Life cycle assessment model for road construction and use of residues from waste incineration

Harpa Birgisdóttir
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Institute of Environment & Resources
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Preface
This Ph.D. thesis was done at the Technical University of Denmark at the Institute of Environment & Resources in collaboration with the Department of Manufacturing Engineering and Management. The work was carried out in cooperation with the Danish Road Directorate – Danish Road Institute, the incineration plant I/S Amagerforbrænding, the incineration plant I/S Vestforbrænding and the cement producer Aalborg Portland A/S. The project was funded by the Technical University of Denmark, the Danish Road Directorate, I/S Amagerforbrænding and I/S Vestforbrænding. The main supervisor of the project was Professor Dr. Agro. Thomas H. Christensen and the co-supervisor was Associate Professor Michael Z. Hauschild. The thesis includes five articles (appendix I-V) and a manual and documentation for the ROAD-RES model (appendix VI). The appendices, which are summarized below, are referred to in the thesis by the roman numerals:

I) A model for life cycle assessment of road construction and disposal of residues (ROAD-RES), by Birgisdóttir, H., Bhander, G., Hauschild, M.Z. and Christensen, T.H.

II) Life cycle assessment of disposal of residues from waste incineration: Recycling in road construction or landfilling evaluated in the ROAD-RES model, by Birgisdóttir, H., Bhander, G., Hauschild, M.Z. and Christensen, T.H.

III) Environmental assessment of roads constructed with and without bottom ash from municipal solid waste incineration, by Birgisdóttir, H., Pihl, K.A., Bhander, G., Hauschild, M.Z. and Christensen, T.H.

IV) Leaching of PAHs from hot mix asphalt pavements, by Birgisdóttir, H., Gamst, J., and Christensen, T.H.

V) Leaching of inorganic constituents from hot mix asphalt pavements, by Birgisdóttir, H. and Christensen, T.H.


The papers are not included in this www-version but can be obtained from the Library at Environment & Resources DTU, Bygningstorvet, Building 115, Technical University of Denmark, DK-2800 Lyngby (library@er.dtuldk).

Apart from the appendices included in this thesis, several documents in Danish have been prepared in relation to the ROAD-RES model. These documents are gathered in a separate annex-report to the thesis. The annex-report includes:

- Data catalogue for ROAD-RES
- Technical description of road construction (in Danish)
- Technical description of upgrading of bottom ash (in Danish)

Copenhagen, July 2005

Harpa Birgisdóttir
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A steering committee consisting of Knud A. Pihl (Road Institute, the Danish Road Directorate), Uffe Juul Andersen (the incineration plant I/S Amagerforbrænding), Kim Crillesen (the incineration plant I/S Vestforbrænding) and Dirch Bager (the cement producer Aalborg Portland) was affiliated to the project. They are all thanked for their co-operation during the project.

The members of staff at the Environmental Research Group at the University of New Hampshire are greatly acknowledged for their hospitality during my visits there. Defne Apul is specially thanked for interesting discussions and motivating cooperation within modeling of water movements in roads, and for our friendship. Paula Eskola at VTT the Technical Institute of Finland is acknowledged for the introduction to their work within life cycle assessment on recycling residues in roads and the hospitality in Finland in the beginning of my Ph.D. work.

I thank my office mates, Trine Lund Hansen and Janus T. Kirkeby, for good discussions within the world of waste and happy times during the years. The Institute of Environment & Resources has been a pleasant place to work and I thank my colleagues at the institute, my research group and my fellow Ph.D. students for both social and professional inputs.

Finally I would like to thank three very important persons in my life, Michael, Gyða and Gunvor for their very valuable support.
Summary

Large amounts of materials are used in the road sector. The use of virgin materials predominates, but recycled materials are used increasingly. Construction of new roads often implies considerable interference with the environment, both related to the alignment of the road and the procurement of the large amounts of natural aggregates needed for the construction. Residues from waste incineration, especially bottom ash, can be utilized in road construction. In Denmark, approximately 80% of the 640 000 tons of bottom ash generated annually are utilized for construction purposes. The use of residues promotes the goals of minimizing the use of natural resources. However, many residues have a chemical composition that differs considerably from that of conventional materials, and when in contact with water constituents might leach from the materials into the environmental compartments. Introduction of residues into the road area therefore calls for augmented awareness of the environmental impacts. Laboratory leaching tests and field tests have been used to both estimate leaching from residues and for comparison with conventional materials. Assessment methods, such as risk assessment and life cycle assessment, assessing the overall environmental impacts related to the residues have been suggested as a means of evaluating the consequences of recycling in broader perspective.

A new life cycle assessment model for road construction and disposal of residues, named ROAD-RES, has been developed. The model has two purposes: (i) to evaluate the environmental impacts and resource consumption in different life cycle stages of road construction with virgin materials and residues from waste incineration; (ii) to evaluate and compare two disposal methods for waste incineration residues, namely landfilling, and utilization in roads. Methods to predict the leaching from materials as well as the distribution of leached constituents into the five environmental compartments (air, soil, groundwater, fresh surface water and marine surface water) have been developed and preliminary values are provided. The model includes a new characterization method for contamination of groundwater due to leaching of salts; this method is named Potentially spoiled groundwater resource. In addition, characterization factors for Human Toxicity through groundwater due to emissions of heavy metals have been calculated. To account for the long-term leaching, the model includes a new impact category: Stored Ecotoxicity in water and soil that accounts for the presence of heavy metals and very persistent organic compounds that in the long term might leach.

The ROAD-RES model has been used in the assessment of two hypothetical case studies: disposal of municipal solid waste incineration (MSWI) bottom ash, and construction of secondary road with and without MSWI bottom ash. The outcomes of the cases studies have shown that the model is useful for making comparisons of different options, for both road constructions and disposal of residues. The model has been thoroughly tested for errors, both in the calculation method of the model and the data available in databases.
Dansk sammenfatning

ROAD-RES er en ny livscyklusvurderingsmodel for vejbygning og bortskaffelse af restprodukter som er blevet udviklet på Danmarks Tekniske Universitet. Modellen har to overordnede formål; (i) at evaluere de potentielle miljøpåvirkninger og forbrug af ressourcer i vejens levetid, hvor der både kan anvendes naturlige materialer og restprodukter fra affaldsforbrænding; (ii) at evaluere og sammenligne to bortskaffelsesmetoder for restprodukter fra affaldsforbrænding, nemlig deponering og genanvendelse i vejsektoren. I forbindelse med udviklingen af modellen har der været udviklet metoder for at estimere den langsigtede udvaskning af komponenter fra materialerne og distribution af dem i miljøet (luft, jord, grundvand, ferskvand og marint vand). Modellen indebærer en ny karakteriseringsmetode for forurenning af grundvand på grund af udvaskning af salte. Denne metode kaldes potentielt ødelagt grundvandsressource. Endvidere er der blevet beregnet karakteriserings faktorer for human toksicitet via grundvand for emissioner af tungmetaller til grundvand. For at evaluere miljøpåvirkningerne fra den langsigtede udvaskning af tungmetaller og persistente organiske komponenter anvender modellen en relativt ny miljøpåvirkningskategori som kaldes potentielt deponeret økotoksicitet via vand og jord (på engelsk Stored Ecotoxicity).

ROAD-RES modellen har været anvendt til at vurdere to hypotetiske scenarier; (i) bortskaffelse af slagge fra affaldsforbrænding i deponi og veje; (ii) anlægning og vedligeholdelse af en landevej med og uden slagge som bundsikringslag. Resultaterne fra disse scenarier har vist at modellen er et værdifuldt værktøj, når forskellige muligheder indenfor både vejbygning og bortskaffelse af restprodukter skal evalueres og sammenlignes. Modellen har været grundigt kvalitetssikret for fejl, både mht. beregningsmetoder men også mht. de data som er tilgængelige i databasen.
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1 Introduction

The waste hierarchy is an important tool in the waste management policy in many countries where prevention of waste production has the highest priority. For the waste management options, recycling ranks higher than incineration with energy recovery, and landfilling ranks the lowest (Danish EPA, 1999). The annual production of waste in Denmark was roughly 13 million tons in 2003. Approximately 66% was recycled, 26% incinerated and 8% landfilled (Danish EPA, 2005). The 3.3 million tons that are incinerated result in a yearly production of municipal solid waste incineration (MSWI) residues of approximately 0.73 million tons; bottom ash constituting approximately 0.64 million tons; fly ash and air pollution control residues 0.09 million tons (Danish EPA, 2005). Approximately 80% of the bottom ash is recycled in Denmark, while the remaining part of the residues is landfilled. The bottom ash is landfilled in Denmark while the other residues are disposed of in quarries and old mines in Norway or Germany (Danish EPA, 2005).

Recycling of bottom ash is restricted by the statutory order for recycling of residual products and soil in building and construction work (Ministry of Environment and Energy, 2000). According to the statutory order, the residual product must fulfill certain requirements for total content and leachability of heavy metals and salts; this is predicted in a batch leaching test with liquid to solid ratio of 2 l/kg (Ministry of Environment and Energy, 2000). Astrup and Christensen (2005) reported that for Danish bottom ash, the leaching of several constituents occasionally exceeds or is close to the threshold values of the statutory order. Leaching of salts (Cl, Na and SO₄) and heavy metals such as Cu, Cr, and to some extent As, Ni, Cd and Pb are usually the most problematic constituents.

Although many countries are rich in natural aggregates and rock material, these materials are non-renewable resources. Their extraction is not only energy consuming; it often implies considerable interference with the environment. Sustainable use and management of resources is an important global issue. It has been proposed that the total environmental impact associated with the entire life cycle of raw materials should to be considered in the EU (Moll et al., 2003). Furthermore the use of alternative materials in road constructions should be encouraged (Reid et al., 2001). Denmark is rich in natural aggregates, while rock material is rarer. The yearly extraction of natural aggregates in Denmark is more than 30 million m³; from this approximately 65% is used in the road sector (Statistics Denmark, 2003). In addition to this amount, rock materials are imported from Sweden and Norway for use in the road sector.

Construction of new roads often implies considerable interference with the environment, related to both the alignment of the road and the procurement of the large amounts of natural aggregates needed for the construction. Increased environmental awareness within the road sector has focused on minimization of the use of resources and transportation of materials. Although use of virgin materials predominates in the road sector, use of recycled materials is increasing. There is a general political will in the European countries to encourage the use of alternative materials and this is expressed in legislations, action plans and directives. Most countries have set targets for recycling and employ landfill tax to prevent landfilling. Some countries have even introduced or are considering introducing a tax on natural
materials (Reid et al., 2001). Economic factors (related to the transport and treatment of alternative materials) can, however, be a barrier for the use of residues, especially in countries that are rich in natural aggregate (Reid et al., 2001).

Many residues have a chemical composition that differs considerably from that of conventional materials, and when in contact with water constituents might leach from the material into the environmental compartments. Introduction of residues into the road area therefore calls for augmented awareness of the environmental impacts. Issues concerning sustainable recycling of residues in roads and constructions have been discussed at several international conferences (Norwegian Public Roads Administration, 2005, Wascon, 2003, Eighmy, 2001) and several approaches have been proposed and applied for the evaluation of the environmental impacts from residues.

Concentrations of constituents leaching from residues applied in roads have been measured in several field tests (e.g. Bruder-Hubscher et al., 2001, Lind et al., 2001, Hartlén et al., 1999, Fällman, 1997). Field experiments are valuable for gathering information on both the technical and environmental aspects of recycling residues. The leaching process of residues recycled in roads or disposed of in landfills has a very long time horizon, tens to many thousands of years (Hellweg, 2000, Sundquist, 1999). Apart from being time consuming and therefore resource demanding, field tests of several years can give information on only the initial stage of leaching.

Consequently, the use of accelerated laboratory leaching tests has been suggested and generally accepted as a method to estimate the potential leaching from residues (Kosson et al., 1996, Chandler et al., 1997, Kosson et al., 2002). Several types of leaching tests can be used to predict the potential leaching; availability test, column leaching test, batch leaching test, pH-dependent batch leaching test, and tank leaching test (Chandler et al., 1997, Kosson et al., 2002). Column leaching tests are believed to provide the most detailed simulation of the actual leaching behavior, while leaching tests with high liquid to solid (L/S) ratios (such as availability tests at L/S-ratio of 100 or 200 l/kg) are of limited value for road construction applications (Reid et al., 2001).

It has been mentioned that the results from laboratory leaching tests alone might not be adequate to predict the impacts of recycling and that they should be applied together with broader evaluations of the impacts on the environment and humans, such as risk assessment or life cycle assessment. As an example, the threshold values for leaching properties in the Danish statutory order for recycling of residual products and soil in building and construction work have been developed from evaluation of general disposal scenarios based on risk assessment (Dahlstrøm and Rasmussen, 1999). It has, however, been pointed out that since risk assessment requires case-specific data, it cannot be applied for the use of materials in more general terms (Lidelöw, 2004).

Life cycle assessment (LCA) is a method that can be used to assess the potential environmental impacts of a material for its total life cycle (Wenzel et al., 1997). LCA can be used to show where in the life cycle of the material the potential impacts are the greatest and, for example, what constituent in the material or process related to the material contributes with the greatest impacts. LCA has been used in several countries to assess the environmental impacts related to road construction (Stripple, 1995,
Häkkinen and Mäkelä, 1996, Danish EPA, 1997, Svingby and Båtelsson, 1999), and also for assessment of recycling of residues in road construction (Olsson et al., 2005, Mroueh et al., 2000, Mroueh et al., 2001). It has been suggested that life cycle assessment has a good potential for use in planning of the strategic level of recycling residues (Lidelöw, 2004).

The aim of this thesis is to improve the conditions for decision-making in relation to sustainable management in the road sector and disposal of residues from waste incineration; accordingly an LCA-model has been developed that can be used for two purposes:

1) To assess the environmental impacts related to road construction with both conventional materials and residues.

2) To assess the environmental impacts related to disposal of MSWI residues in landfills and recycling in roads.
2 Road construction

Considerable amounts of resources are used in the road sector: in the construction of new roads and in the operation, maintenance and upgrading of the existing road network. In addition to the consumption of resources, the road systems contribute to different environmental impacts, such as pollution of the surrounding environment and interference with the landscape.

In this chapter, the road constructions that were included in the model are briefly outlined in terms of their structure, materials involved, water movement and the life cycle stages.

2.1 Types of road construction and structure

Three different road constructions were included in the model: roads, parking areas and embankments. Figure 1 shows the structure of the road constructions in the model. These three types of road construction were chosen since they constitute the main part of the Danish road network and were seen as important in terms of recycling of residues.

![Figure 1: Structure of the road constructions in the model: secondary road, parking area and embankment.](image)

Roads

The road pavement is constructed in several material layers, both unbound granular layers and bound layers that are either bound by bitumen or cement. Horizontally, a road is divided into different road elements that serve the various means of traffic (vehicles, bicycles and pedestrians) and other purposes such as central reserves that separate oncoming traffic. In general, the vertical structure of roads differs considerably, since it depends on both the road elements included and the traffic load of the road.

Figure 2 shows a traditional structure of the vertical layers of a road. The pavement is constructed on the top of the subgrade. The sub-base layer and the lower base course layer are generally granular layers and the higher base course layer and the wearing course are bound layers.
The following five different types of road were chosen for the model:

- Motorway
- Primary road
- Secondary road
- Urban road
- Gravel road

The roads all differ in terms of the number and thickness of the vertical layers and the number of road elements included in the roads. As an example, a typical Danish 4-lane motorway has a total width of 32m, a thickness of 1m and includes four road elements (lanes, hard shoulder for safety use, shoulders and central reserve), while a secondary road has a total width of 17m, a thickness of 0.7m and includes four road elements (lanes, reserves, shoulders and bicycle paths) (Birgisdóttir, 2005).

Parking areas
The vertical structure of parking areas is similar to roads and has a number of unbound granular layers and bound layers.

Embankments
In the model, the term embankment is understood as a trapezoid construction that can either be placed next to roads and serve as a landscaping noise barrier or be placed beneath a road pavement and serve as fill to obtain the required alignment of the road.

The number of materials used in the construction of an embankment can vary considerably, especially if residues or secondary materials are used. The general assumption for this project was that an embankment could maximally be constructed using three materials: a bottom layer, fill and cover, and that all materials were granular materials.

2.2 Main materials
Both bound and unbound materials are used in the construction of the pavement. The bound materials can be either bituminous or concrete materials. However, the use of bituminous materials predominates in Denmark. The unbound materials used are crushed rock, gravel and sand. Denmark is rich in gravel and sand materials, and road construction sites are often close to quarries. Crushed rock is rare and is mainly imported from Sweden and Norway.
The use of virgin materials predominates in the road sector but many types of residues and secondary materials can be applied. In Denmark, reclaimed asphalt material is commonly recycled in the production of new asphalt material, and fly ash from coal power plants is applied in cement production (Pihl and Milvang-Jensen, 2001). Other residues that can enter the road sector are crushed concrete, bottom ash from waste incineration, steel slag etc (Pihl and Milvang-Jensen, 2001).

After the construction of the road, several other materials are added to the road area in the form of road equipment such as signs, road lighting, safety fences, road markings etc.

2.3 Water movement

Water enters the pavement despite roads being designed with the purpose of preventing it (Apul et al., 2002). Most free water is expected to enter pavements through joints, cracks and pores in the paved road surface (O’ Flaherty, 2002) and through unpaved shoulders (Apul et al., 2002). Some water can also enter pavements from backups in ditches, pores in the road surface (O’ Flaherty, 2002), the melting of ice during freezing/thawing cycles, capillary action and seasonal changes in the water table (Apul et al., 2002). Bituminous and concrete surfacings are expected to act as impermeable barriers to infiltrating surface water. However, due to various design and construction techniques, unsealed joints in concrete roads and development of cracks over time, significant amounts of water can enter the pavement and subgrade (O’ Flaherty, 2002).

The water movement into unpaved roads and embankments serving as noise barriers depends on the permeability of the granular materials used for the construction. Noise barriers with residues and secondary materials are often constructed with liners to prevent water entering the material, which reduces the water movement considerably. In these cases the water infiltration depends on the permeability of the liner, and in the long-term perspective on the condition of the liner. Water entering embankments that serve as fill beneath the road depends on the amount of water entering the pavement and the distance from the groundwater level. The groundwater level affects moisture conditions in the pavement and subgrade if it is within approximately six meters from the surface (Apul et al., 2002). If embankment fills include residues, these are also often constructed with liners.

Water entering the road is important in the evaluation of the potential leaching from residues used in road construction. Although water movement in roads has been investigated in many specific cases as described in Apul et al. (2002), superior knowledge is lacking in terms of general modeling of how much water enters the road area depending on the road structure and condition (Reid et al., 2001). A general estimate of an infiltration rate of 10% of the annual precipitation through asphalted roads has often been used (Kosson et al, 1996, Baldwin et al., 1997, Reid et al., 2001). Olsson et al. (2005), however, used an estimate of approximately 2% of the annual precipitation in their modeling and Mroueh et al. (2000) used approximately 1%. Field observations have, however, shown infiltration of 20% of the annual precipitation (Bruder et al., 2001). For road under construction, while the embankment is not covered, Baldwin et al., (1996) suggested that at least 20% of the annual precipitation should be used in modeling.
2.4 Life cycle stages of road constructions

A road construction can principally be divided into the three stages that define its life cycle:

- Construction stage
- Operation and maintenance stage
- Demolition stage.

Construction stage

In the construction stage, the terrain of the road alignment is prepared in terms of removal of buildings, vegetation, topsoil and unqualified soil for the road (such as soft soil). Afterwards, soil can be removed within the road area, removed from the road area and added to the road area and constructed to reach the required alignment of the subgrade of for the road construction. Construction of an embankment that serves as fill to reach the required alignment can be included in this part of the construction stage. The drainage and water collection system is then usually constructed, followed by the construction of the pavement. The construction stage is finalized by adding different road equipment, such as road lighting, signs, safety fences etc.

Operation and maintenance stage

The operation and maintenance stage, which endures during the service life of the construction, includes different activities that all serve the purpose of keeping the road construction in safe and acceptable condition during its service life. These activities imply maintenance of the pavement and road equipment, cleaning and maintenance of vegetation near the road and winter maintenance in terms of road salting and snow-clearance.

Demolition stage

The development of the road network during the last century has been a continuous expansion of the existing road system, and therefore complete demolition of roads has been rare. However, a road construction can reach an end in its service life. When a road construction reaches this stage in the life cycle, the general procedure has been to either let the materials in the pavement remain in place or to demolish the road and dispose of or recycle the materials in the pavement.
3 Residues from waste incineration

Waste incineration reduces the volume and weight of the waste: volume by approximately 90% and weight by approximately 70-80%. The waste incineration residues are a product of the incineration process and products of the treatment of the stack gasses (Chandler et al., 1997). The amount and quality of the residues can vary and depend on the incineration and gas-cleaning technology applied as well as the composition of the waste.

This chapter provides a short overview of the types of waste incineration residues; their typical chemical composition; leaching properties; and treatment and disposal methods in Denmark.

3.1 Types of MSWI residues

The most common streams of residues from waste incineration are bottom ash, fly ash and air pollution control residues (APC-residues). Other residues are grate siftings, boiler ash and economizer ash, which are usually mixed with main residues.

**Bottom ash**

Bottom ash (which is a product of the combustion process) consists of the non-combustible and un-combusted fractions of the waste. It is formed while the waste is transported on the moving grate through the combustion chamber. Bottom ash is usually very inhomogeneous as it leaves the incineration process; it includes fractions of un-combusted waste, such as paper and plastic, and non-combustibles such as scrap metals, concrete, ceramics, glass etc. Bottom ash is the largest residue stream from the incineration process, typically 150-300 kg/ton of waste incinerated and accounting for 85-95% of all the residues generated (Chandler et al, 1997).

**Fly ash**

Fly ash (which is also a product of the combustion process) consists of relatively fine ash particles that are entrained in the flue gas from the boiler and recovered in electrostatic precipitators or fabric filters. Depending on the APC-technology applied in the incineration plant, fly ash is either collected separately or mixed with the APC-residues. Separately collected fly ash can however be mixed with the APC-residue. The amount of fly ash is usually 10-30 kg/ton of waste incinerated (Chandler et al., 1997).

**Air pollution control residues**

APC-residues (which are a reaction product from neutralization of acidic components in the flue gas with lime) consist of the reaction product and a part of the un-reacted lime. The residue might be in solid form or as sludge depending on the flue gas technology applied. In Denmark, the practice is that APC-residues are often combined with the fly ash. The amount of APC-residues is usually 5-20 kg/ton of waste incinerated (Chandler et al., 1997).

**Other residues**

Grate siftings (approximately 5 kg/ton waste) is the material that passes through the openings in the grate, either because of the small size of the material or because it
melts. This fraction is usually collected and mixed with bottom ash (Chandler et al., 1997). Boiler ash (approximately 5 kg/ton waste) consists mostly of larger ash particles that are removed from the flue gas in or immediately outside the boiler. In Denmark, this fraction is usually mixed with the bottom ash (Christensen, 1998). Economizer ash consists of finer ash particles collected from the flue gas in the economizer. This fraction is usually mixed with the flue gas (Christensen, 1998). Grate siftings, boiler ash and economizer ash are not discussed further in this thesis.

3.2 Chemical characterization of MSWI residues

Knowledge of the chemical characterization of the residues is important when their disposal is considered. The residues are generally alkaline (pH between 9 and 13), with a considerably high buffer capacity and therefore good ability to maintain the alkaline pH-level. The pH can, however, change as the residue is in contact with water and atmosphere.

The chemical composition differs greatly between the three main residues from waste incineration. Metals that are volatile at typical temperatures in the combustion chamber, such as Cd, Hg, Pb and Zn, and compounds, such as HCl and SO4, are more likely to be found in high concentrations in the fly ash and APC-residues (Chandler et al., 1997). Bottom ash, however, often contains Cu and Ni in higher amounts. Table 1 shows examples of the solid content of selected constituents in Danish residues together with Danish gravel pit materials. It should be noted that there is a large variation in the composition of the residues, both between technologies, incineration plants and samples (Astrup and Christensen, 2005).

Table 1: Solid content of selected constituents in Danish bottom ash, fly ash, semi-dry APC-residues and gravel pit materials.

<table>
<thead>
<tr>
<th></th>
<th>Bottom ash1</th>
<th>Fly ash2</th>
<th>Semi-dry APC-residues3</th>
<th>Gravel pit materials4</th>
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<td>Hg</td>
<td>mg/kg</td>
<td>0.1</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Mn</td>
<td>mg/kg</td>
<td>900</td>
<td>900</td>
<td>500</td>
</tr>
<tr>
<td>Ni</td>
<td>mg/kg</td>
<td>140</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>Pb</td>
<td>mg/kg</td>
<td>1000</td>
<td>7000</td>
<td>5000</td>
</tr>
<tr>
<td>Zn</td>
<td>mg/kg</td>
<td>3000</td>
<td>20000</td>
<td>20000</td>
</tr>
</tbody>
</table>

1: Average values for samples from I/S Vestforbrænding (4-107 samples 1993-2001) from (Astrup and Christensen, 2005)
2: One sample from I/S Vestforbrænding from (Lundtorp, 2001)
3: One sample from I/S Amagerforbrænding from (Lundtorp, 2001)
4: Average values for Danish gravel pit materials (4 samples) from (Birgisdóttir, 2005)

3.3 Leaching properties of MSWI residues

Knowledge of the leaching properties of the residues is important when their disposal is considered. Leaching of heavy metals and salts from residues placed in landfills or used in construction is characterized by very long time horizons: salts leaching over decades and heavy metals over many thousands of years (Hellweg, 2000, Sundquist,
1999). The total leaching process for residues can therefore not be predicted by field measurements, since these give information on only the initial stage of the leaching process. Leaching is therefore usually estimated in accelerating laboratory leaching tests. Leaching from granular materials is quantified in terms of the total availability for leaching, and solubility or availability controlled leaching as a function of the liquid to solid ratio. Leaching from monolithic materials is quantified in terms of the total availability for leaching, and diffusion controlled leaching as a function of the surface area of monolith in contact with water. Several types of leaching tests have been developed to predict the long-term leaching, both in terms of the amount of water in contact with the residue and how changes in the pH level in the residue alter the leaching properties (Kosson et al., 2002).

Batch leaching tests with a liquid to solid ratio of 2 l/kg are the most frequently used tests in Denmark to predict the leaching properties of residues (CEN, 2002). These tests are used in Denmark for regulating utilization of bottom ash in constructions (Ministry of Environment and Energy, 2000). Table 2 shows examples of concentrations of selected elements in an L/S 2 l/kg batch leaching test with Danish residues and gravel pit materials.

<table>
<thead>
<tr>
<th>Element</th>
<th>Bottom ash</th>
<th>Fly ash</th>
<th>Semi-dry APC-residues</th>
<th>Gravel pit materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca mg/l</td>
<td>290</td>
<td>3100</td>
<td>31000</td>
<td>37</td>
</tr>
<tr>
<td>Cl mg/l</td>
<td>560</td>
<td>45000</td>
<td>85000</td>
<td>44</td>
</tr>
<tr>
<td>Na mg/l</td>
<td>500</td>
<td>1300</td>
<td>13000</td>
<td>4.2</td>
</tr>
<tr>
<td>SO₄-S mg/l</td>
<td>220</td>
<td>870</td>
<td>200</td>
<td>&lt;2.0</td>
</tr>
<tr>
<td>As µg/l</td>
<td>3.4</td>
<td>11</td>
<td>13</td>
<td>&lt;2.9</td>
</tr>
<tr>
<td>Ba µg/l</td>
<td>130</td>
<td>60</td>
<td>13000</td>
<td>17</td>
</tr>
<tr>
<td>Cd µg/l</td>
<td>&lt;0.16</td>
<td>36</td>
<td>5.6</td>
<td>0.70</td>
</tr>
<tr>
<td>Cr µg/l</td>
<td>27</td>
<td>8.6</td>
<td>16</td>
<td>&lt;1.5</td>
</tr>
<tr>
<td>Cu µg/l</td>
<td>1400</td>
<td>39</td>
<td>12000</td>
<td>&lt;0.43</td>
</tr>
<tr>
<td>Hg µg/l</td>
<td>&lt;0.067</td>
<td>0.49</td>
<td>1.8</td>
<td>-</td>
</tr>
<tr>
<td>Mn µg/l</td>
<td>&lt;0.95</td>
<td>0.2</td>
<td>0.86</td>
<td>5.6</td>
</tr>
<tr>
<td>Ni µg/l</td>
<td>14</td>
<td>1.0</td>
<td>3.6</td>
<td>&lt;0.94</td>
</tr>
<tr>
<td>Pb µg/l</td>
<td>210</td>
<td>290000</td>
<td>240000</td>
<td>&lt;0.22</td>
</tr>
<tr>
<td>Zn µg/l</td>
<td>96</td>
<td>4800</td>
<td>22000</td>
<td>&lt;1.5</td>
</tr>
</tbody>
</table>

1: Average values of upgraded bottom ash for samples from I/S Vestforbrænding (40 samples 2001-2002) from (Birgisdóttir, 2005)
2: One sample from I/S Vestforbændring from (Lundtorp, 2001)
3: One sample from I/S Amagerforbrænding from (Lundtorp, 2001)
4: Average values for Danish gravel pit materials (4 samples) from (Birgisdóttir, 2005)

This example shows a high concentration of salts leached from semi-dry APC-residues, approximately three orders of magnitude higher than for gravel pit materials. Concentrations of the heavy metals, Cr, Cu and Ni were generally high in leachates from bottom ash, while concentrations of As, Cd, Pb and Zn were high in fly ash and semi-dry APC-residues. For all constituents, concentrations were the lowest in leachates from gravel pit materials, except for Cd, where concentration of Cd in leachate from gravel pit materials was higher than from bottom ash.

3.4 Treatment and disposal of MSWI residues

In Denmark, bottom ash is generally utilized in the road sector (Astrup and Christensen, 2005), while fly ash and APC-residues are currently exported and disposed of in quarries and old mines in Norway and Germany (Astrup, 2005).
The Danish Road Directorate recommends utilization of bottom ash as sub-base layers in smaller roads and fill in embankments (Pihl et al., 2004). Bottom ash is upgraded before utilization in a process that involves sorting in several fractions and a carbonation process. The sorting process generally includes sorting into; (i) upgraded bottom ash (<50 mm) for utilization, (ii) ferrous-metals for recycling, and (iii) residue (>50 mm) for landfilling (Birgisdóttir, 2005). Recently, the incineration plants have also experimented with sorting of non-ferrous metals, such as copper, zinc and aluminium. The carbonization process varies as minimum for 3 months and implies uptake of carbon dioxide from the atmosphere.

Several treatment methods have been developed for fly ash and APC-residues. Examples of these are extraction and separation, chemical stabilization, solidification and thermal treatments. Only a minor part of the treatment technologies are commercially available and are applied only in a laboratory or on a pilot-scale (Astrup, 2005). Currently, the residues are not treated in Denmark before export to Norway or Germany. Prior to disposal in Norway, the residues are mixed with acidic residues and thereafter solidified with gypsum. Prior to disposal in salt mines in Germany, residues are solidified with cement (Astrup, 2005). Both the Danish EPA and the incinerators are currently evaluating other possibilities with the aim of developing a domestic solution for treatment and disposal of residues.
4 Life cycle assessment

Life cycle assessment (LCA), also known as cradle-to-grave assessment, is a method for environmental assessment of products or systems where all contributions in the whole life cycle of the product/system are quantified and accounted for in the assessment (Wenzel et al., 1997). This chapter gives a brief introduction to the LCA method and aspects that are important when roads and residues are evaluated in LCA.

4.1 The LCA method

LCA includes inputs of energy and resources as well as outputs of waste and emissions to air, water and soil. Figure 3 shows the phases of an LCA according to the ISO 14040-14043 framework of LCA (ISO, 1997).

![Figure 3: Life cycle assessment framework – phases of an LCA (ISO, 1997)](image)

The objective of an LCA study and the system boundaries are defined in the goal and scope (Wenzel et al., 1997). In the inventory, all inputs and outputs are quantified as amounts. Emissions are considered as pulse emissions of the actual amounts released into different environmental compartments (air, water and soil). The concentrations of the constituents entering into the environmental compartments and the time horizon for the release are therefore not considered. In the impact assessment, the list of resources and emissions are aggregated into (i) consumption of resources and (ii) environmental impacts. Examples of environmental impacts are Global Warming, Acidification and Ecotoxicity\textsubscript{water}. The unit of resource consumption is amount (usually kg), while units of environmental impacts are related to the actual impact (e.g. kg CO\textsubscript{2}-equivalents for Global Warming, kg SO\textsubscript{2}-equivalents for Acidification and m\textsuperscript{3} water for Ecotoxicity\textsubscript{water}). The impact assessment can further be normalized by the impact related to the impact of one person pr. year yielding units for both resources and environmental impacts in Person Equivalents (PE) and finally weighted according to political goals.

4.2 Residues and roads in LCA

Life cycle assessment has previously been used in relation to environmental assessment of road constructions with virgin materials (Stripple, 1995, Stripple, 2001,
Häkkinen and Mäkelä, 1996, Danish EPA, 1997, Svingby and Båtelsson, 1999), in relation to evaluation of the environmental impacts of recycling residues in roads (Mroueh et al., 2000, Mroueh et al., 2001 Olsson et al., 2005), and to evaluate the impacts of landfilling residues (Sundquist, 1999, Hellweg, 2000).

The most important environmental impacts that might arise when residues are disposed of in landfills or utilized in roads are the impacts related to the presence of heavy metals and salts and the potential long-term leaching. Due to the assumption of pulse emissions, existing LCA models are not well geared to account for long-term leaching. The assumption of pulse emission means that in LCA it cannot be distinguished between the impacts from low emissions in the long term and high emissions in the short term as long as the total amount leached is the same. The predicted time horizon for the potential leaching is important, since the amount of constituents leached increases with time. Another important time horizon for the evaluation of the road is length of service life included in the assessment, since the materials used for maintenance of the road also increases with time and therefore also the resource consumption and environmental impacts.

Time horizons previously used in LCA, concerning both the service life of the road and the time horizon for the evaluation of leaching, vary considerably between the different assessments, which makes it more complicated to compare the results of different studies. The Danish Road Directorate often uses a time frame of approximately 20 years in the long-term planning of roads. Some of the road materials might not, however, have reached the end of their life cycle after 20 years. Longer time horizons need to be introduced to road planning when life cycle perspectives are used for environmental evaluation of materials. Several different time horizons for the service life have been used in previous life cycle assessments of roads: 40 years in Stripple (2001), 50 years in Mroueh et al. (2001) and 100 years in Olsson et al. (2005).

It has also been suggested that even longer time horizons are needed when the impacts related to leaching from residues are assessed. However, no common framework for the time horizon for leaching (Finnveden, 1999, Sundquist, 1999, Bjarnadóttir et al., 2002) has been reached. Two time horizons have been proposed for application: (i) a relatively short time frame representing the surveyable time horizon (e.g. 100 years) and (ii) an infinite time horizon including the total leaching time horizon (Bjarnadóttir et al., 2002). Hansen et al. (2004) presented a new environmental impact category, Stored Ecotoxicity, which accounts for the occurrence of metal compounds and very persistent organic compounds in landfills and other deposits after the end of the surveyable time horizon (usually 100 years). The environmental impact is assessed as the amount of the compounds with the potential to cause ecotoxicity in water and soil in the infinite time horizon. The same characterization factors are used for Stored Ecotoxicity and Ecotoxicity, while the normalization reference is different.

The main concerns have focused on leaching of only heavy metals and the impacts heavy metals might have on the surroundings (Sundquist, 1999, Hellweg, 2000, Mroueh et al., 2001). Mroueh et al. (2000) estimated the leaching of Cl and SO$_4^{2-}$, but the real impacts in the environment were not modeled. Residues contain considerable amounts of salts, and salts are also used in large amounts in the operation of roads. Although salts are not toxic to humans and the ecosystem, the leaching of salts can
contaminate groundwater and give salt concentrations that render it unqualified as drinking water. Leaching of salts from bottom ash, especially Cl, SO$_4^{2-}$ and Na, has also been problematic according to the threshold values of the statutory order.
5 The ROAD-RES model

The ROAD-RES model is a life cycle assessment tool for road construction and
disposal of residues. It can be used for two purposes:

1) As an environmental management decision support tool for the road sector,
   assisting in both designing of new roads and operation and maintenance of
   existing roads.

2) As a decision support tool to manage sustainable disposal of residues, either
   by landfilling or utilization in roads.

The goal was to create an LCA-model that was user friendly, transparent and flexible,
while at the same time being capable of handling the complex evaluation of the
potential long-term leaching from the residues. It was decided to develop ROAD-RES
as a software program using C++ and PARADOX database.

This chapter gives an introduction to the ROAD-RES model. The scope and structure
are first briefly described followed by the two modeling possibilities in ROAD-RES:
modeling road constructions, and modeling disposal of residues. A more detailed
description of the model is found in Birgisdóttir et al., (I) and Birgisdóttir (VI),
respectively.

5.1 Scope

The scope definition of a scenario modeled in ROAD-RES can follow the scope
definition suggested in the ISO standard for LCA (ISO, 1997), where the goal of the
study, system boundaries and the functional unit are to be defined and allocation
issues should be considered. In ROAD-RES, the user defines the scope of the study
during modeling the scenario by choosing the functional unit of the scenario (e.g.
construction of 10km of 4-lane motorway with operation and maintenance of 100
years), and by choosing the different materials, transport means and distances,
maintenance strategies etc. However, to ensure consistent scope definition throughout
the scenario, it is recommended that the user defines the goal and scope of the study
beforehand. The model has a specific documentation sheet for the scope definition.
The details of the data material are also important for the scope definition, e.g. if the
data for production of the machines used for road construction are included, or if data
for landfill site construction before landfilling are included. The model has flexible
system boundaries since the user can add more detailed data and thus expand the
system boundaries of the scenario.

5.2 Structure

The overall model structure of ROAD-RES is shown in Figure 4. The road system
and the landfill are the core systems in the model, and extraction of resources,
upgrading of resources and residues, energy production and transport are upstream
processes. These processes cause releases of emissions and waste that contribute to
different environmental impacts. The model provides an inventory of all
environmental exchanges in the life cycle of the road or landfill, and a life cycle
impact assessment where the environmental exchanges are transformed to
contributions to impact categories and consumption of resources.
Figure 4: Overall model structure of ROAD-RES.

The ROAD-RES model can be divided into two parts: a road construction part and a disposal part for residues. The road construction part covers the total life cycle of different road constructions where both conventional materials and residues can be used as construction materials. The disposal part covers the life cycle impacts related to the presence of the residue in either landfills or in road construction. Both parts of the model allow comparisons of different scenarios that give the user the possibility of evaluating the effects of different initiatives and changes. Depending on the assessed scenarios, recycling of residues in road construction can substitute natural materials, thus avoiding landfilling. For instance, when two disposal methods for bottom ash are assessed: (i) landfilling of bottom ash and (ii) recycling bottom ash as sub-base layer in road, the recycling in road saves on the use of natural aggregate. The impacts from extraction of aggregate, transport and avoided leaching impacts from natural aggregate can therefore be subtracted in the road scenario.

ROAD-RES includes a set of databases that are used in the scenario calculations. The most important databases are those covering:

- Environmental exchanges: a list presenting resources and emissions included in the model and that in the LCA-databases are linked to different impact categories.
- Unit process datasets: including environmental exchange data for production of materials, upgrading of residues, road construction, landfilling, transport etc.
Leaching profiles for construction materials: including leaching data for both monolithic and granular residues as well as conventional materials (asphalt, concrete and gravel pit material). Transfer coefficients for the distribution of the constituents into different environmental compartments are a part of the leaching profiles.

LCA databases: including impact categories, characterization factors and assessment methods.

EDIP97 (Wenzel et al., 1997, Hauschild and Wenzel, 1998) is the default life cycle impact assessment method in ROAD-RES. The user can, however, supplement the model with other life cycle impact assessment methods, such as Eco-indicator 95 (Goedkopp, 1995), Eco-indicator 99 (Goedkoop and Spriensma, 2000) or CML 2001 (Guinée, 2001). The model can handle an unlimited number of substances and resources that are all included in the inventory. However, to include all substances or resources that are important for the scenario in the impact assessment, the user must ensure that they are linked to an impact category of the assessment method. The model has a feature that easily shows the user if the chosen substance or resource is linked to an impact category.

5.3 Evaluation of leaching in ROAD-RES

Leaching from all road construction materials, both granular and bound materials, and granular materials landfilled can be assessed in the model. Each material has a leaching profile that can be used to estimate leaching during a time horizon chosen by the user.

Leaching from monolithic materials is calculated as a function of the surface area of material that is in contact with water. Diffusion controlled leaching is assumed and increased cracking in the material increases the surface area and therefore also the potential for leaching. Data from 64-day tank leaching tests (NEN 7345) are applied to calculate the potential leaching during the time horizon chosen by the user.

Leaching from granular material is calculated as a function of the liquid to solid ratio in percolation-dominated scenarios. The infiltrated amount is calculated as a percentage of yearly precipitation infiltrated through the materials. Leaching curves describing the concentration of the constituents as a function of the liquid to solid ratio are found in column and batch leaching tests and used to calculate the potential leaching during the time horizon chosen by the user.

Transfer coefficients are used to route the constituents to five different environmental compartments. The amount of constituents that is left in the landfill or road after the chosen time horizon contributes to the new environmental impact category introduced by Hansen et al. (2004): Stored Ecotoxicity. Calculations of leaching in ROAD-RES are explained in Box 1.
Box 1: Calculation of leaching in the RAOD-RES model.

1. Equations and methods for calculating the leached amount during the time horizon chosen by the user.

**Granular materials**

Percollation-dominated scenarios:

Availability or solubility controlled leaching. Leaching curves describing the concentration of constituent X as a function of the L/S-ratio are found from column and batch leaching tests. Equation 1 describes the curve and Equation 2 the amount of the constituent X leached out.

\[
\text{Eq. } 1: \quad C = a \cdot LS^n
\]

\[
\text{Eq. } 2: \quad M = \frac{\alpha}{b + 1} \cdot LS^{\alpha - 1} \cdot V \cdot p
\]

**Monolithic materials**

Flow-around scenarios:

Diffusion controlled leaching. The leached amount of constituent X after the time t is described by Equation 3 (Kosson et al., 1996).

\[
\text{Eq. } 3: \quad M = 2 \cdot A \cdot \frac{1}{100} \cdot \rho \cdot C_x \left( \frac{D_{eq} \cdot t}{\pi} \right)^{1/2}
\]

- \( C_x \): Concentration of constituent X (kg/m³)
- \( M_x \): Amount of constituent X leached (kg)
- \( V \): Volume of the material (m³)
- \( \rho \): Density of the material (kg/m³)
- \( A \): Surface area of monolithic material (m²)
- \( T_x \): Time that material is wetted (%) 
- \( C_x \): Availability of constituent X (kg/kg)
- \( D_{eq} \): Diffusion coefficient for constituent X (m²/seconds)
- \( t \): Time (seconds)

The leached amounts are further calculated in the impact assessment. Leaching of heavy metals contributes to human toxicity and ecotoxicity. As explained in Birgisdóttir et al., (I), leaching of salts is calculated as the potential amount of groundwater resource that can be spoiled, according to the Danish drinking- and groundwater criteria.

2. Routing of constituents into different environmental compartments.

The model routes the leached amount to waste water treatment plant and as emitted amount to the surroundings. The leached amount is routed further into different environmental compartments:

- Groundwater
- Marine surface water
- Soil
- Air

3. Calculations of constituents remaining in the material after the chosen time horizon for leaching.

The amount of constituent X leached out is subtracted from the total amount of the constituent X in the material.

The constituents remaining in the material contribute to the environmental impact category Stored Ecotoxicity to water and soil developed by Hansen et al. (2004).

5.4 Road construction

The ROAD-RES model enables the user to assess environmental impacts and resource consumption in different stages of the road construction and compare several solutions for road design and maintenance options. The user can track where in the life cycle of a road construction environmental impacts are most important, and which materials and processes contribute to the environmental impacts. If residues are used in this part of the model, the environmental impacts from the residue are seen in context with the environmental impacts in the whole life cycle of the road construction. The road construction part includes the following scenario-modules:
- Road
  - Motorway
  - Primary road
  - Secondary road
  - Urban road
  - Gravel road
- Parking area
- Embankment

The scenario-modules for road constructions are based on guidelines from the Danish Road Directorate. The scenario-modules for roads vary with respect to the road elements that are relevant for the different types of road (lanes, shoulders, central reserves etc.). As an example are footpaths and cycle paths in an urban road, while motorways have a hard shoulder for emergency use (Birgisdóttir, VI).

As shown in Figure 4, the life cycle of a road construction is divided into four stages in ROAD-RES.

**Design stage**

The lifetime and length of the construction, width of road elements and thickness of all layers in the cross-section are defined in the Design stage and the materials for the road construction are chosen. The database includes several different road construction materials that can be chosen by the user, and here the user can also add new materials. The model calculates the total volumes (m³) and masses (tons) of materials in the construction and the area (km²) of each group of road elements and as well as that of the total construction. The road elements and materials that are defined in the Design stage are routed further through the different stages in the model.

**Construction stage**

The Construction stage consists of three sub-phases that describe the activities related to the establishment of a new construction in a terrain. The sub-stages are: (i) Earthworks, (ii) Construction of pavement and (iii) Additional work. In the Earthworks, the consumption of energy and materials and disposal of waste related to clearance of the area, preparation of the subgrade and water collection system is modeled. Experiences from several Danish road projects show that the extent of earthwork processes can vary considerably between different road constructions due to disparity of the terrain. In the Construction of pavement, the energy consumption for the establishment of the pavement is modeled by choosing the transport distance, transport means and the machinery for the construction of the pavement. All transport and machinery processes are linked to the materials chosen in the Design stage. Additional work allows the user to include different road equipment such as safety fences, road lamps, road markings etc.

**Operation & Maintenance stage**

The length of the Operation & Maintenance stage is defined in the Design stage, when the lifetime of the construction is chosen. The Operation & Maintenance stage is divided into four sub-stages that describe the most important activities related to keeping the construction in an acceptable condition during its lifetime and the environmental impacts related to leaching from materials. The four sub-stages are: (i)

In the Regular Maintenance, the energy and material consumption and the amounts of waste related to cleaning and maintenance of the road area, equipment and vegetation near roads, as well as energy consumption for road lighting are modeled.

Pavement Maintenance includes renewal of road materials in the lifetime of the road as well as regular maintenance of wearing courses. It is assumed in the model that only monolithic materials are renewed and the frequency of the renewal depends on the lifetime of the material, which is chosen in this part of the model. The materials are directly linked to the materials chosen in the Design stage and it is assumed that the same materials are used in the same thickness throughout the lifetime of the road. There are two options for the renewal process: (a) the materials are removed from the pavement by milling the monolithic material and thereafter disposed of or recycled, or (b) new material is overlaid on the top of the old material.

Winter Service covers energy consumption for road salting and snow clearance as well as consumption of salt and potential emissions related to road salting.

Leaching Aspects provides the assessment of potential leaching from the materials used in the pavement and the distribution of leached constituents into different environmental compartments. In this part of the model, the user chooses if the road will be demolished after its lifetime (and materials removed), or if the materials will remain in place. The user also chooses if leaching is calculated during the road’s lifetime, or for an extended period. This feature allows the user to consider different time horizons for leaching. After the ended time horizon for leaching, the constituents remaining in the materials are assessed as Stored Ecotoxicity.

Demolition stage

Inclusion of Demolition stage is optional in the ROAD-RES model. The Demolition stage consists of two sub-models. The Removal of materials involves energy consumption for machinery and transport related to removal of materials, and disposal or recycling of materials. The materials that were chosen in the Design stage are rooted to the Demolition stage. The Area rehabilitation includes energy and material consumption for rehabilitation processes.

5.5 Disposal of residues

The disposal part includes the disposal of residues in landfills and utilization in different types of road construction. The disposal part of the model quantifies energy consumptions, leaching from the residues and avoided consumption of resources and environmental impacts through recycling of residues. In the disposal part of the model, the environmental impacts included are related only to the residues. This means that for utilization of bottom ash in road, only emissions from the bottom ash are included and all emissions from the other materials in the road construction are excluded. The disposal part of the model enables the user to perform comparisons of environmental impacts and resource consumption when residue is landfilled or recycled in roads.
**Landfilling**

The landfill scenario-module consists of two sub-modules: (i) Materials and Transportation and (ii) Leachate Generation and Collection. The height of the landfill and the amount of residue landfilled are defined. Materials and Transportation covers transport of the residue to the landfill and energy and material consumption during the operation of the landfill. All data are entered per unit residue landfilled (kg) and are multiplied by the amount of material landfilled. The generation of leachate will vary in the different stages of the landfill. As an example, the infiltration can be higher during the landflling process and until the top cover is established. The leachate collection can also vary in the different stages.

The aim with landfilling of waste will usually be to change the operation of the landfill to passive operation after a certain period, eventually 30-50 years. To reflect the different conditions during the active and passive state of the landfill, four different time periods are defined in the model. It is assumed that the leaching mechanism in a landfill can be described by percolation-dominated scenarios. The L/S-ratio is calculated for each of the four time periods.

**Utilization in road constructions**

The utilization of the residues in road constructions includes both granular materials and stabilized residues (e.g. cement stabilized residues). When a residue is utilized in road construction, the user has the option of subtracting the impacts that are avoided from the substituted natural material (both production of materials, transport and leaching). The utilization in road construction consists of one sub-module covering all input parameters for the calculations. The model applies the same procedures for leaching calculations as described for the road construction part.

If the same functional unit is chosen as for the landfilling option (in terms of amounts of residue and time horizon for leaching), the impacts of the two disposal methods can be compared, as shown in Birgisdóttir et al. (I).
6 Application of ROAD-RES

Features of two different applications of the ROAD-RES model are illustrated in hypothetical scenarios for disposal of bottom ash and road construction. This chapter gives a brief overview of the scenarios and the major findings, while the scenarios are described in detail in Birgisdóttir et al. (II) and Birgisdóttir et al. (III).

6.1 Disposal of bottom ash

The case study, presented in Birgisdóttir et al. (II), compared disposal of 4400 tons bottom ash in landfill and recycling as sub-base layer in secondary road. It was assumed that the bottom ash was transported 70 km from the incineration plant to the upgrading site, where it was then upgraded as described in Birgisdóttir (2005) and transported to either the landfill (20 km) or road construction site (50 km). The landfilling height was 8 m while the thickness of the sub-base layer was 0.37 m. The area occupation was therefore approximately 300 m² in the landfill scenario and 7000 m² in the road scenario. Utilization of bottom ash in the road scenario substitutes natural gravel material and the impacts from extraction of gravel were therefore avoided. Leaching was estimated for 100 years in both scenarios, where after the heavy metals remaining in the material were calculated as the impact to Stored Ecotoxicity. Infiltration through landfill was divided into four time periods where infiltration rate and leachate collection could be adjusted to the different stages in the landfill (landfilling process without top cover, landfill in active phase with top cover and leachate collection, landfill in passive stage without leachate collection). Infiltration through road was assumed to be 10% on average throughout the whole period. These assumptions result in L/S-ratio of 2.0 l/kg in the landfill scenario and 13.5 l/kg in the road scenario.

As presented in Figure 5 and discussed in Birgisdóttir et al. (II), the impacts related to leaching of heavy metals dominated the environmental impacts for both scenarios resulting in Ecotoxicitywater of approximately 40 PE (or 10 mPE/ton bottom ash) in the Road scenario and 30 PE (or 7 mPE/ton bottom ash) in the landfill scenario. Close to 90% of the contribution to Ecotoxicitywater was due to leaching of copper in bottom ash. Human Toxicitysoil was the second greatest impact for the Road scenario, mainly due to leaching of arsenic from bottom ash. Other impact categories were mostly related to combustion of fossil fuels. The balance of the constituents leached out during the 100 years showed that less than 1% of all heavy metals were leached out from the bottom ash. Therefore the contributions to Stored Ecotoxicity, which is the impact category that takes into account the potential impacts of the heavy metals in long-term perspectives, were much higher than the impacts during the first 100 years. The impacts were mainly the same for both scenarios, approximately 13 000 PE for Stored Ecotoxicitywater and 600 PE for Ecotoxicitysoil. The major part was related to impacts from copper in bottom ash. These impacts are based on the total content of heavy metals in the material and it is assumed that the heavy metals could potentially contribute to toxicity to the environment. Hellweg (2000) modeled the leaching of metals from landfill with bottom ash in a geochemical model PHREEQC, where the time horizon for leaching of copper was 125 000 years. The modeling did not indicate any increase in the concentration of copper in the leachate until after 55 000 years. Although these models are uncertain due to the long time horizons, they illustrate that a certain pulse emission of the copper remaining in the material is not expected for a
great many years. It could therefore be reasonable to weight these impacts differently from those occurring during the first 100 years.

Figure 5: Normalized environmental impacts (in person equivalents) of the Landfill scenario and Road scenario according to the EDIP97-method.

Evaluation of the resource consumption showed that one of the most important impacts was related to the groundwater resource that could potentially be spoiled by leaching of salts from the bottom ash in the Road scenario, or 1400 PE during the 100 years. Salts were also leached out in the Landfill scenario but since the landfill was assumed to be located near the coast, the salts were not assumed to have an impact on the quality of groundwater. The consumption of clay as a resource could also play a significant role in the landfill scenario if clay did not occur naturally in the area. Utilization of bottom ash in road avoided the use of natural aggregate equal to 420 PE.

Table 3: Normalized resource consumption in the two scenarios (in PE).

<table>
<thead>
<tr>
<th></th>
<th>Landfill</th>
<th>Road</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural aggregate</td>
<td>61</td>
<td>-420</td>
</tr>
<tr>
<td>Clay</td>
<td>3700</td>
<td>0</td>
</tr>
<tr>
<td>Potentially spoiled groundwater resource</td>
<td>0</td>
<td>1400</td>
</tr>
<tr>
<td>Crude oil</td>
<td>18</td>
<td>15</td>
</tr>
<tr>
<td>Natural gas</td>
<td>20</td>
<td>2</td>
</tr>
</tbody>
</table>

Sensitivity analysis was performed to investigate which parameters characterizing the scenario were the most sensitive to the results. Three different parameters were chosen: infiltration, distribution of heavy metals in the environment after leaching from the material, and transport distance. Five different scenarios were chosen for comparison with the original scenarios (named A).

- **Landfill B**: 15% of yearly precipitation was infiltrated in time period 3 and 4 (compared to 30% in Landfill A).
- **Road B**: 5% of yearly precipitation was infiltrated (compared to 10% in Road A).
- **Landfill C**: 45% of yearly precipitation was infiltrated in time period 3 and 4 (compared to 30% in Landfill A).
- **Road C**: 30% of yearly precipitation was infiltrated (compared to 10% in Road A).
- **Landfill D**: Distribution of heavy metals: 99% soil and 1% marine water (compared to 85% soil and 15% marine water in Landfill A).
- **Road D**: Distribution of heavy metals: 99% soil and 1% fresh water (compared to 85% soil and 15% fresh water in Road A).
- **Landfill E**: Transport of bottom ash was 10 km (compared to 20 km in Landfill A).
- **Road E**: Transport was 25 km for bottom ash and 10 km for natural gravel (compared to 50 and 20 km, respectively, in Road A).
- **Landfill F**: Transport of bottom ash was 30 km (compared to 20 km in Landfill A).
- **Road F**: Transport was 75 km for bottom ash and 30 km for natural gravel (compared to 50 and 20 km, respectively, in Road A).

As shown in Figure 6, the sensitivity analysis showed minor changes in the Landfill scenario while major changes were seen for the most important impact category, Ecotoxicity\textsubscript{water}. Increasing the infiltration of water into the road from 10% of the precipitation to 30% increased the Ecotoxicity\textsubscript{water} from 40 PE to 70 PE. Changing the distribution of heavy metals in the environmental compartments from the original scenario decreased the Ecotoxicity\textsubscript{water} from 40 PE to 5 PE (or into the same order of magnitude as the impact to Human Toxicity, Global Warming, Nutrient Enrichment and Acidification). The distribution of heavy metals in the environmental compartments (fresh surface water and soil) after leaching from the material was based on calculations on sorption of heavy metals in soil. The calculations indicated that the heavy metals migrated only a few centimeters in the soil during 100 years and therefore it is unlikely that to any large extent they would end up in the water compartments. Rather conservative assumptions were chosen, however, for the original scenario, assuming 15% of all heavy metals ending up in the fresh surface water compartment in the Road scenario and in the marine surface water compartment in the Landfill scenario. The distribution chosen in the sensitivity analysis (scenario D) was assumed to be more likely for the actual situation.
To evaluate how the quality of the bottom ash affected the results of the scenarios, the landfill scenario was modeled using the leaching profile for bottom ash from an incineration plant other than that used in all scenarios in Birgisdóttir et al. (II) and Birgisdóttir et al., (III). The most important difference in the leaching profile of the bottom ash from the two incineration plants was the lower leaching of copper in the new leaching profile. As illustrated in Figure 7, which shows the normalized environmental impacts from Landfill A (identical to Birgisdóttir et al. (II)) and Landfill B (new leaching profile), the quality of the bottom ash can have a significant influence on the results of the assessment. The impacts to Ecotoxicity\textsubscript{water} are approximately 70% lower in Landfill B due to lower leaching of copper. The dominating source of the environmental impacts in Landfill B was emissions from fossil fuels (CO\textsubscript{2} in Global Warming, NO\textsubscript{X} in Nutrient Enrichment and Acidification).
6.2 Road construction

In the case study, presented in Birgisdóttir et al. (III), environmental impacts and resource consumption in a life cycle of 1km secondary road constructed with conventional materials (Scenario A) were evaluated in the ROAD-RES model and compared with a road using bottom ash as sub-base material beneath the road lanes (Scenario B) (as shown in Figure 8).

The road was assumed to consist of two lanes (2x3.5m), two reserves between lanes and bicycle paths (2x1.5m), two bicycle paths (2x1.5m) and two shoulders (2x2.1m). The total width of the road was 17.2m. The total thickness of the road construction was 0.7 m. The scenario was divided into three stages relating to the main activities in a life cycle of a road: (1) design, (2) construction and (3) operation and maintenance. Demolition of the road was excluded since materials often remain in the road area, even after the road has been withdrawn from service.
The total amount of material used as sub-base layer beneath the lanes was 4400 tons and therefore the scenario with bottom ash was similar to the scenario evaluated in Birgisdóttir et al. (II). The difference between the evaluations was that in Birgisdóttir et al. (II) only impacts related to the bottom ash were included, while in Birgisdóttir et al. (III) all impacts related to the road during 100 years were included. By using bottom ash in the road, impacts from landfilling of bottom ash were avoided and subtracted in the calculations.

The difference between a road with conventional materials (Scenario A) and a road with 4400 tons bottom ash as sub-base (Scenario B) was insignificant, as shown in Figure 9 and discussed in Birgisdóttir et al. (III). The assessment showed that the environmental impacts related to other activities in the life stages of the road were more important. Utilization of bottom ash was assumed to relieve society of the impacts of landfilling, and the difference between the impacts of landfilling and utilization (shown in Birgisdóttir et al. (II)) were so small that virtually no increased impacts of utilization of bottom ash were seen in the life cycle of the road.

Figure 9: Normalized environmental impacts for the whole life cycle of the road for Scenario A (with conventional materials) and Scenario B (with bottom ash as sub-base beneath lanes).

The overall conclusions of the scenario were that the environmental impacts from combustion of fossil fuels were of major importance in the life cycle of the roads; emissions of carbon dioxide resulting in Global Warming impacts of 150 PE and emissions of nitrogen oxides contributing to Nutrient Enrichment, Acidification and Human Toxicity,air. The potential impacts to Stored Ecotoxicity were also similar in both scenarios, Stored Ecotoxicity,water and Stored Ecotoxicity,soil were approximately 400-450 PE for both scenarios. The impacts were related to the content of heavy metals in asphalt and granular material. The impacts related to heavy metals remaining in the bottom ash in the road were in a different order of magnitude than the final result: Stored Ecotoxicity,water 13 000 PE and Stored Ecotoxicity,soil 600 PE (as shown in Figure 5). The impacts of the avoided impacts of landfilling of bottom ash were the same order of magnitude and utilization of bottom ash in the road therefore resulted in having no additional impacts to the Stored Ecotoxicity.
Leaching of PAHs, heavy metals and salts was investigated in a 64-day tank leaching test and the results are presented in Birgisdóttir et al. (IV) Birgisdóttir and Christensen (V). The conclusions of the study were that leaching of all constituents measured was generally low. Diffusion coefficients were found for seven PAHs, three heavy metals and six salts. It was, however, pointed out that these diffusion coefficients could eventually overestimate the leached amount, since the leaching tests indicated decreasing leaching at the end of the leaching tests, while the estimation of the diffusion coefficients was based on higher leaching. Including the leaching of those constituents in the scenario of a secondary road (as a conservative estimate of leaching) and using leaching profiles for the newer asphalt specimens, gives (as shown in Table 4) less than 15g of the sum of five PAHs, 300kg of the sum of three salts and 1kg manganese. Calculating the leached amounts of PAHs as environmental impacts gives approximately 0.03 mPE impacts to Human Toxicity_{soil} and 0.003 mPE impacts to Ecotoxicity_{water}, which are trivial impacts compared to the total environmental impacts. Comparing the values for the inorganic constituents to leaching from bottom ash and road salting indicates that leaching of inorganic constituents from asphalt is also insignificant.

Table 4: Modeled leaching of salts, heavy metals and PAHs from asphalt in the secondary road, compared to modeled leaching from bottom ash and road salting.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Leached from asphalt [kg]</th>
<th>Bottom ash [kg]</th>
<th>Road salting [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barium</td>
<td>0.29</td>
<td>6200</td>
<td></td>
</tr>
<tr>
<td>Calcium</td>
<td>224</td>
<td>6000</td>
<td></td>
</tr>
<tr>
<td>Manganese</td>
<td>1.06</td>
<td>8400</td>
<td></td>
</tr>
<tr>
<td>Sodium</td>
<td>49</td>
<td>10000</td>
<td>855000000</td>
</tr>
<tr>
<td>Benz(a)pyrene</td>
<td>0.00039</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluoranthene</td>
<td>0.0028</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluorene</td>
<td>0.000024</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Naphthalene</td>
<td>0.005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phenanthrene</td>
<td>0.0055</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5 shows the most important resources in the whole life cycle of the road (as normalized results) for the two scenarios. The most important resource consumption was the potentially spoiled groundwater resource due to leaching of salts into the groundwater compartment. The impact was less than 10% larger for the road with bottom ash in the sub-base and more than 90% of the impacts were therefore related to road salting during winter maintenance. Consumption of crushed rock and natural aggregate was also important; 2800 PE for natural aggregate and 2900 PE for crushed rock for the road with conventional materials. Recycling of bottom ash saved 400 PE of natural aggregate, or approximately 15%. There was no difference in the consumption of resources for other residues. The overall difference in the consumption of residues was therefore insignificant between the two scenarios. The values for the most important residues were higher than the environmental impacts, when the results were evaluated as normalized results: resource consumption in 400-20000 PE while environmental impacts in 50-200 PE.
Table 5: Normalized resource consumption in PE in the total life cycle of the road with conventional materials only (Scenario A) and road with bottom ash as sub-base layer below lanes (Scenario B).

<table>
<thead>
<tr>
<th></th>
<th>Scenario A</th>
<th>Scenario B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude oil</td>
<td>1150</td>
<td>1150</td>
</tr>
<tr>
<td>Crushed rock</td>
<td>2900</td>
<td>2900</td>
</tr>
<tr>
<td>Natural aggregate</td>
<td>2800</td>
<td>2400</td>
</tr>
<tr>
<td>Natural gas</td>
<td>430</td>
<td>430</td>
</tr>
<tr>
<td>Potentially spoiled groundwater resource</td>
<td>15000</td>
<td>16000</td>
</tr>
</tbody>
</table>
7 Discussion and final remarks

7.1 Status of the ROAD-RES model
The first version of the ROAD-RES model is fully developed and a manual showing all features of the model has been prepared. The model, which is programmed in C++ using PARADOX databases, has been thoroughly tested for errors, both in the calculation method of the model and the data available in databases. All calculations features in the model have been checked in parallel spreadsheet calculations for all modules. Approximately 6000 characterization factors used in the EDIP97 method to calculate the environmental impacts have been quality ensured by an independent person. The model has shown to be very stable considering that this is a first version. Data covering the most important life cycle stages of roads (road construction materials, machinery, maintenance etc.), MSWI residues (chemical composition, leaching characteristics and upgrading processes), and landfills (material and energy consumption) have been collected during the project. The model distinguishes between five environmental compartments: air, soil and three water compartments (fresh surface water, marine surface water and groundwater). Methods to predict the long-term leaching as well as distribution of leached constituents into the five environmental compartments have been developed and preliminary values are provided. The model includes a new characterization method for contamination of groundwater due to leaching of salts: Potentially spoiled groundwater resource. Furthermore, characterization factors for Human Toxicity through groundwater due to emissions of heavy metals have been calculated. In addition, the ROAD-RES model has been used in assessment of two hypothetical case studies: disposal of MSWI bottom ash and construction of secondary road with and without MSWI bottom ash.

7.2 ROAD-RES compared to existing models
Two models covering some of the features of ROAD-RES were available before ROAD-RES was developed. These models are the Swedish spreadsheet model, an inventory model for roads with conventional materials (Stripple, 1995, Stripple, 2001) and the Finnish spreadsheet model (MELI) for roads with residues other than MSWI residues (Mroueh et al., 2000, Mroueh et al., 2001).

The general advantages for the user of using software such as ROAD-RES, compared to spreadsheet models, are the flexibility and user-friendliness of the model. The user can easily expand the databases by adding new materials, scenarios, substances, impact assessment methods etc.. It also contains several features to view and treat the results, and to track the importance of substances and processes. A spreadsheet model able to handle the same number of parameters as ROAD-RES would quickly become very large and complex for the user.

The evaluation of leaching from the residues in the MELI model was limited to the use of data from L/S 2 l/kg and L/S 10 l/kg batch leaching tests of granular materials. Based on input information on precipitation and infiltration, ROAD-RES estimates the L/S-ratio in the granular material and links this information to leaching profiles that describe the leaching as a function of the L/S-ratio. Additionally, ROAD-RES also includes estimation of leaching from monolithic materials. It has not been possible to compare results from ROAD-RES and MELI, since ROAD-RES currently
includes data on only MSWI residues and MELI includes data on residues other than those from waste incineration. ROAD-RES also has a feature to distribute the leached amounts into different environmental compartments, while the leached amounts in MELI are regarded as emissions to soil only.

The results in ROAD-RES can be presented as inventory data and as three stages of the impact assessment (impact potentials, normalized and weighted). EDIP97 is the default impact assessment method of the model, but the user can add other methods such as Eco-indicator 95, Eco-indicator 99 and CML. The two other models are limited to life cycle inventory results. The MELI model has, however, a specific method to weight the inventory data.

7.3 Disposal of bottom ash: recycling or landfilling?

The ROAD-RES model can be applied to evaluate and compare disposal scenarios to obtain a better understanding of the overall impacts from different options for disposal and recycling. As an example of this, the scenarios evaluated in Birgisdóttir et al. (2011) showed that the environmental impacts from utilization of bottom ash were somewhat higher than the environmental impacts from landfilling. Recalculating the results as the impacts related to the annual amount of bottom ash generated pr. person in Denmark (approximately 110 kg), the highest impact during 100 years, Ecotoxicity\text{water}, was in the order of magnitude of 1.2 mPE for utilization and 0.8 mPE for landfilling. Most other impacts related to the scenarios were due to the use of energy in relation to transport and treatment of the residues. There was no clear trend in the consumption of resources; disadvantages of the landfill were higher consumption of fossil fuels and a possible significant consumption of clay (depending on the locality). Disadvantages of the road scenario were the high potential for pollution of the groundwater resource. Savings of natural aggregate was also an advantage of the road scenario.

The sensitivity analysis of the scenario showed that the water movement in roads was important in the evaluation of the two possibilities and that the distribution into the environmental compartments was even more important. More comprehensive knowledge about the transport of water in the roadbed and further migration through the surroundings would undeniably decrease the uncertainties of the results of the modeling. As discussed in chapter 2.3, a wide range of water infiltrating the road has been used in modeling (1-20\% of annual precipitation). Currently, a three-year European research project on water movement in road pavements and embankments is running and is expected finished by the end of 2006 (Dawson, 2004). It is hoped that this project will give a better understanding of the amount of water infiltrating and the pathway in the road. It was mentioned that although calculations on mobility of heavy metals in soil showed high ability for adsorption, rather conservative assumptions were made in the modeling regarding the distribution of heavy metals in soil. Experiences from utilization of bottom ash in two twenty-year-old road sections in France and a five-year-old road section in Denmark supported the calculations that showed low mobility of heavy metals in the soil (Reid et al., 2001); consequently, for the scenarios evaluated, it could be safe to assume a higher fraction of the leached heavy metals ending up in the soil compartment.

Considering the toxicities (Ecotoxicity\text{water} and Stored Ecotoxicity\text{water} and \text{soil}) that are related to the heavy metals inherent in bottom ash, the main difference in the impacts
of the two scenarios is related to the locality and distribution of the potential toxicity. In Denmark, the Ecotoxicities related to bottom ash disposed of in landfills would be located near the coast and would therefore preliminary be in the marine surroundings, while utilization of bottom ash could be in various locations. Landfilling bottom ash limits the dissemination of the toxicities compared to utilization due to the thinner layers used in the road pavement. However, due to the thinner layer in utilization, lower concentrations in the leachate can be reached for many constituents much earlier than in landfilling. This difference in the dissemination of toxicities and level of concentrations cannot, however, be evaluated in LCA, since the assessment methodology is solely based on the amount of constituents leached out from the material.

7.4 What is most important in a road construction?

Most of the environmental impacts of a secondary road with conventional materials (Birgisdóttir et al. (III)) were related to the emissions of carbon dioxides and nitrogen oxides from the combustion of fossil fuels. The emissions were related to processes in all life cycle stages of the road. The production of materials and construction of the road contributed with approximately half of all environmental impacts while 100 years of operation and maintenance contributed with the other half. Asphalt material, which corresponds to only 25% of the material used in the road, contributed with the most environmental impacts. Production of bitumen used in asphalt was especially significant for the environmental impacts. Similar results were obtained by Stripple (2001) and Mroueh et al. (2001). This scenario indicated that it may be important to distinguish between emissions from different types of motor used for combustion of fuels related to different activities in the road construction. Furthermore, it is suggested that requiring contractors to use less polluting machinery would potentially lower the environmental impacts considerably.

The results showed that road salting could potentially pollute significant amounts of groundwater in the area near the road, resulting in amounts equal to the annual consumption of drinking water for 15 000 persons. Consumption of natural aggregate and crushed rock were also considerable, each approximately 3000 PE. The values for the resource consumption were at least one order of magnitude larger than for the environmental impacts. This can be explained by the fact that 65% of the natural aggregate extracted is used for road construction and therefore the normalized consumption of natural aggregate can be expected to be high when road constructions are evaluated.

It should be considered that road constructions differ considerably due to the difference in the terrain of where the road is constructed. The results from this hypothetical case study should therefore not be used for direct evaluation of the environmental impacts of other roads. The main efforts in this Ph.D. project were directed towards developing an environmental management decision support tool. It is hoped that the experience from using the model in evaluation of real case studies will lead to increased understanding of the most important processes in the life cycle stages of roads.
7.5 What does it mean to use MSWI bottom ash in road constructions?

ROAD-RES can be applied to illustrate the difference between a road construction with conventional materials only and using residues as construction materials. It was concluded from the example of a secondary road in Birgisdóttir et al. (III) that there was only a trivial difference in the overall environmental impacts between a road with conventional materials and a road with bottom ash. Since utilization of bottom ash avoided landfilling of bottom ash and since the difference in the environmental impacts of landfilling and utilization was marginal, the overall environmental impacts were insignificant. The potential for pollution of groundwater resources near the road was a significant impact in the evaluation of the disposal scenarios in Birgisdóttir et al. (II). When recycling bottom ash, leaching of salts is often problematic according to the statutory order for recycling of residues and soil in building and construction works. This scenario showed, however, that leaching from bottom ash was insignificant compared to road salting.

It should be considered that the most important environmental impacts in the life cycle of 1km secondary road were impacts related to combustion of fossil fuels and therefore not impacts that directly affected the road area. The local impacts evaluated in the scenario are supposed to be Ecotoxicity water, approximately 40 PE due to leaching from bottom ash, and potential spoiled groundwater resource, 15 000 PE due to road salting and 1400 PE due to leaching from bottom ash. The environmental assessment did not include dispersion of asphalt particles due to wearing of asphalt; further, the impacts related to traffic, e.g. pollution of the soil near the road caused by exhaust, were not included, since these are not directly related to the road.

7.6 Data: quality and sensitivity

More knowledge is needed on how and how much water infiltrates through the materials in the road. Water movement was found important for the results of the disposal scenarios for bottom ash, while it became less important when bottom ash was evaluated as a part of the total impacts of a road.

The transfer coefficients used in the scenarios for distribution of the constituents into the different environmental compartments in the surroundings near landfills and roads were based on calculations of the ability of constituents to adsorb to soil. The calculations indicated that heavy metals would migrate only a few centimeters during the lifetime of the road and landfill and would probably not reach the water compartments. The rather conservative assumptions of modeling 15% of the heavy metals reaching the water compartment (fresh surface water in the road and marine surface water in the landfill) probably overestimated the potential impact of Ecotoxicity water in both scenarios. Field experiences show, however, little transport of heavy metals after 20 years of application (Reid et al., 2001). This supports the idea that it might be safe to use a less conservative assumption regarding mobility of heavy metals.

The leaching data used in the model are all based on laboratory leaching tests. According to Reid et al. (2001), laboratory leaching tests can be used to give a conservative estimate of environmental effects, since, in most cases, laboratory leaching tests will overestimate the actual leaching; consequently, the leaching is most
likely not underestimated in the model. The leaching data used in the scenarios were average values of leaching of upgraded and carbonized bottom ash from the incineration plant I/S Vestforbærending provided during a four-year period. To take into account changes in the quality of bottom ash, e.g. due to changes in the composition of the waste and changes in the technology applied, leaching profiles of bottom ash of different quality should be provided, as well as leaching profiles of bottom ash from other incineration plants in Denmark. The comparison of using two different leaching profiles in the landfill scenario showed that the quality of bottom ash can have a significant impact on the result of the scenario.

The data on production of materials have, as far as possible, been collected from material producers, e.g. production of asphalt in Danish asphalt plants, extraction and production of Danish gravel pit materials from gravel pits, etc. The production of asphalt was found important in Birgisdóttir et al. (III), and therefore efforts were made to collect data on production of the different types of asphalt used in roads and include the variations that might appear in the production. Data on machinery and processes in road construction have also as far as possible been collected from contractors in the road sector in Denmark. Data material on many processes in road construction was available in Stripple (2001). Collection of data that were not covered by Stripple (2001), such as earthworks, regular maintenance of Danish roads, etc. was therefore prioritized in the data collection. Since LCA has been used only in evaluation of hypothetical road cases (Stripple, 2001, Mroueh et al., 2001), further experience is needed to develop more reliable data and results from LCA on roads.

Combustion of fossil fuels related to production of materials, transport and different machinery and processes in all life cycle stages of a road lead to the most important environmental impacts in Birgisdóttir et al. (III). It is therefore important to collect data on emissions from different motors for combustion of fossil fuels and the effects of using equipment to reduce the emissions. It is also important to obtain an overview of the use of different machines in the various processes and include this in the life cycle assessment.
8 Future work

The work included in this thesis resulted in an LCA model that has been tested on hypothetical cases. The future work related to the ROAD-RES model can be divided into the following four main topics:

- **Application of ROAD-RES in real cases**
  To date, the model has been used only in hypothetical cases. The next step is to use the ROAD-RES model in relation to real cases, both within road construction and disposal of residues. Augmented experience with the use of the model will lead to a better understanding of the systems involved and the strengths and weaknesses of the methodology behind the model. The use of the model will most likely eventually lead to a broader understanding of the most important environmental impacts within the life cycle of the systems involved.

- **Improvement of material and process data**
  Data have been collected for most important materials and processes related to road construction and disposal of residues. For many processes, e.g. processes in road construction, the data material is based on single or very few observations. It is important to establish more reliable databases for the systems involved. In this project, the main focus was on collection of data for the main road construction materials, such as gravel and asphalt, and the larger construction and maintenance activities. A further improvement of the database would be to (i) include data on road equipment, such as lamp posts, signs etc., (ii) include data for minor maintenance work on asphalt surfacing, (iii) improve the data on the most important materials, such as asphalt, bitumen, and (iv) add materials such as concrete and other residues.

- **Better understanding of the leaching profiles**
  Leaching profiles are established for several materials, such as asphalt, concrete, natural gravel, bottom ash and cement treated base materials with MSWI residues. The leaching profiles established for bottom ash show that different qualities of bottom ash can have a significant influence on the results of scenarios. Calculations of the leaching from natural gravel materials showed that the leached amounts from natural materials were also noticeable, although they were lower than from bottom ash. The next step is to enlarge the understanding of the general leaching curves for bottom ash and natural materials through further laboratory leaching tests.

- **Comparison of ROAD-RES results with existing models**
  Comparisons of results from the RAOD-RES model with results from the Swedish model (Stripple, 2001) and the Finnish MELI model (Mroueh et al., 2000) would be valuable to evaluate the models and examine if the more detailed modeling in ROAD-RES influences the results of environmental impacts from roads and utilization of residues.
9 References


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