations of Rettenberger (2009).

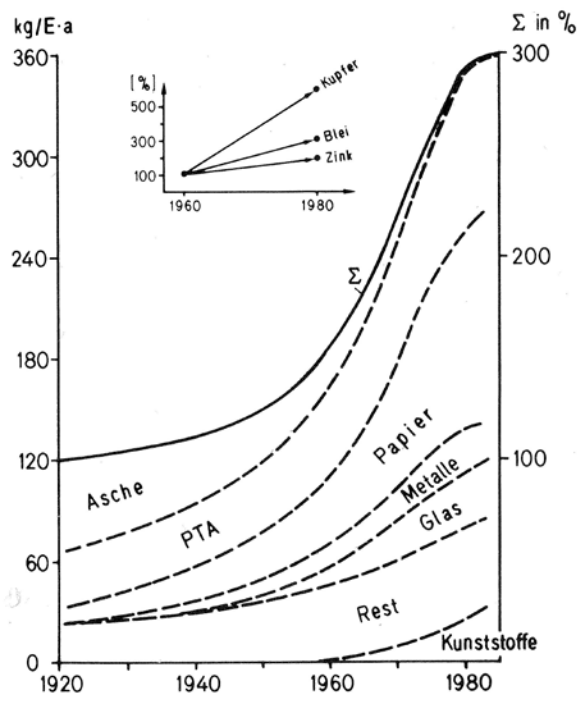


*Figure 24: Changes in the composition of MSW sorted per substances. The upper box shows the relative changes for the concentrations of selected non-ferrous metals. Source: (Baccini, Brunner et al. 1985)*

## *Comparison of the Theoretical Resource Potentials of tailings to the potential of MSW landfills and other secondary resource stocks*

Regarding the uncertainties and discovered factors that limit the theoretical resource potentials of tailings, they could hardly reasonably be compared to MSW landfills. Therefore tailings could only be compared to the theoretical resource stock of MSW landfills by considering their substance flows. In summary, the SFA results for tailings compare to the calculated maximum theoretical resource potential in MSW landfills with: Cu: 2570t/149,000t; Zn 47,000/61,000t; Pb: 81,000t/22,000t. Relating the estimated maximum stock of copper resources hibernating in MSW landfills to the balanced substance flows to tailings of 2570t Cu showed about 50 magnitudes higher stocks in MSW landfills. For zinc, the total stock in MSW landfills nearly equaled the flows to tailings. For lead the balanced substance flows to tailings was about 4 magnitudes higher than the stock in landfills. Because the resource potential of tailings is regarded is regarded to be uncertain, this comparison is only considered to relate the balanced substance flows to tailings to the stock of MSW landfills.

### *How important are the investigated stocks in relation to other secondary stocks*

The goal to assess the importance of the investigated stocks and how they relate to other anthropogenic stocks achieved by relating the findings of this study to data on the anthropogenic stock, consisting of buildings, transport infrastructure, vehicles and alike. In comparison to the in this thesis estimated maximum of 149,000t Cu in MSW landfills, the annual consumption of copper in Austria was estimated with 108,000t/a (Daxbeck, Stockinger et al. 2006). Assuming an annual copper consumption of 108,000t (Daxbeck, Stockinger et al. 2006), only during the last three decades 3.24 Mt of copper have been consumed. The estimated maximum of 149,000t Cu in MSW landfills is only equivalent to about 5% of this total consumption.

Investigating zinc, an anthropogenic stock of Zn of 3.0 million tons in 1997 with an annual growth rate of the stock of 1.5% was estimated by Daxbeck and Schönbauer (1997). Assuming that, the anthropogenic stock consisted of approx. 3.6 Mio t of zinc in 2011. Also other authors state that there are fractions of a higher content of non-ferrous metals compared to MSW, such as building and demolition wastes from electronical and electrical equipment and wastes derived from end of live vehicles (Bertram, Graedel et al. 2002). By relating the investigated resource stocks to the by magnitudes higher amount of resources residing in the anthropogenic stock, it could be shown that their potential is of relative minor importance compared to other material flows and stocks. Nevertheless, even small amounts of recovered secondary resources can partly substitute energy consumptive primary production and reduce environmental burdens.

# 6 Conclusions

With the goal to estimate the resource potentials hibernating in both investigated stocks, non-ferrous metal resources of 2,570t of copper, 47,000t zinc and 82,000t lead were calculated for tailings, compared to 39,000t to 149,000t copper, 44,000t to 61,000t zinc and 6,900t to 18,000t lead estimated in Austrian MSW landfills. The resource potential of MSW landfills were considered to hold as rough estimates, whereas the SFA results for tailings were not considered to represent the today´s stock of resources.

Uncertainties regarding disposal pathways in mineral processing history, like dumping of tailings into local rivers, that were limiting the availability of resources, are considered to be by magnitudes higher than those of the SFA model. Therefore also the high results of the SFA for zinc and lead in tailings were seen to be restricted in representing the substance flows associated with former mineral processing.  The limitations found and the wide range of metal concentrations that was documented for tailings led to the result that in situ measurement are perquisite to estimate resource potentials at sufficient accuracy. A combination of the GIS approach presented in this thesis, with analysis of dump concentrations could be of interest to investigate the resource potential of mining waste. The calculation of the potential of MSW landfills was based on comprehensive analysis of waste incineration slags that sampled high volumes up to18,000t. The methodology of these studies was considered to be state-of-the-art in the determination of non-ferrous metal contents in MSW. For this reason the results of this thesis were considered to be reliable to roughly estimate the resource potentials of MSW landfills that indicate higher potentials compared to tailings.

Answer to the question of how important the investigated resource potentials are, was given by comparing them to the anthropogenic stock, like buildings or transport infrastructure. Assuming an annual copper consumption of 108,000t (Daxbeck, Stockinger et al. 2006), only during the last three decades 3.24 Mt of copper have been consumed. The estimated maximum of 149,000t Cu in MSW landfills is only equivalent to about 5% of this total consumption. The anthropogenic stock of zinc in Austria was estimated with  3 Mt as early as 1997 (Daxbeck, Schönbauer et al. 1997). This indicates that considerably larger amounts of non-ferrous metal resource are hibernating in the anthropogenic stock. Nevertheless, every ton recovered from secondary resources, displaces a ton that must be mined and processed, and therefore relates to higher energy consumption, environmental burdens and social and economic conflicts.

# 7 Glossary

## List of Abbreviations

| | |
|---|---|
| AMD | Acid Mine Drainage |
| BMUJF | Federal Agency of Environment, Youth and Family |
| ECS | Eddy Current Separator |
| GBA | Geological Survey of Austria |
| GHG | Greenhouse-gas |
| MFA | Material Flow Analysis |
| MHB | Montan Handbook of Austria |
| MSW | Municipal Solid Waste |
| Mt | Million tons |
| RWTH | Rheinisch Westfälisch Technische Hochschule Aachen |
| SFA | Substance Flow Analysis |
| UBA | Federal Environmental Agency |
| WEEE | Waste Electric and Electronical Equipment |

For the reader’s convenience first the basic definition of terms regarding the methodology of MFA is given. Short definitions of other technical terms used in this thesis can be found in alphabetical order in the following registers. Definitions adopted from Baccini and Brunner (1991) and (Daxbeck, Merl et al. 1994), others as stated.

*Definition of Terms of MFA*

| | |
|---|---|
| (1) ‘good’ | Materials or material mixtures with functions valued by man |
| (2) ‘substance’ | Chemical elements (e.g. oxygen, copper) and their compounds |
| (3) ‘process’ | Transport, transformation and change of value of substances and goods |
| (4) ‘flow’ | Material and goods quantity per unit time |
| (5) ‘flux’ | Material and goods quantity per unit time and unit area |
| (6) ‘stock’ | Accumulation of examined material in considered process |
| (7) ‘system’ | Notion for the inclusion of parts and their interrelation. It consists of processes, materials, goods and flows and space and time boundaries |

*Short Definitions of Terms*

(1) ‘deposit’ means a material added or resting in a landform. Deposits could be primary deposits such as geological deposits or secondary deposits such as secondary stocks of resources like tailings.

(2) ‘eddy-current-separation’ means a separator that separates nonferrous metals (like aluminum, copper, brass, etc.) from inert materials (glass, stones, plastic, wood, etc.).

(3) ‘fahlore’ consist of a mixture of the minerals Tennantit and Tetraedrit.

(4) ‘heap’ means an engineered facility for the deposit of solid waste on the surface.

(5) ‘landfill mining’ means the method of excavating and processing of solid wastes that have been disposed before. It often is seen to include the removal of dangerous materials, the usage of hibernating energy resources or the reclamation of space and the recovery of materials of interest.

(6) ‘leachate’ means any liquid percolating through the deposited waste and emitted from or contained within a waste facility, including polluted drainage.

(7) ‘metal resource system’ means a system including material flows from excavation, material processing, usage, secondary recovery, recycling and waste disposal.

(8) ‘mineral resource’ or ‘mineral’ means a naturally occurring deposit in the earth's crust of an organic or inorganic substance, such as energy fuels, metal ores, industrial minerals and construction minerals, but excluding water (EU-Mining Waste Directive 2006/21/EC).

(9) ‘mono-landfills’ in the sense cited in this study mean landfills being used for incineration slags only;

(10) ‘municipal solid waste (MSW)’ means waste that is collected and disposed of by or behalf of a local authority. It will generally consist of household waste and commercial waste and waste taken to civic amenity waste collection sites by the general public. In addition it may include road and pavement sweeping and some construction and demolition waste arising from local authorities.

(11) ‘residual wastes’ are regarded to consist of household waste (paper, glass, metals, plastics, textiles etc.), biogenic- and Bulky Waste and in general correspond to the term „Siedlungsabfälle“ as defined by § 2 paragraph 4/2 AWG 2002.

(12) ‘reserve’ means the fraction of a resource that could be profitably explored at a specific moment.

(13) ‘resource’ in the sense of this thesis means a raw or secondary material that can be used or transferred by man. In geological terms it means the sum of a raw material/mineral in a geologic deposit.

(14) ‘resource potential’ if not stated explicit, see ‘theoretical resource potential’.

(15) ‘reworked tailings’ are the amounts tailings that already have been gone through a second process of mineral processing to recover metals.

(16) ‘residual waste’ are "Wastes from households and alike“ that are assumed to insist of paper, glas metal, PVC and textiles including fractions of biogenic waste, bulky waste and contaminated substances similar as defined in § 2 Abs. 4 Z 2 AWG 2002 (UBA, Austria).

(17) ‘sink’ is the antonym for the term source, which stands for the origin of an import of a substance into the anthroposphere. A sink can be one of the following: (1) a place where anthropogenic substances are disposed of, such as a lake, agricultural soil, or a landfill; (2) a conveyor belt that transports anthropogenic materials to environmental compartments, such as a river, urban air, or soil erosion; (3) a transformation process such as incineration that transforms a substance A into a different substance B (After Baccini and Brunner 2012).

(18) ‘slag’ means a mineral substance formed by chemical action and fusion in incinerator plants or arc furnaces.

(19) ‘tailings’ means the waste solids or slurries that remain after the treatment of minerals by separation processes (e.g. crushing, milling, size-sorting and flotation techniques) to remove the valuable minerals from gangue rock, but defined in this thesis to consists only of flotation residues.

(20) ‘theoretical resource potential’ means the total amount of a resource that is estimated to be stored in a deposit or stock, not taking into account interrelations to markets or limitations by recovery techniques;

(21) ‘uncertainty’ in this study is understood as a technical/scientific uncertainty

(22) ‘waste facility for tailings’ means a natural or engineered facility for disposing of tailings, along with varying amounts of waste water, resulting from the treatment of mineral ores.

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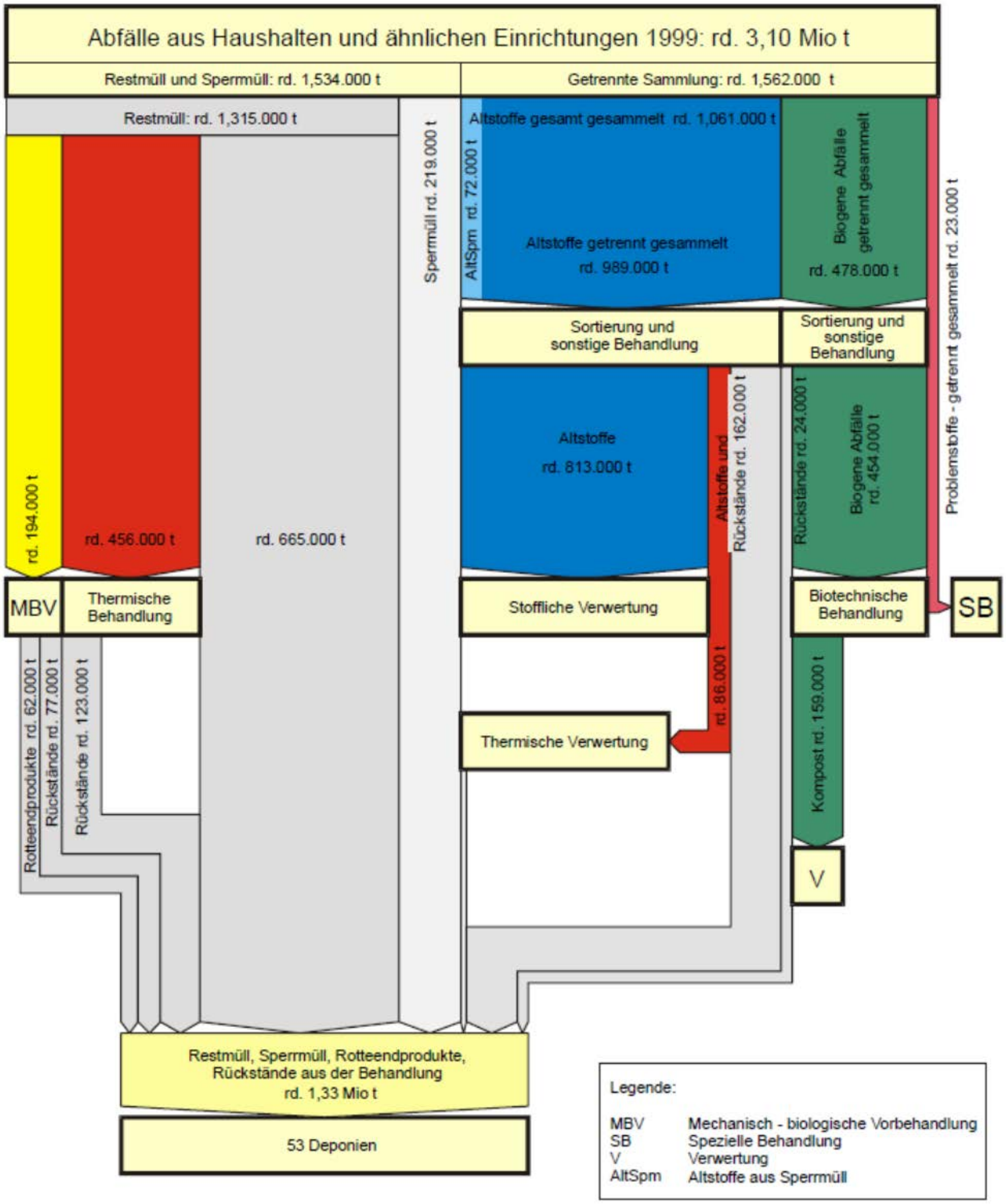
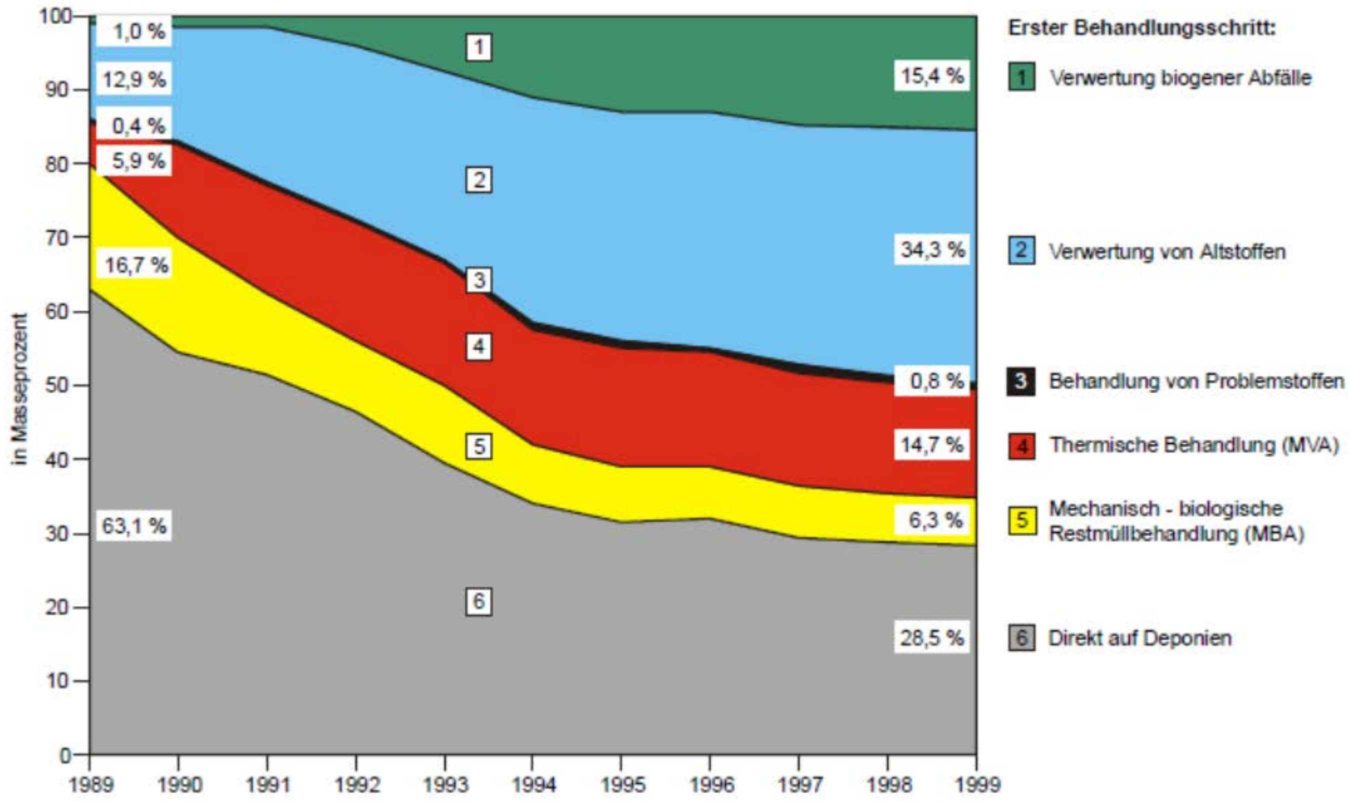
# Annex

9.1




Annex 9.1: Material flows of recycling paths in Austria (From BAWP, 2001)

9.2




Annex 9.2 : Recycling paths in percent from 1989-1999 (From BAWP, 2001)

9.3

| Year | Waste Categories | Waste in t |
|---|---|---|
| **until 1997** | *(43,3 mio m3, assumed average 0,9 t/m3)* | |
| Lunzer et al. (1997) | | 38970000 |

| | | |
|---|---|---|
| **1997** (BAWP 1998) | MSW (Inc. Res., Bulky Waste, MBW) | 2780000 |
| | Household Waste (HW) | 1290000 |
| landfilled | HW (directly deposited) | 666000 |
| | Incineration Residues | 125000 |
| | Bulky Waste | 221000 |
| | MBW Residues | 145000 |
| | | 1157000 |

| | | |
|---|---|---|
| **1998** (assumed) | MSW (Inc. Res., Bulky Waste, MBW) | 2940000 |
| | Household Waste (HW) | 1303000 |
| landfilled | Household Waste (directly deposited) | 704000 |
| | Incineration Residues | 132000 |
| | Bulky Waste | 234000 |
| | MBW Residues | 153000 |
| | | 1223000 |

| Recycling paths in % of MSW (1997) |
|---|
| 23.96 |
| 4.50 |
| 7.95 |
| 5.22 |

| | | |
|---|---|---|
| **1999** (BAWP 2001) | MSW (Inc. Res., Bulky Waste, MBW) | 3100000 |
| | Household Waste (HW) | 1315000 |
| landfilled | HW (directly deposited) | 665000 |
| | Incineration Residues | 123000 |
| | Bulky Waste | 219000 |
| | MBW Residues | 139000 |
| | | 1146000 |

| | | |
|---|---|---|
| **2000** (assumed) | MSW (Inc. Res., Bulky Waste, MBW) | 3163000 |
| | Household Waste (HW) | 1328000 |
| landfilled | HW (directly deposited) | 679000 |
| | Incineration Residues | 285000 |
| | Bulky Waste | 146000 |
| | MBW Residues | 61000 |
| | | 1171000 |

| Recycling paths as % of MSW (1999) |
|---|
| 21.45 |
| 3.97 |
| 7.06 |
| 4.48 |
| 36.97 |
| assumed also for years 2001-2003 |

| | | |
|---|---|---|
| **2001** (assumed) | MSW (Inc. Res., Bulky Waste, MBW) | 3227000 |
| | Household Waste (HW) | 1341800 |
| landfilled | HW (directly deposited) | 692000 |
| | Incineration Residues | 288000 |
| | Bulky Waste | 148000 |
| | MBW Residues | 62000 |
| | | 1190000 |

| | | |
|---|---|---|
| **2002** (assumed) | MSW (Inc. Res., Bulky Waste, MBW) | 3291000 |
| | Household Waste (HW) | 1355000 |
| landfilled | HW (directly deposited) | 706000 |
| | Incineration Residues | 291000 |
| | Bulky Waste | 151000 |
| | MBW Residues | 62000 |
| | | 1210000 |

| | | |
|---|---|---|
| **2003** (BAWP 2006) | MSW (Inc. Res., Bulky Waste, MBW) | 3355000 |
| | Household Waste (HW) | 1369000 |
| landfilled (assumed) | HW (directly deposited) | 720000 |
| | Incineration Residues | 294000 |
| | Bulky Waste | 154000 |
| | MBW Residues | 63000 |
| | | 1231000 |

| | | |
|---|---|---|
| **2004** (BAWP 2006) | MSW (Inc. Res., Bulky Waste, MBW) | **3418700** |
| | Household Waste (HW) | **1382000** |
| landfilled | HW (directly deposited) | **263000** |
| | Incineration Residues | **522000** |
| | Sorting Residues | **110000** |
| | MBW Residues | **181000** |
| | | **814000** |

| | | |
|---|---|---|
| **2005** (assumed) | MSW (Inc. Res., Bulky Waste, MBW) | **3514000** |
| | Household Waste | **1386000** |
| landfilled | HW (directly deposited) | not directly |
| | Incineration Residues | **564000** |
| | Sorting Residues | **50000** |
| | MBW Residues | **180000** |
| | | **794000** |

| | | |
|---|---|---|
| **2006** (assumed) | MSW (Inc. Res., Bulky Waste, MBW) | **3609000** |
| | Household Waste | **1390000** |
| landfilled | HW (directly deposited) | not directly |
| | Incineration Residues | **423000** |
| | Sorting Residues | **49000** |
| | MBW Residues | **181000** |
| | | **653000** |

| | | |
|---|---|---|
| **2007** (assumed) | MSW (Inc. Res., Bulky Waste, MBW) | **3704000** |
| | Household Waste | **1394000** |
| landfilled | HW (directly deposited) | not directly |
| | Incineration Residues | **232000** |
| | Sorting Residues | **50000** |
| | MBW Residues | **190000** |
| | | **472000** |

| | | |
|---|---|---|
| **2008** (assumed) | MSW (Inc. Res., Bulky Waste, MBW) | **3800000** |
| | Household Waste | **1398000** |
| landfilled | Household Waste (from seperation) | not directly |
| | Incineration Residues | **232000** |
| | Sorting Residues | **50000** |
| | MBW Residues | **250000** |
| | | **532000** |

| | | |
|---|---|---|
| **2009** (BAWP 2011) | MSW (Inc. Res., Bulky Waste, MBW) | **3895000** |
| | Household Waste | **1402100** |
| landfilled | Household Waste | not directly |
| | Incineration Residues | **242000** |
| | Sorting Residues | **52000** |
| | MBW Residues | **271000** |
| | | **565000** |
| | 18000 t metals get recovered from Inc. slag | */* **18000t** |
| | | **547000** |

| | | |
|---|---|---|
| Sum landfilled until end of year 2009 | | **51110000** |

Annex 9.3 : Annual waste generation and fraction of landfilled waste 1997-2009, values calculated or derived from BAWP reports (see References)

9.4

| 8. Interim Report Brixlegg 1985 | | | | | | | |
|---|---|---|---|---|---|---|---|
| Type of Heap | Name of Locality | Material | Tonnage (t) | Average Conc. Cu (ppm) | Samples analyzed | Dispersion of conc. Values | Theoretical resources (t) |
| Pochhalde "Poch-heap" | Neujahrspocher | Sand | 6000 t | 4700 | 22 | rel. low | 28.2 |
| Pochhalde "Poch-heap" | Nikolausstollen | Sand | 18000 t | 2500 | 15 | rel low | 45 |
| Pochhalde "Poch-heap" | Sandkapelle | Sand | 20000 t | 3000 | 53 | rel. low | 60 |
| Pochhalde "Poch-heap" | "Alter Pocher" | Sand | not measured | 3500 | 10 | low | – |
| | *Rotenstein area* | | | | | | |
| Taubhalde "Waste Rock" | Oberer Grafenstollen HAL-1 | Waste Rock | not measured | 900 | ? | rel. high | – |
| Taubhalde "Waste Rock" | Oberer Grafenstollen HAL-2 | Waste Rock | not measured | 700 | ? | rel. high | – |
| Taubhalde "Waste Rock" | Auffahrstollen HAL-3 | Waste Rock | not measured | 600 | ? | rel. high | – |
| Taubhalde "Waste Rock" | Auffahrstollen HAL-4 | Waste Rock | not measured | 600 | ? | rel. high | – |
| Taubhalde "Waste Rock" | Grafenstollen HAL-5 | Waste Rock | not measured | 1800 | ? | rel. high | – |
| Taubhalde "Waste Rock" | Grafenstollen HAL-6 | Waste Rock | not measured | 700 | ? | rel. high | – |
| | *Burgstall area* | | | | | | |
| Taubhalde "Waste Rock" | Franziska-Stollen HAL-7 | Waste Rock | not measured | 700 | ? | | – |
| Taubhalde "Waste Rock" | Franziska-Stollen HAL-8 | Waste Rock | not measured | 8200 | ? | | – |

Annex 9.4 : Mining dump analysis of Montanwerke Brixlegg AG (From Austria Metall, 1989)