Long-Term Assessment of Waste Management Options – a New, Integrated and Goal-Oriented Approach

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Abstract

Selected waste management scenarios were evaluated with regard to the goals of the Austrian Waste Management Act, taking into account long-term implications and costs. Municipal solid waste and municipal sewage sludge have been chosen as the system inputs. The scenarios were compared to the status-quo by combining Material Flow Analysis (MFA) and economic evaluation methods. Both, macro-economic Cost-Benefit Analysis (CBA) and Modified Cost-Effectiveness Analysis (MCEA) were applied for this assessment. Unlike classic CBA, MCEA allows to include the long-term impacts of the landfilled material. The results of the CBA correspond to those of the MCEA. Both evaluation methods confirm, that if long-term effects are taken into account, the Austrian goals of waste management can be
reached more efficiently by thermal waste treatment scenarios than by mechanical-
biological scenarios or landfilling without pre-treatment.

**Keywords:** Waste treatment, decision support tool, long-term impacts, Cost-Benefit
Analysis, Modified Cost-Effectiveness Analysis
1 Introduction

Many countries have defined far reaching objectives for waste management, and have implemented sophisticated legislative, technological and logistic systems to reach these objectives. Goals often found in many countries include protection of humans and the environment, conservation of resources, and the precautionary principle (no aftercare needed for landfills) (see for example AWG, 1991). A main question facing these countries is if the present or planned waste management system is the most efficient means to reach the objectives set. For such an assessment, the goals of waste management have to be brought to a assessable level, and criteria have to be defined which allow to evaluate the waste management system on a quantifiable basis. All negative as well as positive effects caused by waste management have to be taken into account. The direct and indirect costs are to be compared to the benefits of the waste management system. A crucial aspect is the time period to be observed in such an assessment.

In this paper, we present a methodology and a case study for the economic evaluation of goal oriented waste management systems. The approach is based on Material Flow Analysis (MFA), Cost-Benefit Analysis (CBA), and Modified Cost-Effectiveness Analysis (MCEA). Special emphasis is given to a comprehensive approach and to long-term processes in landfills. The reason for this is as follows:

A major goal of advanced waste management is the so called “final storage” type of landfill: Contrary to a MSW landfill, final storage landfills do not require after-care once the landfill is closed. Because technical barriers do not prevent that landfilled materials interact with the atmosphere, hydrosphere, and geosphere for long periods of time, the landfilled material itself has to be the main barrier between the landfill and the environment; it must be of so called final storage quality. (Baccini, 1989 and
Brunner, 1992). So far final storage landfills are just a concept. Before implementation aspects of definition, design, and analysis of final storage landfills have to be studied.

At present, there are still some uncertainties concerning ecological necessity and economic costs for the final storage concept: Do the benefits of final storage quality outweigh the costs of enhanced pre-treatment to reach final storage quality? This paper tries to identify and answer the crucial aspects of this question.

Thus, the following three steps were essential for this study:

- **Modeling the waste management system**

  A model combining waste treatment and waste disposal and their long-term effects has not been created for the whole MSW and municipal sewage sludge management so far. GUA & IFIP (1998) developed a first step of a comprehensive model by limiting the system boundary for landfill emissions to 100 years and by roughly estimating the implications caused by reuse of secondary products. A literature review of waste management models operating on local, regional and national levels is provided by Ljunggren (2000). However most models, including the one presented by Ljunggren, concentrate on gaseous emissions from treatment plants and on short-term gaseous emissions from landfills only. There are some models considering liquid emissions but long-term impacts have been neglected in all models so far. Many comparisons of different waste treatment options are based on life-cycle assessment (LCA), that neglect long-term impacts from landfills, too (e.g. Wallmann, 1998).

- **Determination of long-term implications**

To assess long-term implications caused by waste management processes (mainly by landfills and use of secondary products such as plastics and cement produced with RDF), substance and energy flows of processes have to be determined over centuries to millennia. For landfills this has been done e.g. by Belevi & Baccini (1989), Stegmann & Heyer (1995), AGW (1992) and Förstner & Hirschmann (1997). All studies show that long-term emissions must be taken into account when assessing the total implications of waste management.

The results of this research were used to create models for determining long-term emissions from landfills in this study. In addition processes known from natural and anthropogenic analogues, such as peat depositions and mining waste tailings, have been included in the models.

• Assessment of implications and costs

To realize the precautionary principle a sound base for decision making is needed, that includes economic as well as ecological criteria. For that purpose a CBA is suitable. It allows to assess external expenses of resources and energy as well as external effects caused by processes and use of energy sources (e.g. emissions of air pollutants) in terms of money. CBA in the field of waste management have been done e.g. by Bruvoll (1998), EPCEM (1998), GUA (1998), GUA & IFIP (1998), Clarke (2000) and Partl (2001). However, there are some effects which cannot be expressed in terms of money (e.g. contamination of cement produced with RDF). To integrate these intangible effects mostly Cost-Effectiveness Analyses or Multi-Criteria Analyses have been carried out (e.g. Wasmer, 1985; Maystre et al., 1994; Pipatti & Wihersaari, 1998). Due to
methodological problems appearing when applying these methods a new hybrid method of Cost-Effectiveness Analysis and Multi-Criteria Analysis, the so-called “Modified Cost-Effectiveness Analysis” (MCEA) was created for the case study.

In view of the legal background and the economic and ecological uncertainties the authors carried out the case study “Assessment of Waste Management Options to Achieve Long-Term Maintenance-Free Landfills” (Brunner et al. 2001). This project was supported by the governments of the Austrian provinces of Styria, Upper Austria and Vienna, as well as the Austrian Federal Environmental Protection Agency.

The main goal of this case study was to search for the best options to treat MSW and municipal sewage sludge considering both – economic costs and fulfilment of the goals defined in Austria’s Waste Management Act, especially the precautionary principle and the associated demand for aftercare-free landfills. Usually the expenses of treatment increase with the quality of the residues to be landfilled. Therefore a model for simulation and prediction is needed which allows to support decisions regarding the kind of treatment technology required to create residues of final storage quality at least cost. Because of the lack of such models, a new methodology had to be developed. Special emphasis was given to the following questions:

- What quality is required for the residues of waste treatment to fulfil the precautionary principle?

- Which waste management option yields least total costs when both the level of waste pre-treatment and long-term processes in landfills and “final storages” are taken into account?
2 Methodology

The following steps were carried out in the study:

- Definition of the comprehensive system “waste management in Austria” (see 2.1)
- Definition of scenarios to be investigated (see 2.2)
- Assessment of the flows of goods, selected substances and energy, and associated costs (see 2.3)
- Modelling of short-, mid- and long-term landfill processes and subsequent emission flows (see 2.3.2)
- Assessment of ecological impacts and costs (see 2.4)

2.1 System definition

For the comparison of different waste management options it was necessary to exactly define the system to be investigated according to the method by Baccini and Brunner (1991). An overall view of the defined system is given in figure 1. The system consists of the boundary in time and space (dotted line), processes (boxes), goods/substances (ellipses) and flows of goods/substances (arrows).

The spatial system boundary was defined as the border of the Republic of Austria. Two balancing periods were chosen for the flows and stocks in the system: 1 year for all processes, goods/substances and flows before “landfilling”, and 10,000 years for landfills and underground waste disposal facilities.
The annual amounts of MSW and municipal sewage sludge in the year 1996, as well as fuel, air, water and auxiliary agents serve as the system input. Sewage sludge, which is deposited in agriculture has not been considered for this study. Emissions and secondary products were defined as system outputs. Landfilled goods were kept within the system and were handled as stocks. The export of hazardous residuals in underground waste disposals to areas outside Austria is part of the system. Other waste imports and exports were neglected because they are small in amount and in importance.

2.2 Definition of scenarios

To fulfil the requirements for organic carbon and energy content of the Austrian Landfill Ordinance, MSW and sewage sludge have to be pre-treated before landfilling: in most cases, either thermal or mechanical-biological treatment will be applied. Thus the search for the best combination for treatment and disposal options
has to concentrate mainly on those two technologies. Against this legal background, the following scenarios which include different thermal and mechanical-biological treatment technologies were investigated. Each of these scenarios varies in the ecological quality of the products and the amount of residues to be landfilled.

Table 1: Definition of the scenarios: In all scenarios M1 to M3d, selected wastes are recycled and reused as in the status quo scenario P0. The remaining wastes are landfilled (M1), incinerated (M2), or mechanically-biologically treated followed by various thermal treatments (M3).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>status-quo continues, no change of waste management measures</td>
<td>P0</td>
</tr>
<tr>
<td>landfilling of untreated waste</td>
<td>M1</td>
</tr>
<tr>
<td>incineration without after-treatment</td>
<td>M2a</td>
</tr>
<tr>
<td>incineration with cement stabilization of the residues</td>
<td>M2b</td>
</tr>
<tr>
<td>high temperature treatment</td>
<td>M2c</td>
</tr>
<tr>
<td>mechanical-biological treatment with the light fraction from sorting and splitting (LF) processed in a fluidized-bed furnace</td>
<td>M3a</td>
</tr>
<tr>
<td>mechanical-biological treatment with the light fraction from sorting and splitting (LF) processed in a cement kiln</td>
<td>M3b</td>
</tr>
<tr>
<td>mechanical-biological treatment with the heavy fraction of high calorific value (HF) processed in an incinerator and the LF in a fluidized-bed furnace</td>
<td>M3c</td>
</tr>
<tr>
<td>mechanical-biological treatment with the heavy fraction (HF) of high calorific value processed in an incinerator and the LF in a cement kiln</td>
<td>M3d</td>
</tr>
</tbody>
</table>

The input into the subsystem “treatment” consisted nearly of the same amounts of wastes for all scenarios. The subsystems collection (including transport), sorting and recovery had to be adjusted slightly to each scenario. The material and energy flows calculated by the analysis of the scenarios served as inputs into the landfill model (table 1).

The status-quo (P0) serves as a reference scenario. This scenario describes the situation as it was in Austria in 1996: 46% of the yearly amount of 2.8 Tg MSW were collected separately and were recovered or recycled. The remaining 54% were treated or landfilled. 17% of this amount was incinerated, 15% was treated in
mechanical-biological plants and 68% was landfilled without any pre-treatment. In 1995, 0.56 Tg municipal sewage sludge were produced. 34% of this amount was treated in thermal plants, 13% was used in mechanical-biological plants and 31% was dewatered and landfilled (BAWP, 1998). The remaining 22% used in agriculture were not included in this study.

All other scenarios including short-, mid- and long-term landfill processes were compared to P0. Hence, only the relative efficiency of the respective waste treatment method was analysed and assessed.

**Scenario M1** stands for landfilling without pre-treatment of MSW and municipal sewage sludge.

The **group of scenarios M2** includes various thermal waste treatment technologies. Scenario M2a represents incineration of MSW without any after-treatment of the residues. In scenario M2b wastes are incinerated and the bottom and filter ashes are stabilized with cement before landfilling. As an alternative treatment method a high-temperature smelting-redox procedure was chosen for scenario M2c. This process results in three solid residues: a granulate, which comes close to earth-crust quality, and two high concentrated by-products – a heavy metal concentrate and an iron-copper alloy. The latter is suitable for recovery. Compared with other alternative methods, numerous data exists for this method. The municipal sewage sludge was processed in a fluidized-bed furnace in all scenarios of group M2.

The **group of scenarios M3** represents maximum mechanical-biological treatment (MBT). The whole amount of MSW and municipal sewage sludge is treated in mechanical-biological plants. The separated light fraction is either incinerated in fluidized-bed furnaces (M3a) or in cement kilns (M3b). The heavy fraction (residues
from biological treatment) is landfilled. The remaining residues from the sorting process are landfilled without any treatment.
Scenario M3c is similar to M3a, scenario M3d to M3b. The difference is that the residues from biological treatment are separated again. The fraction of high calorific value is incinerated. The fraction which is poor in carbon and heating value is landfilled. The remaining residues from sorting were incinerated as well.

2.3 Determination of material and energy flows and costs

2.3.1 Waste treatment preceding landfilling
The case study is based on the system defined in 2.1. In the following, the waste treatment processes are discussed as subsystems. For one year, all flows of goods, energy, money and selected emissions caused by the subsystems “collection”, “sorting”, “recovery”, “treatment” and “landfilling” of MSW and municipal sewage sludge were assessed. For that purpose, a Material Flow Analysis (MFA) for the substances C, N, S, Cl, Hg, Cd, Pb, Zn and their relevant chemical compounds as listed below was carried out using the methodology of Baccini & Brunner (1991). The following emission loads (kg a⁻¹) relevant to waste management have been included: CO₂, CH₄, CO, CₓHᵧ (NMVOC), particulate matter, CFC, PCDD, PCDF, TOC, NOₓ, NH₃, NO₃⁻, NO₂⁻, NH₄⁺, SO₂, H₂S, SO₄²⁻, HCl, Cl⁻, Cd, Hg, Pb, Zn. The substitution of primary production emissions by recycling was calculated as well. Additionally the composition of the residues to be landfilled was determined.
For each process an energy balance was carried out. Besides expenditures and returns, the substituted energy from avoiding primary production was calculated. The energy balance was split into two categories of power – final energy (electricity, heat
to households and heat to/from industry) and primary energy (diesel oil, fuel oil, hard
coal and natural gas).

Material (goods and substances) and energy flow analyses were performed for the
following subsystems:

- Sorting of separately collected secondary materials:
  - Sorting of paper, packaging material (plastics and metals), bulky waste,
    glass, textiles

- Recovery of separately collected secondary materials:
  - Recovery of paper, plastics, non-iron metals, iron, glass
  - Agricultural, low-tech and high-tech composting, anaerobic treatment of
    biogenic waste

- Treatment of not separately collected fractions of MSW (mixed municipal waste),
municipal sewage sludge and residues from sorting and recovery:
  - Mechanical treatment followed by aerobic biological treatment
  - Incineration without after-treatment, incineration with cement stabilization of
    residues, high temperature smelting-redox process, treatment in cement
    kilns, and in fluidized-bed furnaces

- Landfilling of residues from sorting, recovery and treatment: see 2.3.2

If available, the calculation of the economic costs and benefits of these plants were
based on distinct, existing plants. Investment costs as well as fixed and proportional
operational costs and profits were taken into account.
2.3.2 Subsystem landfilling

The solid residues of the previous subsystems are assigned to the following landfill types:

Table 2: Allocation of the residues to landfill types

<table>
<thead>
<tr>
<th>Type of treatment</th>
<th>Residue</th>
<th>Landfill type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>M1 No treatment</strong></td>
<td>residual waste</td>
<td>landfill for MSW *</td>
</tr>
<tr>
<td></td>
<td>municipal sewage sludge</td>
<td>landfill for sewage sludge *</td>
</tr>
<tr>
<td><strong>M2 Thermal treatment</strong></td>
<td>Conventional incineration</td>
<td>bottom and fly ash§</td>
</tr>
<tr>
<td></td>
<td>incineration filter cake</td>
<td>landfill for incineration residues</td>
</tr>
<tr>
<td></td>
<td>incineration filter cake</td>
<td>underground disposal site</td>
</tr>
<tr>
<td></td>
<td>Incineration with cement stabilization</td>
<td>stabilized bottom and fly ash§</td>
</tr>
<tr>
<td></td>
<td>incineration filter cake</td>
<td>landfill for incineration residues</td>
</tr>
<tr>
<td></td>
<td>incineration filter cake</td>
<td>underground disposal site</td>
</tr>
<tr>
<td></td>
<td>High-temperature-process</td>
<td>granulate</td>
</tr>
<tr>
<td></td>
<td>concentrate of heavy metals</td>
<td>landfill for incineration residues</td>
</tr>
<tr>
<td></td>
<td>gypsum cake</td>
<td>landfill for demolition waste</td>
</tr>
<tr>
<td></td>
<td>Fluidized-bed furnace</td>
<td>bottom and fly ash§</td>
</tr>
<tr>
<td></td>
<td>filter cake</td>
<td>landfill for incineration residues</td>
</tr>
<tr>
<td></td>
<td>gypsum cake</td>
<td>underground disposal site</td>
</tr>
<tr>
<td></td>
<td>Cement kiln</td>
<td>clinker – demolition waste**</td>
</tr>
<tr>
<td></td>
<td></td>
<td>landfill for demolition waste</td>
</tr>
<tr>
<td><strong>M3 Mechanical-biological treatment</strong></td>
<td>residues from MBT</td>
<td>landfill for residues from MBT</td>
</tr>
<tr>
<td><strong>P0-M3 Waste from recovery</strong></td>
<td>slag from iron smelting</td>
<td>- ***</td>
</tr>
<tr>
<td><strong>P0-M3 Waste from sorting</strong></td>
<td>waste from sorting (if not</td>
<td>landfill for MSW *</td>
</tr>
<tr>
<td></td>
<td>incinerated)</td>
<td></td>
</tr>
</tbody>
</table>

§ This disposal route for bottom and fly ash has been chosen because it reflects actual practice in Austria in the 1990ies.

* Note: Landfill in a reference scenario. Landfilling of MSW will not be allowed in Austria after 2004.

** The clinker is used for cement production. The buildings constructed with concrete have a modelled down-cycling life time of 500 years. After this period the construction waste is deposited in a landfill for demolition waste and the emissions are calculated.

*** The amount of wastes from iron recycling is low. Nearly the same amount occurs in every scenario. Therefore this waste was excluded from the model.

Only monofills are modelled for calculating the emissions over 100, 1,000 and 10,000 years. Each landfill is constructed according to the requirements of the Austrian Landfill Ordinance. The following simplifications were made:
(1) The short, medium and long-term amount of landfill leachate is equal to the
difference between the average annual precipitation rate and the average annual
evaporation-transpiration rate for recultivated landfill surfaces in Austria.

(2) The lifetime of landfill construction elements e.g. surface liner, base liner and
man-made geological barrier is limited to 100 years. The ability of the geological
barrier to bind heavy metals (geochemical barrier) does not decrease during the
whole period of 10,000 years.

(3) The landfill is a homogenous reactor (monolith) without preferential leachate
flow.

The assessment of the landfill emissions was based on the schemes shown below.
Key-reactions and changes in the physical-chemical conditions in the landfills were
defined as well as the relationship between the substances. Additionally, the
predominant species of the substances under different conditions can be seen.
Organic landfills (MSW, sewage sludge, residuals from MBT)

Combinations of Cl, N, S, Hg

Gaseous emissions during methane production phase

Discharge of chloride

Discharge of ammonium/nitrate

Discharge of sulfate

MeS

Hum-Me

Exchange reactions on clay minerals

Degradation of humic substances = decrease of redox-buffering capacity

Diffusion of oxygen into the landfill

Acidic phase

Aerobic phase

CH₄-production phase

Aerobic phase

Time [a]

Figure 2: Reaction and emission scheme for organic landfill types. Double arrow: chemical reaction; single arrow: discharge; Me: metals; Hum: humic substances; CM: clay minerals; OM: organic matter; boxes: solids

Inorganic landfills (residues from thermal treatment)

Discharge of chloride

Discharge of ammonium/nitrate

Discharge of sulfate

Exchange reactions on clay minerals

Degradation of organic matter

Increase of metal mobility

Discharge of carbonate buffer

Diffusion of oxygen into the landfill

O₂

Time [a]

Figure 3: Reaction and emission scheme for inorganic landfill types. Double arrow: chemical reactions; single arrow: discharge. Me: metals, CM: clay minerals; boxes: solids
Calculation of gaseous and liquid emissions of carbon compounds from organic landfill types

Gaseous (CH\(_4\), CO\(_2\)) and liquid (TOC) carbon emissions from organic landfills were calculated by adapting the model introduced by Marticorena et al. (1998) to the case studies.

\[ \text{MP}_{(t,i)} = \text{MP}_{(0,i)} \cdot \exp\left(\frac{-t}{k_i}\right) \]

The model supposes an initial maximum gas production potential (MP\(_{(0,i)}\)). Assuming that the whole amount of organic carbon is degradable during the observation period, MP\(_{(0, \text{total})}\) can be calculated using Avogadro’s law: 1,000 kg of TOC results in 1,867 m\(^3\) emitted landfill gas. The TOC content of MSW, municipal sewage sludge and residues of MBT was calculated by splitting them into their main organic constituents such as cellulose, sugar and proteins, and by determining the TOC contents of these compounds (substance groups \(\mathcal{I}\)). The emitted amount of gas at the time \(t\) is equal to the difference of MP\(_{(0,i)} \cdot \text{MP}_{(t,i)}\) and is a function of MP\(_{(0,i)}\), time \((t)\) and a velocity constant \((k_i)\), which can be calculated estimating the half-time of the different organic combinations.

In the model applied, gas production starts after the acidic phase (5 years) and lasts during the whole investigation period (10,000 years). During the anaerobic phase, the CH\(_4\)/CO\(_2\) ratio is assumed to be 55/45 vol-%. The transfer coefficient of carbon into the liquid phase was assumed to be 0.0015 (Belevi & Baccini, 1989). Oxygen diffusion into the landfill is completed after 600 years (Bozkurt, 1998); during the following period, aerobic conditions will cause CO\(_2\)-emissions only. According to natural analogues, such as soils, the transfer-coefficient of carbon into the liquid
phase will shift to 0.05 in aerobic systems. In addition, main greenhouse gas emissions were calculated separately for all landfills.

During the intensive methane-production phase, which lasts for 15 years, gaseous emissions of N, S, Cl and Hg-combinations were determined, too.

**Calculation of liquid emissions of non-metals and calcium**

Emissions of other non-metals (N, S and Cl) and calcium were calculated by applying the model of Belevi & Baccini (1989). This model describes the leachate concentrations of these elements using first-order kinetics:

\[
(c(t)) = (c(0)) \cdot \exp(-t \cdot \frac{V \cdot (c(0))}{M \cdot m(0)})
\]

The substance concentration at the time \(t\) \((c(t))\) is a function of the leachate volume \(V\), the waste mass \(M\) and the available amount of the substance \((m(0))\).

The prevailing species, depending on the physical-chemical conditions, were taken into account by using the schemes above. The resulting concentrations \((mg l^{-1})\) were transferred into loads \((kg a^{-1})\) by applying the simplified water balance described above. TOC emissions from inorganic landfills were calculated the same way.

**Calculation of heavy-metal emissions**

Heavy metal emissions (Pb, Zn, Cd, Hg) are supposed to be constant in time depending on the predominant physical-chemical conditions only. Therefore the concentration shifts twice in organic landfills: at the end of the acidic phase it will become lower due to the anoxic and alkaline milieu during the methane production phase. After oxygen diffusion into the landfill is completed, the concentration will increase again due to the oxic and acidic conditions. Concentrations were estimated
using data from existing landfills and from natural analogues, such as peat deposits and mining waste deposits.

In the case of landfills for thermal residues (inorganic landfills), emission phases and correlated concentrations are based on the model of AGW (1992). The following phases can be expected in landfills for thermal residues without after-treatment: carbonatization (1-30 years), depletion of carbonate buffer (30-5,000 years) and an “acidic” phase (5,000-10,000 years). It was assumed that cement stabilization of thermal residues prohibits the depletion of the carbonate buffer for the whole investigation period.

Calculation of remedial measures

The dilution of leachate emissions in a hydrogeologically defined aquifer (representing a typical landfill site in Austria) was calculated. The accumulation of heavy metals in the landfill’s subsoil after failure of the technical barrier (base liner) was considered as well. The results were used for evaluating remedial measures. The costs and time for remedial treatment of the landfill were estimated, as well as the costs for design, construction, operation and maintenance of the modelled landfills.

The calculated emission loads (kg) were summed up after 1, 100, 1,000 and 10,000 years, respectively, and were used as inputs for the assessment routine described in 2.4.
2.4 Assessment of costs and ecological impacts

Which of the defined scenarios is the most advantageous? Which treatment options should be recommended? To answer questions like these, numerous assessment methods are available. Within the present case study, two assessment methods have been introduced. Both, a Cost-Benefit Analysis (CBA) and a newly developed method, the “Modified Cost-Effectiveness Analysis” (MCEA) have been carried out. Main input data to both methods are a internal cost balance (including investment cost, operating cost and profits), a balance of goods, an emission inventory and an energy balance of the waste management processes studied.

The aim of CBA is to consider and to value in monetary terms all (positive or negative, internal or external) effects in order to compare the costs with the benefits induced by a scenario (see figure 4). Within this case study not all effects could be valued in monetary terms, as some of them remain intangible, e.g. emissions of substances with impact on ozone depletion and emissions of dioxines, chloride, sulphate, hydrogen sulphide, salt acid and ammonia. Emissions affecting ground water and soil have been taken into account indirectly by the costs of remediation measures. These intangibles were described qualitatively but could not be considered quantitatively. Therefore the resulting variables, the cost-benefit balance and the benefit-cost ratio are based on incomplete input data.
Another crucial point in CBA is the factor of time. Due to the very long observation period, compliance with the precautionary principle and also the impossibility to estimate technological progress during the observation period, the discounting rate for the CBA was chosen to be zero.

Within a sensitivity analysis concerning the CBA, the following parameters were varied: external costs for emissions, costs for remediation measures of waste sites, tax for remediation of old landfill sites\(^1\) and market prices of comparable products or intermediates manufactured from primary raw materials.

The traditional Cost-Effectiveness Analysis (CEA) displays, on the one hand, the costs of a scenario and, on the other hand, the effectiveness with regard to the achievement of the targets under consideration. In many cases there is no ranking possible. Modification of the CEA (resulting in the MCEA) consists of an aggregation
step of the single effectiveness values to obtain a total effectiveness value. The procedure is similar to the multi-criteria decision analysis or to the effectiveness determination in a life-cycle assessment procedure. The result of the MCEA is a total effectiveness value-cost ratio, which serves as a basis for the ranking of the scenarios. Hence, MCEA compares costs with the efficiency of reaching defined targets.

The MCEA is based on a hierarchy of goals, in which the three objectives of the Austrian Waste Management Act - AWG (protection of humans and the environment, conservation of resources\(^2\), and aftercare-free landfills\(^3\)) are situated at the top level (table 3). To consider the different importance and public preferences, each one of the goals was awarded a specific weight by a group of waste management experts of several province governments with various waste management systems. The influence of weighting was investigated by sensitivity analysis.

Table 3: Hierarchy of targets used in MCEA.

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\(^1\) So called “Altlastenreinigungsbetrag” (= landfill tax)

\(^2\) material, energy and land

\(^3\) no endangering of future generations – precautionary principle
<table>
<thead>
<tr>
<th>Highest</th>
<th>← level of goals →</th>
<th>Lowest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection of humans and the environment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protection of air quality</td>
<td>Reduction of impact by regionally important pollutants</td>
<td></td>
</tr>
<tr>
<td>Protection of water quality</td>
<td>Reduction of the anthropogenic greenhouse-effect</td>
<td></td>
</tr>
<tr>
<td>Protection of soil quality</td>
<td>Reduction of damage to the ozone layer</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Environmentally compatible emissions to surface water</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Environmentally compatible emissions to ground water</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No accumulation of pollutants in soil surface</td>
<td></td>
</tr>
<tr>
<td></td>
<td>No accumulation of pollutants in underground soils</td>
<td></td>
</tr>
<tr>
<td>Conservation of land</td>
<td>Minimization of landfill space</td>
<td></td>
</tr>
<tr>
<td>Conservation of raw materials</td>
<td>Minimization of resource consumption by recycling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Maximum production of secondary resources</td>
<td></td>
</tr>
<tr>
<td>Conservation of energy</td>
<td>Balance of the energy amounts of the targets.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Maximum energy substitution by utilizing energy recovered from waste and landfill gas</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Minimization of energy demand for waste management and treatment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Minimization of energy demand by recycling: reducing energy used for primary production</td>
<td></td>
</tr>
<tr>
<td>Aftercare-free landfills</td>
<td>Minimization of the long-term reactivity of the landfilled residues and of the mobility of pollutants within the landfill</td>
<td>Minimization of pollutants in landfilled residues</td>
</tr>
<tr>
<td>(precautionary principle)</td>
<td>Allocation of residues to appropriate landfill types</td>
<td></td>
</tr>
</tbody>
</table>

To be able to assess the abstract goals of the AWG, it is necessary to find specific, operational and measurable goals. Therefore, on the lowest level of the hierarchy of objectives are those, which are evaluated by using integrative target criteria, which are based on measurable technical data. On this level a total amount of 110 goals were defined and evaluated. The integrative target criteria are: greenhouse-potential, ozone depletion potential, critical air volume, critical water and soil volumes, space used for landfilling, availability of raw materials, energy sources and “substance-concentrating-efficiency” (SCE). SCE stands for the power of a scenario to concentrate or dilute substances in products, residues and emissions of waste treatment processes (Rechberger, 1999). For each criterion a quantitative goal
value\(^4\) was defined, and the level of target achievement (target revenue) was determined for each scenario. Thus, the target revenue relating to the reference scenario (P0) is calculated and then transformed into the effectiveness value (see figure 5).

![Diagram of the method of measuring efficiency in MCEA](image)

**Figure 5:** Method of measuring efficiency in MCEA

The effectiveness values within a single scenario and the reference scenario are weighted with the correspondent average weighting factor provided by the waste management expert group discussed above. Finally, the effectiveness values are aggregated to form the weighted total effectiveness value. The costs of each scenario were related to the costs of the reference scenario and thus standardised. In the final step, the standardized costs and the weighted total effectiveness values were used to calculate the ratio of the total effectiveness value to costs for each scenario (see figure 6). This ratio finally was used to rank the different scenarios.

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\(^4\) The value which can be reached by directing the waste management system to just fulfil this one target
3 Results

3.1 Material and energy balances, emissions and costs

3.1.1 Waste treatment preceding landfilling

All flows of materials (goods and substances) and energy within the system were quantified by material and energy flow analyses. The flow of goods in scenario P0 is shown as an example in figure 7. Substance flows were calculated based on either the flows of goods and the corresponding substance concentrations in these goods or existing emission data.

An example of the results of the energy balances is given in figure 8, which shows the amount of electric power used in the different scenarios.

Finally, all data calculated went through the assessment routine.
3.1.2 Subsystem landfilling

An example of the calculation of emissions from landfills is shown graphically in figure 9. For each scenario, the emissions of all landfill types were added up to a single emission value e.g. for chloride or methane (figure 10).
Figure 9: Chloride and methane emissions from the MSW landfill in scenario P0 “status-quo”. For leachate concentrations (Cl), both maximum and minimum ranges were calculated.

Figure 10: Total chloride (maximum range) and methane emissions from landfills after 100, 1,000 and 10,000 years for all scenarios.

3.1.3 Private costs

The following private costs were calculated and taken into account in the CBA and MCEA. Investment costs (calculated as periodical capital expenditures), fixed and variable operational costs, and a risk-and-profit surcharge. The private costs of all scenarios and the break down by each treatment step is given in figure 11.
3.2 Social costs and ecological impact

3.2.1 Results of the Cost-Benefit Analysis

Generally, the ranking based on the cost-benefit balances (economic losses) concurs with the one based on benefit-cost-ratios (figure 12); scenarios P0 and M3a, which appear close to each other in both ranking systems, change positions when ranked in the other ranking system. Scenario M2a yields the lowest economic loss, followed by the scenarios M2b and M2c. In general, thermal waste treatments show the best results, scenario M1 (landfilling of untreated waste) shows a much higher economic loss.
3.2.2 Results of the Modified Cost-Effectiveness Analysis

Figure 13 shows the total effectiveness value-cost ratios for all scenarios. This ratio is highest for scenario M2c (high-temperature-waste treatment); the other scenarios based on thermal treatment (M2a, M2b) follow. In general, thermal waste treatment options yield the best results. For the mechanical-biological options, scenarios M3d and M3c show better results than scenarios M3a and M3b. The latter scenarios dispose of more residues in landfills. The total effectiveness-cost-ratios of the scenarios M3 are better than the results of the reference scenario (P0). This means that both thermal treatment as well as mechanical-biological treatment (preferably with thermal recovery and treatment of the fraction of high calorific value) of MSW and sewage sludge are to be preferred to the present status quo in Austria. While it is true that scenario M1 (maximization of the landfilling of untreated MSW and municipal sewage sludge) involves the lowest private cost, the total effectiveness
value and the total effectiveness value-cost ratio is clearly below the values of the reference and all other scenarios. The result confirms, that the Austrian Landfill Ordinance, which mandates waste pre-treatment before landfilling, represents an important and appropriate step towards reaching the goals of waste management.

![Figure 13](image)

Figure 13  Ranking of the scenarios based on total effectiveness value, standardized costs and total effectiveness-cost ratios.

3.2.3 Summary of ranking results

<table>
<thead>
<tr>
<th>Ranking based on MCEA</th>
<th>P0</th>
<th>M1</th>
<th>M2a</th>
<th>M2b</th>
<th>M2c</th>
<th>M3a</th>
<th>M3b</th>
<th>M3c</th>
<th>M3d</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>9</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Ranking based on cost-benefit-balance</td>
<td>8</td>
<td>9</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Ranking based on benefit-costs-ratio</td>
<td>7</td>
<td>9</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>8</td>
<td>6</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

In general, the results obtained by the use of CBA concurred with those of MCEA. The thermal M2 scenarios were rated best, followed by the mechanical-biological M3 scenarios, the status-quo P0, and the landfill scenario M1. However, in a few cases where the results of the methods applied were very close, the internal positioning within the scenario groups M2 and M3 changed according to the ranking method.
Overall, the thermal scenario M2a showed the smallest macro-economic loss of all scenarios.

Some of the external effects remain intangible within the CBA:

- The CBA did not take directly into account emissions to groundwater and soil but the costs of remedial treatment when evaluating the external effects of landfilling,

- Concentrations in water, air and soil, which are below limiting values, have not been taken into account.

Because of these deficiencies, the authors prefer the results of the MCEA and consider this method better suited to support decision making in waste management.

4 Conclusions

4.1 Conclusions regarding methodology

According to the precautionary principle stated in the objectives of the Austrian Waste Management Act, environmental effects from waste management have to be taken into account regardless whether they occur today or in 10,000 years time. In this study, a methodology was developed to evaluate costs and effects of different waste management scenarios over very long periods of time. After careful screening, Cost-Benefit Analysis and Cost-Effectiveness Analysis were selected to tackle the evaluation problem. The latter had to be modified to include and evaluate all effects important in this study (MCEA).

In a comprehensive case study, both methods were applied to rank nine different waste management scenarios. CBA and MCEA yielded the same results, giving preference to thermal waste treatment. Although there are important differences
between the two methods, they both can serve well as decision support instruments in waste management.

The main purpose of CBA is to support decisions regarding the efficient use of resources. CBA includes not only costs and benefits valued with market prices, but also goods valued implicitly by individuals. On the condition that all the cost and benefit flows which are induced by a project are valued in monetary terms, the CBA is a suitable tool for giving recommendations whether a project should be realized and, if so, which project alternative is to be preferred. If the benefits induced by a project exceed its costs, the project is valued positively. Due to the fact that CBA includes only those effects, for which a monetary valuation is possible, some relevant (mostly negative external) effects remain excluded from the analysis. Thus, the result of CBA often is incomplete.

Alternative methods must be able to take into account non-monetary effects. The MCEA, which was developed by the authors from the classical CEA, is such a method. MCEA answers the question, which of the scenarios fulfils best the goals of waste management as defined in the Austrian Waste Management Act. Based on these main goals, sub-goals were defined. Criteria were developed to operationalize the sub-goals on a specific and measurable level. The weighting of the goals and sub-goals was done by waste management experts. In any case, this weighting should involve all stakeholders and actors engaged in a waste management system. Hence, a maximum of objectivity and appropriate subjectivity is guaranteed. For all scenarios, the efficiency of attaining the waste management goals is to be compared with the incurred costs. The use of MCEA made it possible to evaluate almost all the effects which remained intangible within the CBA, especially those connected with influence on the environment. MCEA does not only enable to include monetarily non-
valuable effects, it also provides a better basis for decision makers than the “classical” CEA, which leaves the politicians alone with (at least in this study) almost 140 efficiency values on the lowest level of the goal-hierarchy.

4.2 Conclusions regarding waste management

The private costs of landfilling untreated waste are small in comparison, but CBA and MCEA show that when long term impacts are considered, the overall performance of landfilling without pre-treatment is poor.

The closer landfilled wastes and residues come to final storage quality the better the scenario performs in the total economic assessment. This is due to lower landfill emissions during mid-term and long-term periods. A reduction of reactivity of landfill material induces directly a reduction of total economic costs. Therefore thermal treatment options, such as incineration and high-temperature treatment, are rated better than mechanical-biological treatment (MBT) options. Incinerator bottom ash comes closer to final storage quality than residues from MBT. MBT produces landfill material with higher TOC values and thus higher biochemical reactivity. It is interesting to note, that the ranking of the scenarios does not depend on the time period investigated (years, centuries, millenniums) but is constant for all three cases. The longer the observation period is, the more distinct becomes the advantage of thermal treatment.

Incineration followed by the appropriate stabilization of bottom- and fly ash (M2b) entails lower landfill emissions during long-term periods than incineration without stabilization (M2a). In the economic assessment this advantage did not compensate the energy requirement for the production of the stabilization material (cement).
The results show the advantage of high temperature processes such as the smelting-redox process investigated in M2c: the residues are very close to so called “final storage” quality, and thus M2c was ranked above conventional incineration. Investment costs as well as operating costs of high temperature processes are high. These costs are compensated by the least environmental long-term impacts. High temperature processes appear to be a cost effective alternative. It can be expected that costs will decrease during the further development of the process.

It is important to note that the comparison of the scenarios did not include reliability of operating experience with waste treatment processes. Hence, new processes with yet unknown performance records have been equally weighted as reliable, state of the art processes with a long and successful record.

In both economic assessments (CBA and MCEA), thermal treatment options show significantly better results than mechanical-biological treatments. Still, MBT scenarios are ranked above the status quo scenario. The more extensively the fractions of mechanical-biological treatment are thermally treated, the better the scenario performs in the economic assessment (M3c and M3d superior to M3a and M3b). Treating the light fraction in a fluidized-bed furnace (M3a and M3c) or in a cement kiln (M3b and M3d) makes no significant difference. The emission loads from fluidized-bed furnaces equipped with advanced air pollution control systems are smaller than those from cement production. The pathways and final sinks of pollutants in the solid residues are well known for landfilled incineration residues, and less predictable for cement and concrete. Thus, following the precautionary principle, the treatment and utilization of MBT residues with high pollutant loads in fluidized bed incinerators appears more appropriate than in cement kilns.
5 References


Brunner, P.H. (1992): Wo stehen wir auf dem Weg zur Endlagerqualität ?(How far have we got on our path towards a final storage quality?). Österreichische Wasserwirtschaft 9/10, 269-273.


