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Comparative Life Cycle Assessment of Geosynthetics versus Conventional Construction Materials

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on behalf of the

European Association for Geosynthetic Manufacturers (EAGM)

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Executive Summary

"Comparative Life Cycle Assessment of Geosynthetics versus Conventional Construction Materials"

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Goal and Scope Definition

Geosynthetic materials are used in many different applications in the civil and underground engineering. In most cases, the use of geosynthetic material replaces the use of other materials. The European Association for Geosynthetic Manufacturers (EAGM) commissioned ETH Zürich and ESU-services Ltd. to quantify the environmental performance of commonly applied construction materials (such as concrete, cement, lime or gravel) versus geosynthetics. To this end a set of comparative life cycle assessment studies are carried out concentrating on various application cases, namely filtration, foundation stabilised road, landfill construction and slope retention. The environmental performance of geosynthetics is compared to the performance of competing construction materials used. The specifications of the four construction systems are established by the EAGM members representing the European market of geosynthetic materials. They represent best current practice.

Tab. S. 1: Overview of the objects of investigation

Description	Alternatives	Case
Filter layer	gravel based filter	1A
	geosynthetics based filter	1B
Road foundation	conventional road (no stabilisation needed)	2A
	geosynthetics based foundation	2B
	cement/lime based foundation	2C
Landfill construction	gravel based drainage layer	3A
	geosynthetics based drainage layer	3B
Slope retention	reinforced concrete wall	4A
	geosynthetics reinforced wall	4B

The study adheres to the ISO 14040 and 14044 standards. A critical review is performed by a panel of three independent experts. The study refers to the year 2009. Foreground data about geosynthetic materials gathered by questionnaires refer to the year 2009 or, in a few exceptional cases, 2008. Data available about further material inputs and about the use of machinery are somewhat older. All data refer to European conditions.

The alternatives in each case are defined such that they can be considered technically equivalent or at least comparable. The geosynthetics used in the four cases represent a mix of different brands suited for the respective application. The conventional systems represent the most common type of construction.

The environmental performance is assessed with eight impact category indicators. These are Cumulative Energy Demand (CED), Climate Change (Global Warming Potential, GWP100), Photochemical Ozone Formation, Particulate Formation, Acidification, Eutrophication, Land competition, and Water use.

In order to evaluate the uncertainty of the data used, Monte Carlo analyses are performed. The Monte Carlo analyses are performed in a way that excludes depending uncertainties. The results of the analyses show the effects of the independent uncertainties of the two alternatives compared. The lifetime and the technical specification (layer thicknesses etc.) of the different constructions are not included in the uncertainty assessments. However, uncertainty due to variability in gravel density and in matching the thickness of the layers (95 % interval of +/- 7 %, or about +/- 3.5 cm for a 50 cm gravel layer) or of transport services required (95 % interval of about + 100 %/- 50 %) is taken into account.

Sensitivity analyses are carried out to further explore the reliability of the results. On one hand the thickness of the filter is varied in case 1 taking into account different technical specifications. On the other hand four alternatives for road foundations are analysed in case 2. This includes 2 alternative road foundations using reinforcement with geosynthetics and two alternatives for the stabilisation of the road using cement or quick lime only.

Object of Investigation and Inventory Analysis

The functional units of the four cases are distinctly different. That is why the results of the four cases should not be compared across cases.

Filter layer: The function of the first case is the provision of a filter layer. Geosynthetics can serve as separator or filter layer between the well compacted foundation and the subgrade. This is essential to make sure the foundation keeps its bearing capacity. The geosynthetic prevents on one hand the foundation aggregates from sinking into the subgrade and on the other hand from pumping of fines from the subgrade into the foundation.

The functional unit is thus defined as the construction and disposal of a filter with an area of 1 square meter, with a hydraulic conductivity (k-value) of 0.1 mm/s or more and a life time of 30 years.

Foundation stabilisation: In the second case concerning the improvement of weak soils, a conventional road, where no stabilisation is needed (case 2A), is compared to a geosynthetic reinforced road (case 2B) and to a cement/quicklime stabilised road (case 2C).

The function of the second case is the provision of a road class III on stabilised foundation. The functional unit is thus defined as the construction, and disposal of a road class III with a length of 1 meter, a width of 12 meters and a lifetime of 30 years.

Landfill construction: The third case compares the use of a geosynthetic drainage system (case 3B) with a gravel drainage system (case 3A) in a cap of a waste landfill site. A geosynthetic on top of the drainage gravel is often used to prevent moving of fines of the top soil into the drainage, and a second geosynthetic is used below the drainage as a protection layer to secure that the sealing element is not damaged to the drainage. Hence, in practice both solutions use geosynthetics - on top of and below of the drainage layer. All the other layers in a landfill site change neither in thickness nor in material requirements.

The function of case 3 is to provide a drainage layer in a landfill cap of hazardous/non-hazardous waste landfill site. The purpose of this drainage layer is to discharge infiltrating rainwater from the surface. The functional unit is defined as the construction and disposal of 1 m^2 surface area drainage layer with a hydraulic conductivity (k-value) of 1 mm/s or more and an equal life time of 100 years.

Slope retention: It may be necessary in some cases, especially in the construction of traffic infrastructure, to build-up very steep walls. For such walls, supporting structures are necessary. The retaining walls need to meet defined tensile and shear strengths. Retaining walls reinforced with concrete (case 4A) are compared to soil slopes reinforced with geosynthetics (case 4B).

The function of the fourth case is to provide a slope retention with a very steep and stable wall. The functional unit is defined as the construction and disposal of 1 m slope retention with a 3 meters high wall, referring to a standard cross-section. Thus, the functional unit is independent of the length of the wall.

For all cases, data about geosynthetic material production are gathered at the numerous companies participating in the project. The company specific life cycle inventories are used to establish average life cycle inventories of geosynthetic material. Average LCI are established per case on the basis of equally weighted averages of the environmental performance of the products manufactured by the participating member companies. The technical specifications of the four cases (e.g. how much gravel and diesel is required) are verified with civil engineering experts. The materials and processes needed to erect the constructions are modelled with generic, background inventory data. The primary source of background inventory data used in this study is the ecoinvent data v2.2 (ecoinvent Centre 2010), which contains inventory data of many basic materials and services.

Results

In Fig. S. 1 to Fig. S. 5 the environmental impacts of the full life cycle of the four cases are shown. For each indicator, the environmental impacts of the alternative with higher environmental impacts are scaled to 100 %. The total impacts are divided into the sections infrastructure (road, landfill, slope retention), raw materials (bitumen, gravel, geosynthetic layer, cement, quicklime, concrete, reinforcing steel, wooden board), building machine (construction requirements), transports (of raw materials to construction site) and disposal (includes transports from the construction site to the disposal site and impacts of the disposal of the different materials).

A filter using a geosynthetic layer (case 1B) causes lower impacts compared to a conventional gravel based filter layer (case 1A) with regard to all impact category indicators investigated. For all indicators the filter with geosynthetics causes less than 25 % of the impacts of a conventional gravel based filter. The non-renewable cumulative energy demand of the construction of 1 square meter filter with a life time of 30 years is 131 MJ-eq in case 1A and 19 MJ-eq in case 1B. The cumulative greenhouse gas emissions amount to 7.8 kg CO_2-eq/m^2 in case 1A and 0.81 kg CO_2-eq/m^2 in case 1B.

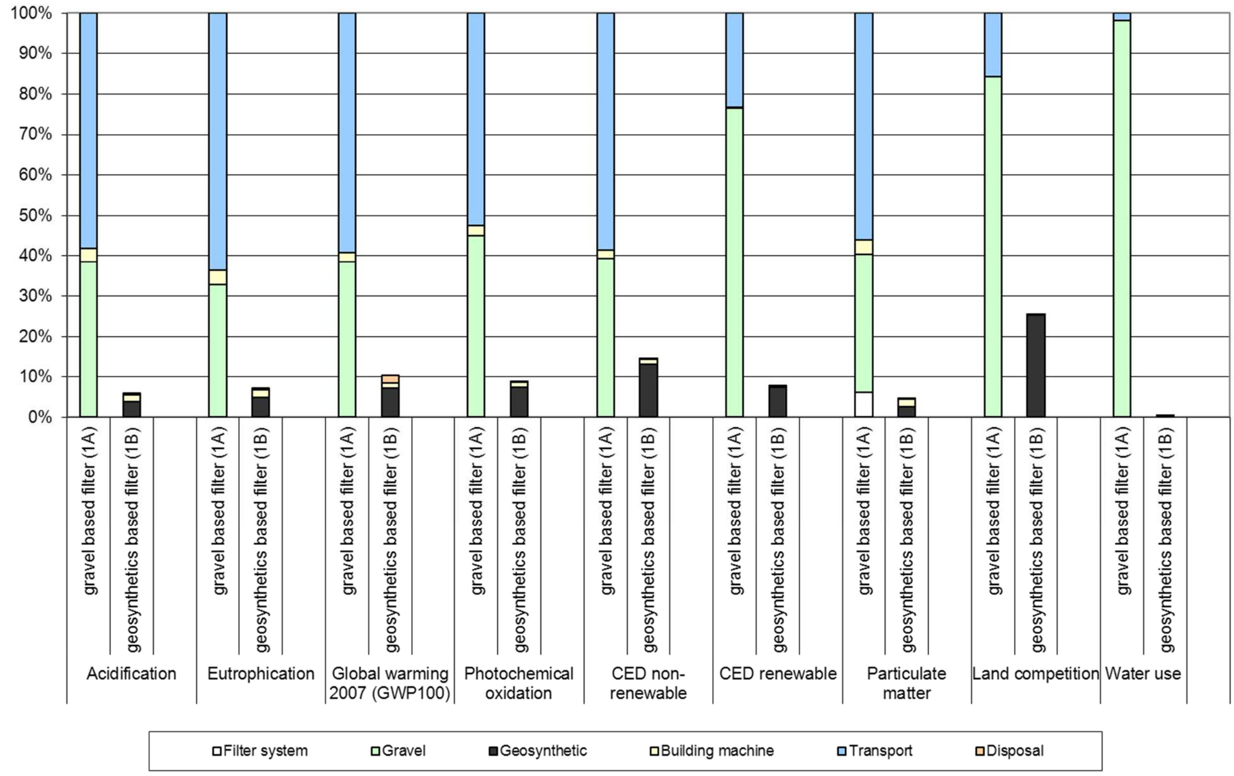

Fig. S. 1: Environmental impacts of the life cycle of 1 m^2 filter for the cases 1A and 1B. For each indicator, the case with higher environmental impacts is scaled to 100%.

A conventional road (case 2A) causes higher impacts compared to a road reinforced with geosynthetics (case 2B) with regard to all impact category indicators. The higher impacts of case 2A are caused by the emissions and the resource consumption related to the production and transportation of the additional amount of gravel required. With regard to global warming, the road construction with a cement/lime stabilised foundation (case 2C) causes higher impacts compared to cases 2A and 2B mainly because of the geogenic CO_2 emissions from the calcination process in the clinker and quick lime production. With regard to land use, the impacts of all three alternatives are more or less equal, with a maximal deviation in case 2C, using only 2.2 % less land than case 2A. Case 2C causes lower eutrophying and particulate matter emissions and requires less water compared to cases 2A and 2B,

The non-renewable cumulative energy demand of the construction and disposal of 1 meter stabilised road with a width of 12 meters and a life time of 30 years is 25'200 MJ-eq in case 2A, 23'900 MJ-eq in case 2B and 24'400 MJ-eq in case 2C. The cumulative greenhouse gas emissions amount to 0.73 t CO_2-eq/m^2 in case 2A, to 0.65 t CO_2-eq/m^2 in case 2B and to 0.95 t CO_2-eq/m^2 in case 2C. Correspondingly, the cumulative greenhouse gas emissions of 1 km stabilised road are 730 t CO_2-eq in case 2A, 650 t CO_2-eq in case 2B and 950 t CO_2-eq in case 2C.

The uncertainty assessment confirms that case 2B causes lower environmental impacts than case 2A with regard to all indicators. For the comparison of case 2B and case 2C the uncertainty analysis shows lower impacts for the categories CED renewable, photochemical oxidation and global warming potential for case 2B. Regarding the indicator land competition the case 2B causes higher environmental impacts than case 2C. With regard to all other indicators the uncertainty analysis reveals no clear ranking between cases 2B and 2C.

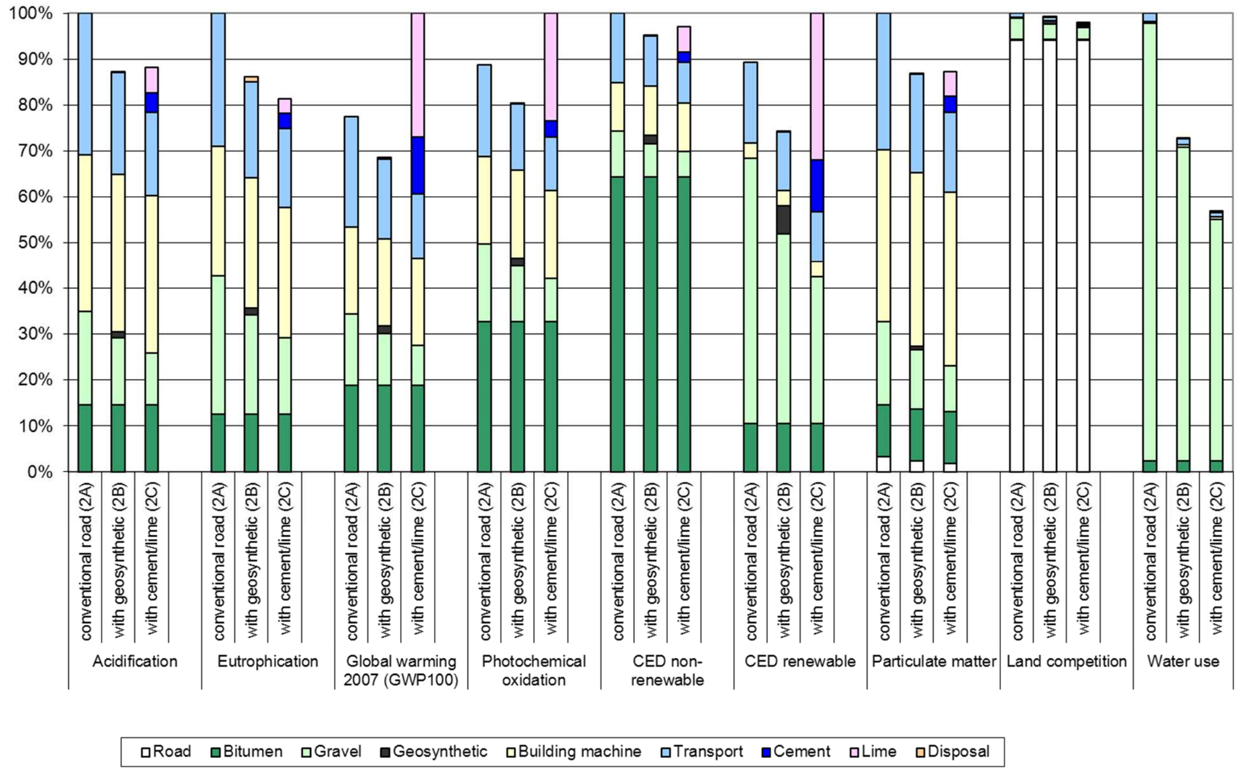

Fig. S. 2: Environmental impacts of the life cycle of 1 m road with stabilised foundation, cases 2A, 2B and 2C. For each indicator, the case with higher environmental impacts is scaled to 100%.

Fig. S. 3 shows the sensitivity analyses for road construction reinforced with geosynthetics with soil replacement (case 2BS1) and without separation geosynthetic (case 2BS2), and for road construction with stabilised foundation using quicklime only (case 2CS1) and using cement only (case 2CS2).

Using quicklime as stabiliser causes the highest environmental impacts with regard to global warming, photochemical oxidation, CED non-renewable, and CED renewable. Choosing cement as stabiliser leads to higher environmental impacts for global warming, CED renewable and water use compared to case 2B.

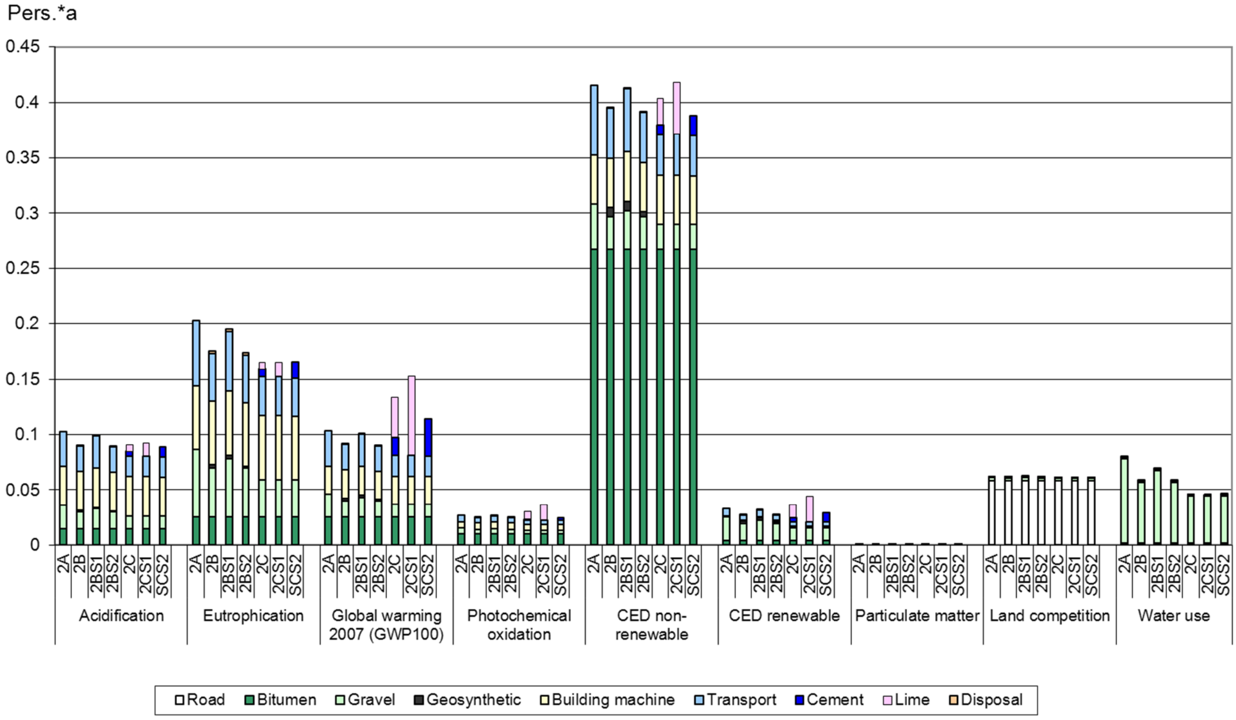

Fig. S. 3: Sensitivity analyses: environmental impacts of the life cycle of 1 m road class III, cases 2A, 2B and 2C. Case 2BS1: construction of a class III road reinforced with geosynthetics with soil replacement; case 2BS2: construction of road reinforced with geosynthetics without separation geosynthetic; case 2CS1: construction of road reinforced with quicklime stabiliser; case 2CS2: construction of road reinforced with a cement stabiliser. For each indicator, the results are normalised with the annual world impacts per capita.

A geosynthetic drainage layer (case 3B) causes lower environmental impacts compared to a gravel based drainage layer (case 3A) in all impact categories considered except land competition which is about the same in both cases. The non-renewable cumulative energy demand of the construction and disposal of 1 square meter drainage layer is 194 MJ-eq in case 3A and 86 MJ-eq in case 3B. The cumulative greenhouse gas emissions amount to 10.9 kg CO_2-eq/m^2 in case 3A and 3.6 kg CO_2-eq/m^2 in case 3B. Correspondingly, the cumulative greenhouse gas emissions of the drainage layer of a landfill with an area of 30’000 m^2 are 330 t CO_2-eq in case 3A and 110 t CO_2-eq in case 3B respectively.

The Monte Carlo Simulation reveals a probability of more than 99 % that the geosynthetic drainage layer has lower environmental impacts than the mineral drainage layer for all indicators investigated except land competition. Regarding land competition, the probability that geosynthetic drainage layer has lower environmental impacts than the mineral drainage layer is 62 %.

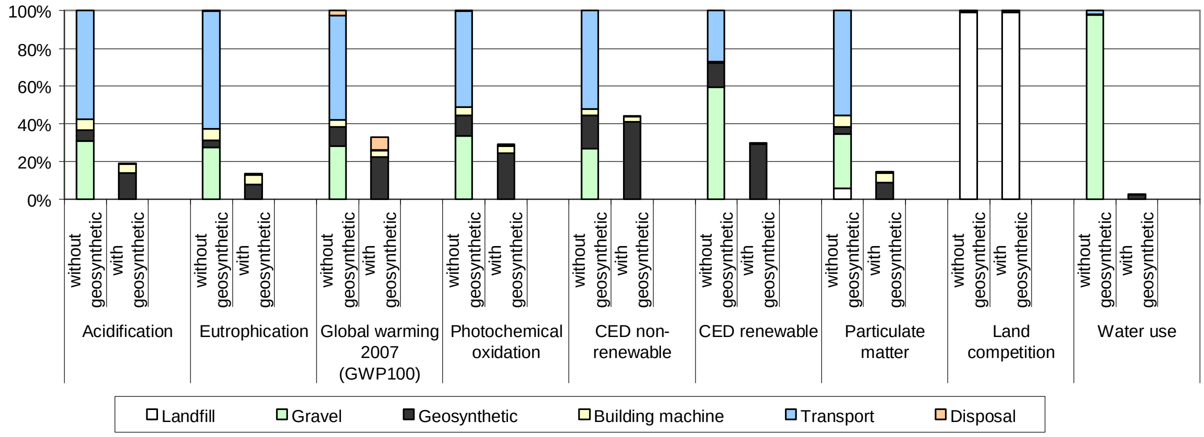

Fig. S. 4: Environmental impacts of the life cycle of 1 m^2 mineral drainage layer (case 3A) and a geosynthetic drainage layer (case 3B). For each indicator, the case with higher environmental impacts is scaled to 100%.

A geosynthetic reinforced wall (case 4B) causes lower environmental impacts compared to a reinforced concrete wall (case 4A) in all impact categories considered. The non-renewable cumulative energy demand of the construction and disposal of 1 meter slope retention with a height of 3 meters is 12'700 MJ-eq in case 4A and 3'100 MJ-eq in case 4B. The cumulative greenhouse gas emissions amount to 1.3 t CO_2-eq/m in case 4A and 0.2 t CO_2-eq/m in case 4B. Correspondingly, the cumulative greenhouse gas emissions of 300 m slope retention are 400 t CO_2-eq in case 4A and 70 t CO_2-eq in case 4B respectively. The Monte Carlo simulation shows a probability of 100 % that the environmental impacts of the conventional slope retention are higher compared to the environmental impacts of the geosynthetic slope retention with regard to all indicators.

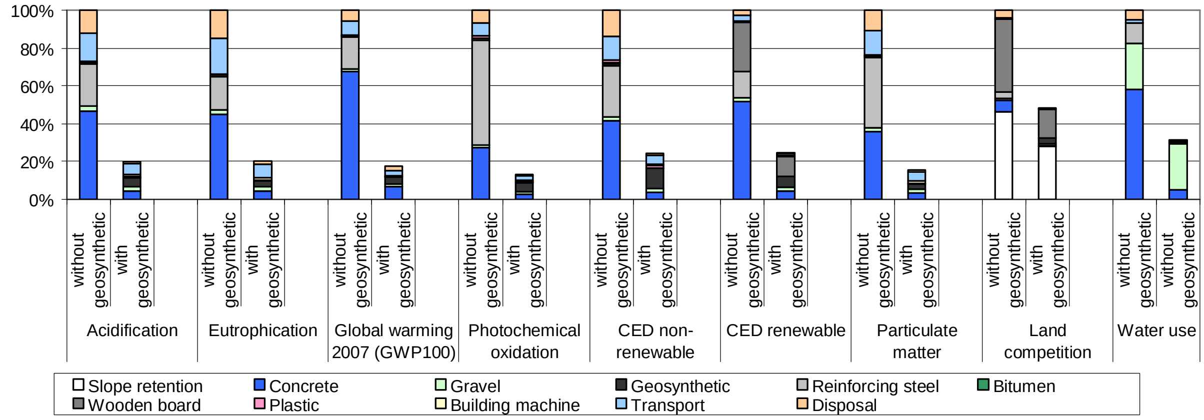

Fig. S. 5: Environmental impacts of the life cycle of 1 m slope retention, cases 4A and 4B. For each indicator, the case with higher environmental impacts is scaled to 100°%.

A sensitivity analysis regarding transportation of the materials with a Euro5 lorry instead of a fleet average lorry shows lower environmental impacts regarding those indicators and cases where the transportation of the materials has an important share in the result. This applies for the conventional separator layer in case 1, the geosynthetic stabilised layer in case 2B (see Fig. S. 3), the conventional drainage layer in case 3A and in both types of slope retention. The sequence of the environmental impacts of the cases compared does not change in any of the four cases.

Conclusions and Recommendations

A **filter layer with geosynthetics** has lower environmental impacts compared to a conventional alternative (gravel). The difference is considerable for all indicators (more than 85 %) and reliable. The difference in the environmental impacts arises mainly because the applied geosynthetic substitutes gravel, which causes considerably higher impacts when extracted and transported to the place of use. At least a layer of 8 cm of gravel must be replaced by geosynthetics used as a filter in order to cause the same or lower environmental impacts regarding all indicators.

When comparing the use of **geosynthetics in road construction** in order to reinforce the road foundation (case 2B) and the conventional road construction (case 2A), the environmental impact is reduced for all indicators when using geosynthetics. When road construction using geosynthetics (case 2B) and the road construction with cement/lime stabilised foundation (case 2C) are compared, a trade-off between the cases 2B and 2C can be observed. On the one hand, the use of a cement/lime stabiliser causes higher climate change impacts mainly because of the geogenic CO_2 emissions from the production process of cement and quicklime. On the other hand, the use of a geosynthetic stabiliser shows higher results for the environmental indicators eutrophication, water use and particulate matter because of the emissions and the resource consumption related to the production and transportation of the additional amount of gravel required. The use of quick lime only (case 2CS1) causes higher environmental impacts than the use of cement (case 2CS2) for the stabilisation of the road foundation. At least a layer of 25 cm of gravel in a conventional road must be replaced by geosynthetics used in road foundation in order to cause the same or lower environmental impacts regarding all indicators.

The **uncertainty analysis** shows that results are reliable for all indicators when comparing case 2A and 2B and that the results are stable for the indicators photochemical oxidation, global warming, land competition and CED renewable when comparing the case 2B and 2C. Regarding the other indicators the difference between the cases 2B and 2C is considerably less reliable.

The main driving forces for the difference between the geosynthetic **drainage layer in a landfill site** and the conventional gravel drainage layer is the extraction and transportation of gravel used in the conventional case. For all indicators except land competition, the impacts of the conventional drainage layer are more than twice as high as compared to the impacts from the geosynthetic drainage layer. The Monte Carlo simulations show that differences can be considered reliable and significant with regard to all indicators except land competition. Regarding the latter, the two alternatives can be considered as equivalent.

Compared to the conventional slope retention, the geosynthetic **reinforced wall** substitutes the use of concrete and reinforcing steel, which results in lower environmental impacts of between 52 % and 87 %. The uncertainty analysis shows that it is reliable that the use of geosynthetics causes lower environmental impacts compared to a conventional slope retention.

The main share of the environmental impacts of the manufacture and disposal of geosynthetic layers are caused by the raw materials and electricity consumption. However, the shares in the total environmental impacts of the four cases are small, except in case 4 where geosynthetics can have an important contribution in some indicators. The variation in environmental impacts of geosynthetics manufacture does not affect the overall results as shown with the Monte Carlo simulations. Hence the results shown in this report are valid for the products of any particular manufacturer.

Geosynthetic layers and geogrids can contribute to civil engineering constructions with significantly lower climate change impacts in all cases considered. The use of geosynthetic layers may also lead to lower environmental impacts such as acidification, eutrophication, and to lower cumulative energy demands, except for the case of foundation stabilisation (case 2), where these environmental impacts are higher compared to conventional solutions.

It is recommended to establish key parameter models for each of the four cases, which allow for an individual assessment of alternatives of any particular construction. This is particularly true for case 4, where actual situations may ask for highly specific technical solutions. In such key parameter models the main determining factors such as amount of gravel, cement, concrete or geosynthetics needed, can be entered to calculate the environmental impacts of the construction alternatives at issue.

Abbreviations

CED	Cumulative Energy Demand
EAGM	European Association for Geosynthetic Manufacturers
FSS	Frost Sensitive Soil
GWP	Global Warming Potential
IEA	International Energy Agency
LCA	Life Cycle Assessement
LCI	Life Cycle Inventory
NMVOC	Non-methane volatile organic compounds
PE	Polyethylene
PET	Polyethylene terephtalate
PP	Polypropylene

Contents

1 Goal and Scope Definition

1.1 Outline of the Study

Geosynthetic materials are used in many different applications in the civil and underground engineering. They are used in road construction, in foundation stabilisation, in landfill construction and in slope retention. In most cases they are used instead of minerals based materials such as concrete, gravel or lime.

Environmental aspects get more and more relevant in the construction sector. That is why the environmental performance of technical solutions in the civil and underground engineering sector gets more and more attention.

The European Association for Geosynthetic Manufacturers (EAGM) shall be provided with comprehensive qualitative and quantitative information of the environmental performance of commonly applied construction materials (such as concrete) versus geosynthetics. This is achieved by performing a set of comparative life cycle assessment studies concentrating on various application cases, namely road construction, foundation stabilisation, landfill construction and slope retention. The environmental performance of geosynthetics is compared to the performance of competing construction materials used.

The study shall adhere to the ISO 14040 and 14044 standards. In the case of comparisons intended to be used in comparative assertions intended to be disclosed to the public, the ISO standards require a critical review performed by a panel of at least three independent experts.

1.2 Organisation of the Study

The study was commissioned by the European Association for Geosynthetic Manufacturers in January 2010. It is conducted by ESU-services Ltd. and ETH Zürich. Members of the project panel are:

- Henning Ehrenberg (Convener Working Group of EAGM)
- Dave Williams (Working Group of EAGM)
- David Cashman (Working Group of EAGM)
- Harry Groenendaal (Working Group of EAGM)
- Heiko Pintz (Working Group of EAGM)
- Heinz Homölle (Working Group of EAGM)
- Karl Wohlfahrt (Working Group of EAGM)
- Kjell De Rudder (Working Group of EAGM)
- Klaus Oberreiter (Working Group of EAGM)
- Nicolas Laidié (Working Group of EAGM)
- Massimo Antoniotti (Working Group of EAGM)
- Prof. Dr. Holger Wallbaum (ETHZ)
- Dr. Rolf Frischknecht (ESU-services Ltd.)
- Sybille Büsser (ESU-services Ltd.)
- René Itten (ESU-services Ltd.)
- Matthias Stucki (ESU-services Ltd.)

A first version of the LCA report was completed and reviewed in Fall 2010. Some of the members of EAGM did not agree on the basic set-up of cases 1 and 2. That is why cases 1 and 2 were amended and a second version of the final report was completed and reviewed in Fall 2011.

1.3 Critical Review Process

A critical review according to ISO 14040 and 14044 is being carried out by a panel of three independent external experts:

- Hans-Jürgen Garvens, Falkensee, Germany (chair)
- Maartje Sevenster (MaS), Isaacs, Australia
- Lars-Gunnar Lindfors, IVL, Stockholm, Sweden

1.4 Use of the Study and Target Audience

Primarily, the study and its results are intended to be used within EAGM.

They should assist the members of EAGM in their efforts to

- continuously improve the environmental performance of their products,
- formulate requirements to their upstream suppliers (of e.g. auxiliaries) and
- communicate the environmental information to customers, clients and other stakeholders involved (e.g. via Environmental Product Declarations (EPD) for the applications mentioned or for a product group).

1.5 Objects of Investigation

Four construction systems are investigated in this comparative life cycle assessment. The specifications of the four construction systems are established by the EAGM members representing approximately 80 % of the European market of geosynthetic materials. A detailed description of every construction system is given in the respective Chapters.

Tab. 1.1: Overview of the objects of investigation

Description	Alternatives	Case	Chapter
Filter layer	gravel based filter geosynthetics based filter	1A 1B	2
Road foundation	conventional road (no stabilisation needed) geosynthetics based foundation cement/lime based foundation	2A 2B 2C	3
Landfill construction	gravel based drainage layer geosynthetics based drainage layer	3A 3B	4
Slope retention	reinforced concrete wall geosynthetics reinforced wall	4A 4B	5

1.6 Functional Unit

The function of the constructed infrastructure elements differ from case to case, thus, the functional unit is defined for each case separately and described in the respective Chapters. The constructions are designed in a way that the two alternatives compared are technically equivalent. The infrastructure elements analysed represent new constructions (no refurbishments of existing constructions).

Reference flows quantify the function of the case studies. In these four case studies the quantification is given within the definition of the functional units.

The functional units of the four cases are distinctly different. That is why the results of the four cases should not be compared across cases.

1.7 System Boundaries and cut-off rules applied

1.7.1 System boundaries

The life cycle assessments carried out within this study follow a cradle to grave approach. The product systems of the infrastructure elements analysed in the four cases encompass the extraction of the raw materials, its processing to building materials, construction and disposal of the infrastructure elements. Operation and maintenance of the infrastructure element are excluded except for the land occupation. The difference in expected lifetimes is accounted for. Transport processes and infrastructure are included. All processes describe average European conditions.

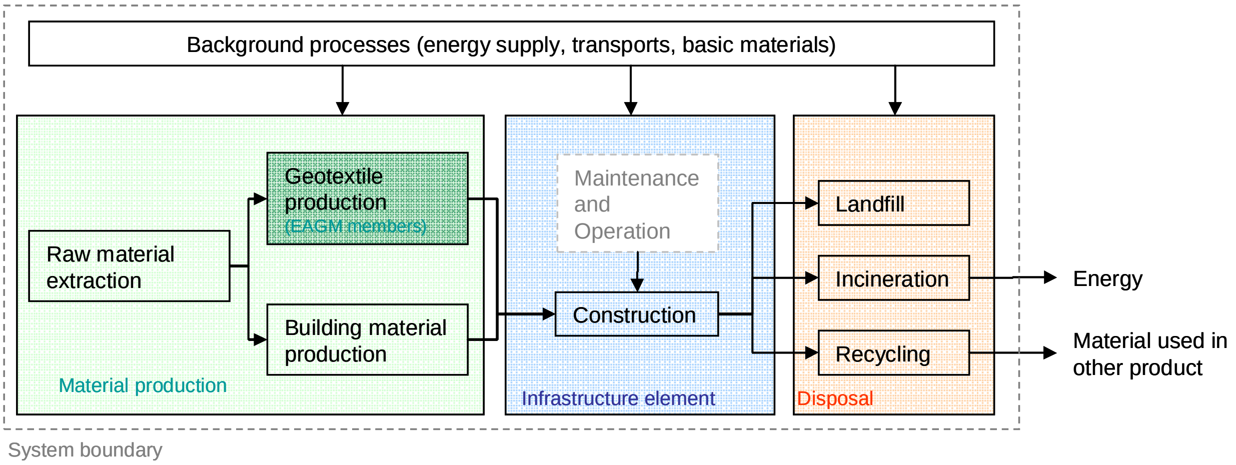

Fig. 1.1: Simplified process flow chart. The simplified chart shows the most important process steps. Maintenance and Operation of the infrastructure element are not included in the system boundaries.

Not included are:

- Operation and maintenance of the infrastructure element (e.g. lightning, de-icing of roads, traffic), because these activities are outside the system analysed
- Manufacturing equipment (machinery) at the manufacturer's site, because of its minor importance (see e.g. Frischknecht et al. 2007a)
- Operation of the storage of raw and geosynthetic materials at the manufacturer's site, because the energy consumption is considered negligible
- Packaging of the geosynthetics, because they are of minor importance (less than 3 % of mass contribution)

1.7.2 Cut-off rules

As far as possible all inputs are considered. In some cases data availability was limited. That is why packaging of the geosynthetics is not considered, because they contribute less than 3 % to the total mass. C apital goods are included, except for the equipment used in geosynthetics manufacture, which is excluded because of its low importance. Process specific emissions such as NMVOC are included in the life cycle inventories as far as indicated by the companies. They are included independent of their contribution to the cumulative emissions of the respective substance (no threshold of a mass based cut-off is applied).

1.8 Data Gathering and Data Quality

Data about geosynthetic material production are gathered at the numerous companies participating in the project using pre-designed questionnaires. The company specific life cycle inventories are used to establish average life cycle inventories of geosynthetic material.

The data collected include qualitative information of system relevant products and processes from the producer, information from suppliers of the producer (where possible) as well as data from technical reference documents (e.g. related studies, product declarations, etc.). Qualitative information about reinforced concrete stems from technical reference documents and expert knowledge. Average LCI are established per case on the basis of equally weighted averages of the environmental performance of the products manufactured by the participating member companies.

The primary source of background inventory data used in this study is the ecoinvent data v2.2 (ecoinvent Centre 2010), which contains inventory data of many basic materials and services.

Time reference

The study refers to the year 2009. Foreground data about geosynthetic materials gathered by questionnaires refer to the year 2009 or, in a few exceptional cases, 2008. Data available about further material inputs and about the use of machinery are somewhat older. The characterisation of the four cases represents current best practice. Differences in age are discussed in the data quality section of the results chapters.

Geographical coverage

All data refer to European conditions. Some background data referring to Switzerland are used as estimation for European conditions, in particular regarding landfilling and incineration of wastes.

Technical reference

The two alternatives in each case are defined such that they can be considered technically equivalent or at least comparable. The geosynthetics used in the four cases represent a mix of different brands suited for the respective application. The conventional systems represent the most common type of construction.

Uncertainty assessment

In order to evaluate the uncertainty of the data used, Monte Carlo analyses are performed. The Monte Carlo analysis is performed in a way that excludes depending uncertainties. The results of the analyses show the effects of the independent uncertainties of the two alternatives compared.

To perform a Monte Carlo analysis, standard deviation needs to be defined for every inventory entry in the ecoinvent background data as well as in the foreground data of the geosynthetic manufacturing and the construction and disposal of the infrastructure elements. Standard deviations are shown in the respective ecospold tables in Annex C. Normally, the standard deviations are determined applying the ecoinvent pedigree approach. However, for some inputs of the foreground processes this approach is not appropriate and uncertainty parameters are calculated manually: This is the case, if

- the uncertainty range is known, as it is the case for the geosynthetic production or e.g. it is known in case 2CS2 that the share of cement in the stabilised foundation layer is between 3 and 6 weight-%, or
- the standard deviation calculated with the pedigree approach is obviously too large (or too low). This is e.g. the case for land use of the road (case 2). Because the length and width of the road are defined in the functional unit, there is no uncertainty concerning land use and the geometric standard deviation equals one.

Lifetimes, layer composition and dimensions of the infrastructure elements are not part of these uncertainty analyses but assumed to be exactly the same for both (all) cases or part of the functional unit definition. For instance, the thickness of the gravel filter layer is considered to be part of the functional unit and is exactly 0.3 meter in case 1A (with two alternative technical specifications of 0.2 and 0.4 meter, respectively used in sensitivity analyses). Uncertainty related to the amount of gravel needed (in tons) is +/- 7 % (95 % interval) or +/- 3.5 cm for a 50 cm gravel layer. This uncertainty is due to the variability in gravel density and the variability in matching the thickness specified. The uncertainty of all transport services required is represented with a geometric standard deviation of more than 2 (95 % interval of about + 100 %/- 50 %).

To assess the standard deviation in the average geosynthetic production the pedigree approach is not considered to be appropriate as the variations between the companies are known. The standard deviation is calculated assuming that the maximum and minimum values given represent the 95% confidence interval. This results in equation (1), whereby m represent the mean and s the standard deviation. The resulting quadratic equation gives two results, one positive (4) and one negative (5). The positive result represents the standard deviation of the mean value which is used to perform the Monte Carlo simulation.

(1) $$m * s - \frac{m}{s} = \max - \min$$

(2) $$s^2 - s * \frac{\max - \min}{m} - 1 = 0$$

(3) $$D = (-\frac{\max - \min}{m})^2 - 4*1*(-1)$$

(4) $$s_1 = \frac{-\frac{\max - \min}{m} + \sqrt{D}}{2*1}$$

(5) $$s_2 = \frac{-\frac{\max - \min}{m} - \sqrt{D}}{2*1}$$

whereby,

m = mean

s = standard deviation

D = Determinant

max = maximum value given considering all questionnaires of one case

min = minimum value given considering all questionnaires of one case

1.9 Allocation

1.9.1 Multi-output processes

No multi-output datasets are established in the foreground system. Thus multi-output processes only occur in the background system. In ecoinvent data v2.2 allocation based on exergy content is used for multi-output processes that produce heat and electricity. In most other cases, allocation based on economic revenues is used. Mass allocation is applied in the remaining multi-output datasets. In the product systems analysed, co-products in the background do not contribute significantly to the overall results. Hence, no sensitivity analyses related to allocation in multi-output processes are performed.

When plastics are disposed of in an incineration, heat and electricity can be produced as by-product to the waste treatment service. With the cut-off approach, those by-products leave the system without burdens. That is why the emissions from incineration are fully attributed to the product disposed of.

1.9.2 Recycling

Recycling of materials is modelled according to the recycled content approach. The recycled content approach represents the concept of strong sustainability (see also Frischknecht 2007, Frischknecht 2010). Materials to be recycled leave the system neither with burdens nor with credits. Materials made from secondary raw materials bear the loads of scrap collection, sorting and refining. This gives an incentive to use recycled materials in the product systems under study.

1.10 Life Cycle Impact Assessment

The environmental performance is assessed with the following impact category indicators:

- Cumulative Energy Demand (Primary Energy Consumption, split into non-renewable and renewable fractions),
- Climate Change (Global Warming Potential, GWP100),
- Photochemical Ozone Formation,
- Particulate Formation,
- Acidification,
- Eutrophication,
- Land competition, and
- Water use.

This set of indicators enables a comprehensive analysis of the environmental performance of the product systems under study and the shift of environmental burdens is likely to be avoided. Cumulative energy demand is used to get insights into the efficiency of using energy resources. Climate change and water use are considered because of their large environmental damage potential and their importance in international environmental policy. Land use is selected because the cases analysed deal with systems that occupy a land area. The remaining impact category indicators reflect emissions occurring during extraction and preparation of the raw materials (gravel and plastics) and during transportation.

In the following sections the category indicators are described.

1.10.1 Cumulative Energy Demand (CED)

The CED (implementation according to Frischknecht et al. 2007c) describes the consumption of fossil, nuclear and renewable energy sources along the life cycle of a good or a service. This includes the direct uses as well as the indirect or grey consumption of energy due to the use of, e.g. plastic or wood as construction or raw materials. This method has been developed in the early seventies after the first oil price crisis and has a long tradition (Boustead & Hancock 1979; Pimentel 1973). A CED assessment can be a good starting point in an assessment due to its simplicity in concept and its comparability with CED results in other studies. In this study, the CED indicator is used as a resource indicator.

The following two CED indicators are calculated:

- CED, non-renewable [MJ-eq.] – fossil and nuclear
- CED, renewable [MJ-eq.] – hydro, solar, wind, geothermal, biomass

1.10.2 Global Warming Potential 2007 (GWP)

All substances, which contribute to climate change, are included in the global warming potential (GWP) indicator according to IPCC (Solomon et al. 2007). The residence time of the substances in the atmosphere and the expected immission design are considered to determine the global warming potentials. The potential impact of the emission of one kilogram of a greenhouse gas is compared to the potential impact of the emission of one kilogram CO_2 resulting in kg CO_2-equivalents. The global warming potentials are determined applying different time horizons (20, 100 and 500 years). The short integration period of 20 years is relevant because a limitation of the gradient of change in temperature is required to secure the adaptation ability of terrestrial ecosystems. The long integration time of 500 years is about equivalent with the integration until infinity. This allows monitoring the overall change in temperature and thus the overall sea level rise, etc..

In this study a time horizon of 100 years is chosen, which is also used in the Kyoto protocol.

1.10.3 Further Environmental Impact Category Indicators

The remaining category indicators considered in this study derive either from the CML 2001 (Guinée et al. 2001a; b) or ReCiPe (Goedkoop et al. 2009) method. They are described in the following.

- *Acidification* [kg SO_2 eq]

  Acidification describes a change in acidity in the soil due to atmospheric deposition of sulphates, nitrates and phosphates. Major acidifying substances are NO_X, NH_3, and SO_2. This covers all relevant substances as in the foreground system no emissions of other acidifying substances as HCl, HF, etc occur. Derived from CML.

- *Eutrophication* [kg PO_4^{3-} eq]

  Eutrophication can be defined as nutrient enrichment of the aquatic environment. In inland waters eutrophication is one of the major factors that determine its ecological quality. Derived from CML.

- *Photochemical oxidation* [kg ethane eq] – average European ozone concentration change

  Also known under “summer smog”. Photo-oxidant formation is the photochemical creation of reactive substances (mainly ozone), which affect human health and ecosystems. This ground-level ozone is formed in the atmosphere by nitrogen oxides and volatile organic compounds in the presence of sunlight. Derived from CML.

- *Land competition* [m^2a]

  Not all types of land occupation have the same effect on the biodiversity. However, this fact is not considered on this level of assessment. The land competition indicator includes the total, unweighted sum of the area occupied. Derived from CML.

- *Particulate matter formation* [kg PM10 eq] – intake fraction of PM10

  Particulate matter (PM) causes health problems as it reaches the upper part of the airways and lungs when inhaled. Among others, secondary PM10 aerosols are formed from emissions of SO_2, NH_3 and NO_X. This indicator considers PM emitted by or formed from anthropogenic sources. Derived from ReCiPe.

- *Water use* [m^3]

  This indicator expresses the total amount of water used (excluding water turbined in hydroelectric power plants). Indicator created by the authors.

1.11 Sensitivity Analyses

Sensitivity analyses are conducted to verify the reliability of the results. The following scenarios are chosen:

- The average thickness of the gravel based filter in case 1A (30 cm) is varied between 20 and 40 cm to reflect different realistic technical specifications.
- Soil stabiliser material in case 2: In addition to the case 2C standard scenario with a 50/50 % cement/lime stabiliser, scenarios with a 100 % cement and a 100 % quicklime stabiliser are considered.
- Frost sensitivity of soil in case 2: In regions where the frost penetration depth reaches frost-sensitive soil F3, an upgrade of the frost-sensitive soil F3 in case 2B to non frost-sensitive soil F2 is required and the geosynthetic cannot directly be applied on the existing surface.[1] Hence, in a sensitivity analysis a scenario is considered, where the foundation is stabilised by removing the soil and replacing it with non frost-sensitive soil.
- Separation geosynthetic in case 2: In some cases no separation geosynthetic is needed in case 2B. Hence, a scenario is considered excluding the use of the separation geosynthetic.
- No allocation sensitivity is calculated for the recycling of concrete in the cases 4A and 4B, since recycling and primary concrete have about the same environmental impacts (Kytzia 2010) and hence, no credits can be given for recycling concrete. The same is true for recycling reinforcing steel, because reinforcing steel is made from scrap.
- No allocation sensitivity is calculated for the recycling of geosynthetics. In the first version of the report a sensitivity analysis on end of life allocation was performed using the end of life recycling approach. The results were hardly affected by a change in allocation approach.

1.12 Limitations of the Study

The life cycle assessments of the four cases filter layer, foundation stabilisation, landfill construction and slope retention are defined in a way that they represent commonly applied new constructions. Nevertheless construction methods may vary from one EU member state to the other. Thus the cases should be perceived as exemplary models of common and frequent applications of geosynthetic materials.

The results of the LCAs do not allow answering the question whether or not constructions based on geosynthetic materials are generally the environmentally preferable option. The specific situation and the particular construction in which the geosynthetic material is being used and the particular alternative options available should be taken into account.

1.13 Contents of this report

This report contains the life cycle assessment of the four cases of civil and underground engineering mentioned in Subchapter 1.5. Each of the Chapters 2 to 5 describe one of the four cases, including results discussion and data quality considerations. Chapter 6 contains overall conclusions and recommendations. Annex A contains a general description of the LCA methodology. Annex B shows the impact assessment result tables and Annex C contains the life cycle inventory information. Annex D contains the critical review report.

[1] Personal communication with Henning Ehrenberg , EAGM Project Working Group (31. May 2011)

2 Case 1 – Filter layer

2.1 Characterisation of the Alternatives

Geosynthetics is used in soil engineering, where it can serve as filter medium.

The case of the construction of a filter where geosynthetics are used (case 1B) is compared to the case of mineral filter (case 1A).

The average of 3 types of different geosynthetics is used to represent its' performance, namely

- filament,
- staple fibre, and
- woven grids

Polypropylene granules are used as basic material (in case 1B). They need to be UV stabilised to meet the requirements. The average weight of the polymer is 175 g/m^2.

The way of the construction of the filter depends on several factors. The basic conditions are shown in Tab. 2.1 and Fig. 2.1. A more detailed cross section of the boundary area is shown in Fig. 7.2. The cases 1A and 1B compare the environmental impacts of one square meter of the filter area below the road. The deeper excavation needed at the boundary area for case 1A is not considered in the comparison.

Tab. 2.1: Design criteria of the filter system of cases 1A and 1B

Parameter	Unit	Case 1A Mixed grain filter	Case 1B Filter with geo-synthetics
Filter size	m^2	1	1
Filtration geosynthetic	g/m^2		175
Gravel	cm	30	0

From these parameters it is calculated that the **required thickness D of the mineral filter (case 1A) is 300 mm** and the **one with the filter layer – i.e. with the geosynthetic, case 1B – is 1-2 mm**. Fig. 2.1 shows a cross section of the filter profile as modelled in this LCA.

In a sensitivity analysis the thickness of the gravel filter is varied by +/- 10 cm.

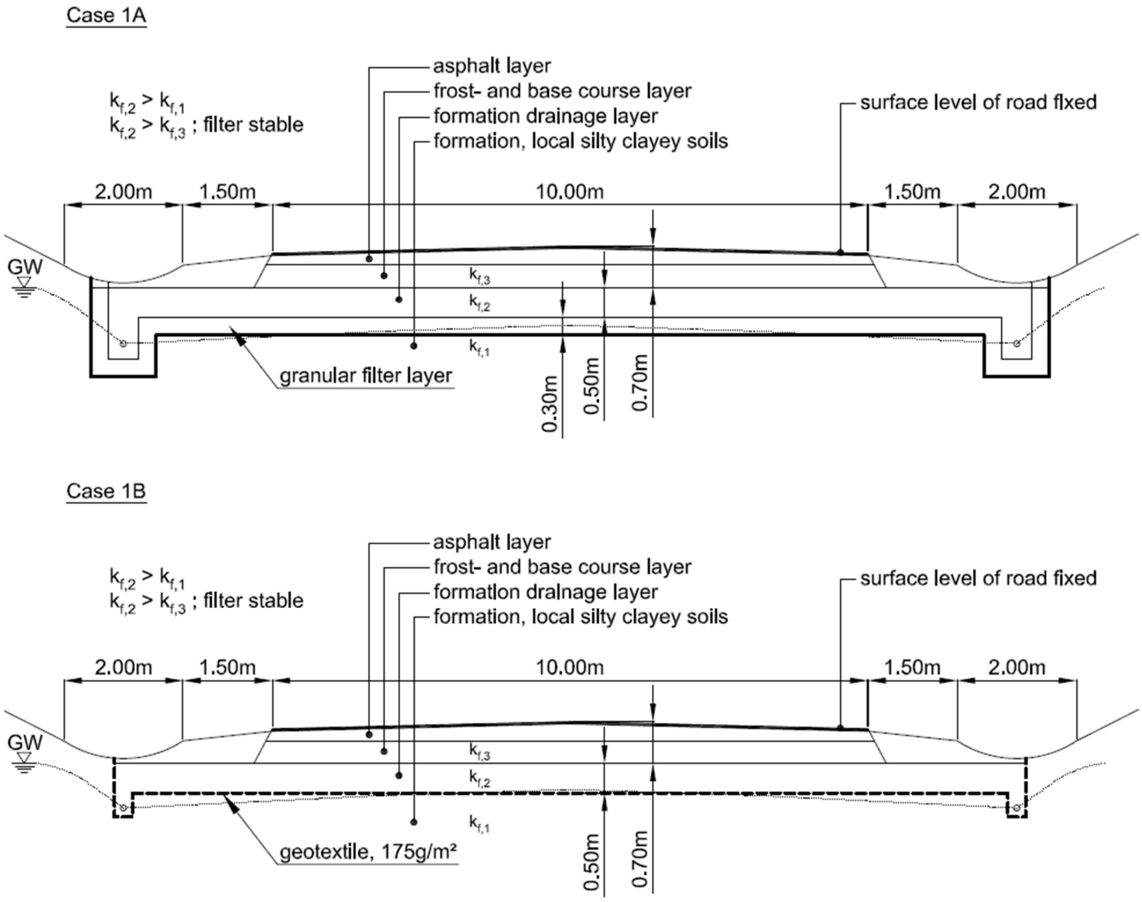

Fig. 2.1: Cross section of the mineral filter (case 1A, top) and geosynthetic filter system (case 1B, bottom)

The typical life time of the filter system in case 1A or 1B is estimated with 30 years.

2.2 Functional Unit and Definition of the System

The functional unit of case 1 is the provision of 1 m^2 of filter with a hydraulic conductivity (k-value) of 0.1 mm/s or more and an equal life time of 30 years.

2.3 Life Cycle Inventory

A detailed description of the life cycle inventory of the case 1A and case 1B filter system and the geosynthetic layers is placed in the Annex C.1. A general description of the infrastructure element and the geosynthetic layers is given in the following sections.

2.3.1 LCI of Infrastructure Element

Case 1A and case 1B differ in the design of the filter. The difference between the two cases lies in the amount of primary gravel used, the energy consumption that is related to the filter material used (material transportation, excavation etc.), and the use of geosynthetics. Recycled gravel is not considered for the filter system since no onsite recycled gravel is available when building a filter for the first time.

Some important key figures of the construction of the case 1A and case 1B are summarized in Tab. 2.2. The information refers to one square meter filter and a life time of 30 years. The shown figures regarding the particulate emissions refer to emissions from mechanical processes (e.g., pouring, compacting of gravel). Direct land use is not included in this LCI because the type of land use under which the filter is being built in is not known.

Tab. 2.2: Selected key figures referring to the construction of one square meter of filter for the cases 1A and 1B

	Unit	Case 1A Total	Case 1B Total
Gravel	t/m^2	0.69	-
Geosynthetic layer	m^2/m^2	-	1
Diesel used in building machines	MJ/m^2	2.04	1.04
Transport, lorry	tkm/m^2	34.5	0.035
Transport, freight, rail	tkm/m^2	-	0.07
Particulates, > 10 µm	g/m^2	4.8	0
Particulates, > 2.5 µm & < 10 µm	g/m^2	1.3	0

2.3.2 LCI of Geosynthetic Layer

In total 13 questionnaires concerning the production of geosynthetic layers used in filter applications are included. The quality of the data received is considered to be accurate. The level of detail is balanced in a few cases before modelling an average geosynthetic layer. A detailed description of the life cycle inventory is shown in Annex C.1.4.

Tab. 2.3 shows important key figures of the production of an average geosynthetic layer.

Tab. 2.3: Selected key figures referring to the production of 1 kg geosynthetic layer used in filter applications

	Unit	Value
Raw materials	kg/kg	1.05
Water	kg/kg	2.16
Lubricating oil	kg/kg	0.0026
Electricity	kWh/kg	1.14
Thermal energy	MJ/kg	1.49
Fuel for forklifts	MJ/kg	0.09
Building hall	m^2/kg	$2.51*10^{-5}$

2.4 Life Cycle Impact Assessment

2.4.1 LCIA of Filter layer

In this Subchapter the environmental impacts of 1 square meter filter over the full life cycle are evaluated. The life cycle includes the provision of raw materials as well as the construction and disposal phases.

In Fig. 2.2 the environmental impacts of the full life cycle of the filter are shown. The environmental impacts of the case with higher environmental impacts (case 1A) are scaled to 100°%. The total impacts are subdivided into the sections filter system, raw materials (gravel, geosynthetic layer), building machine (includes construction requirements), transports (of raw materials to construction site) and disposal (includes transports from the construction site to the disposal site and impacts of the disposal of the different materials).

Fig. 2.2 shows that case 1B causes lower impacts compared to case 1A with regard to all indicators investigated. The non-renewable cumulative energy demand of the construction and disposal of 1 square meter filter with a life time of 30 years is 131 MJ-eq in case 1A and 19 MJ-eq in case 1B. The cumulative greenhouse gas emissions amount to 7.8 kg CO_2-eq in case 1A and to 0.81 kg CO_2-eq in case 1B.

The environmental impacts of the filter layer of the case with higher environmental impacts (case 1A) are scaled to 100 %. The filter layer in case 1B causes between 0.2 % and 14.3 % of the environmental impacts of the filter layer in case 1A (water use, CED non-renewable). The greenhouse gas emissions caused by the filter according to case 1B are 10.4 % of the greenhouse gas emissions caused by the filter according to case 1A.

The main source of difference is the use and transportation of gravel. Hence, the use of geosynthetics may contribute to reduced environmental impacts of filter layers, because it substitutes the use of gravel.

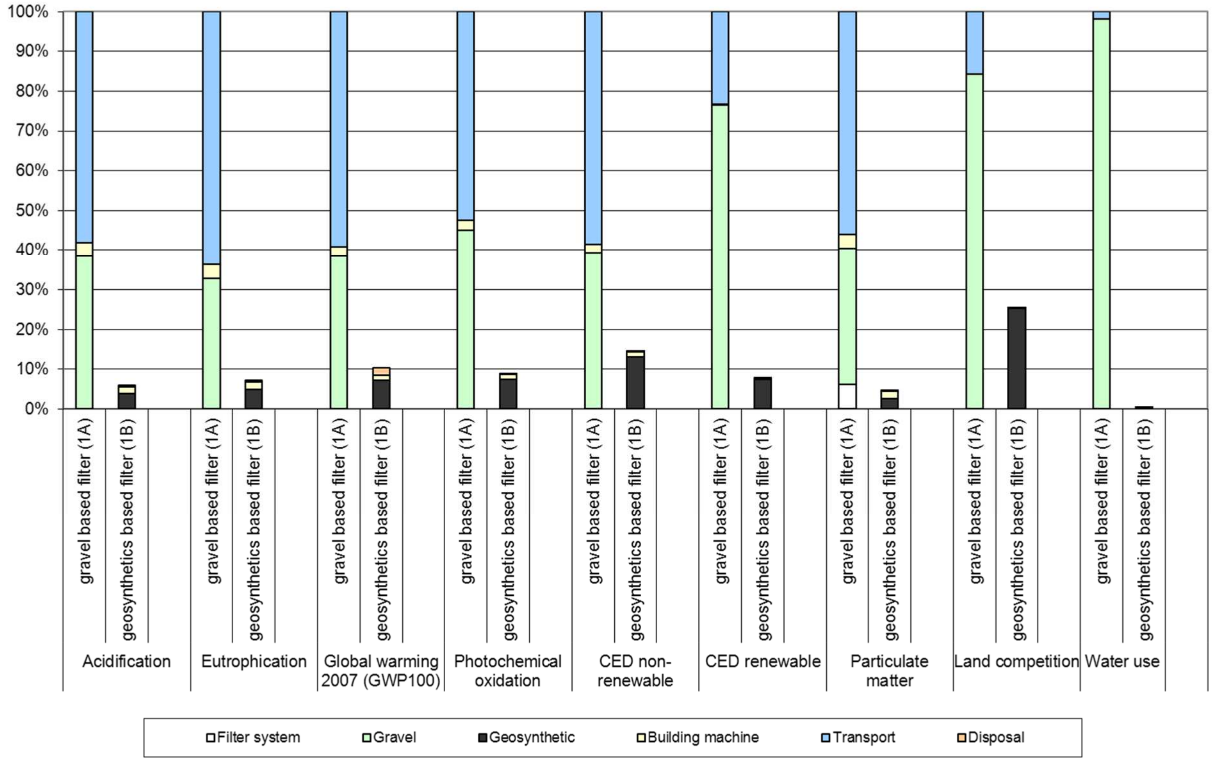

Fig. 2.2: Environmental impacts of the life cycle of 1 m^2 filter cases 1A and 1B. For each indicator, the case with higher environmental impacts is scaled to 100%.

2.4.2 Sensitivity Analysis

In a sensitivity analysis (cases 1AS1 and 1AS2), it is analysed how the results of the gravel filter layer change, if the thickness of the mineral filter is increased by 10 cm to a total thickness of 40 cm (1AS1) or if the thickness of the mineral filter is decreased by 10 cm to a total thickness of 20 cm (1AS2).

Fig. 2.3 reveals that, if a thicker filter layer is constructed (case 1AS1), the environmental impacts of the gravel based filter increase by 33 % and if a thinner filter layer is constructed (case 1AS2), the environmental impacts of the gravel based filter are decreased by 33 %. Nevertheless, the environmental performance of a filter with geosynthetics (case 1B) is considerably better than the environmental performance of a gravel based filter (cases 1A, 1AS1, 1AS2).

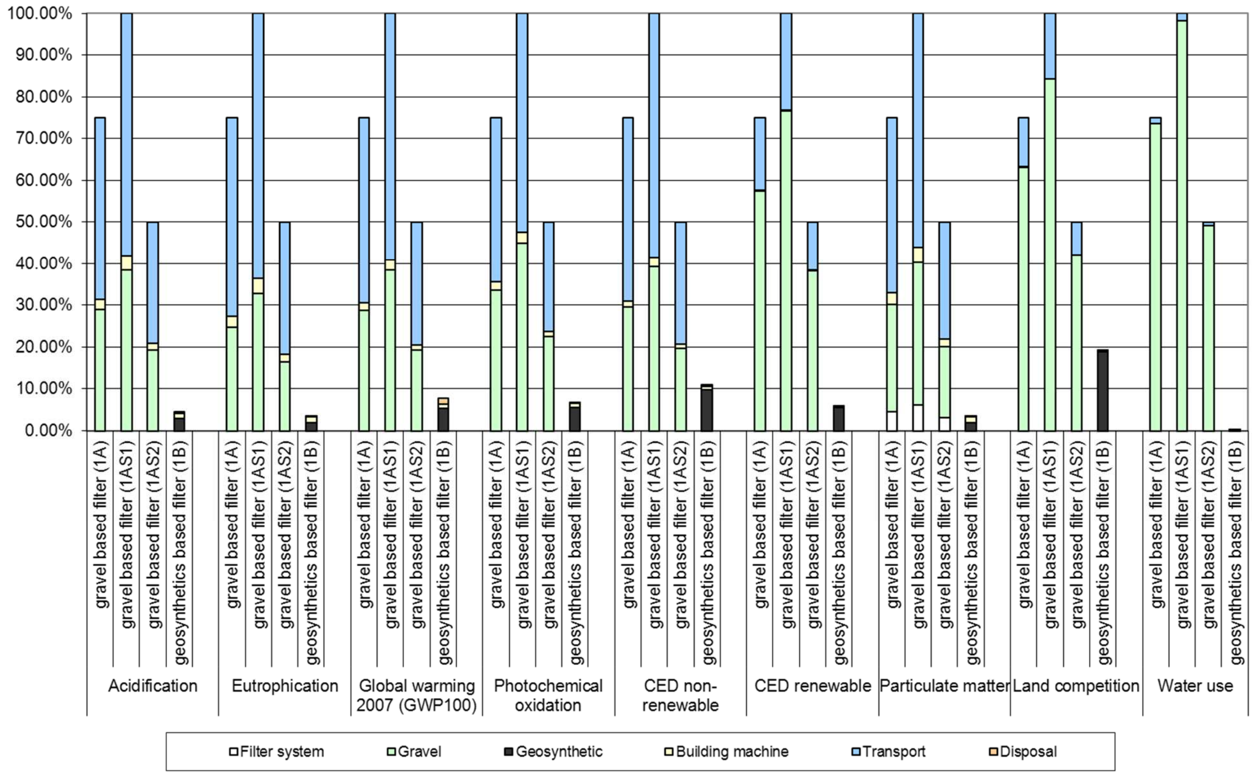

Fig. 2.3: Sensitivity analysis: environmental impacts of the life cycle of 1 m of filter layer, cases 1A and 1B. 1AS1 and 1AS2 refer to the sensitivity analysis with a different thickness of the gravel based filter layer. For each indicator, the case with highest environmental impacts is scaled to 100%.

2.4.3 Contribution Analysis Geosynthetic Production

In this section the environmental impacts of 1 kg geosynthetic layer are evaluated. Included are the provision and use of raw materials, working materials, energy carriers, infrastructure and disposal processes. The category geosynthetic in Fig. 2.4 comprises the direct burdens of the geosynthetic production. This includes land occupied to produce the geosynthetic as well as process emissions (e.g. NMVOC, particulate and COD emissions) from the production process but not emissions from electricity and fuel combustion.

The environmental impacts of the foundation separator are shown in Fig. 2.4. The cumulative greenhouse gas emissions amount to 3.2 kg CO_2-eq per kg.

Environmental impacts are mostly dominated by the raw material provision and electricity consumption. Raw material includes plastics, chemicals, printing colours, and other additives. Plastic raw materials are responsible for between 4 % (land competition) and 80 % (CED non renewable) of the overall impacts, printing colours, chemical and additives for between 2 % and 10 %.

Country-specific electricity mixes are modelled for each company and thus impacts of electricity consumption depend not only on the amount of electricity needed but also on its mix. The high share of electricity in CED renewable can be explained by the use of hydroelectric power plants in several electricity mixes.

Heating energy and fuel consumption for forklifts are of minor importance. With regard to land competition the geosynthetic production plays an important role (92 % of overall impacts). The impacts are dominated by the direct land use, i.e. land which is occupied by the manufacturer plant in which the geosynthetic is produced. Indirect land use, i.e. land occupation stemming from upstream processes, is significantly lower because no land occupation is reported in the inventories of plastic feedstocks and no land intensive products as e.g. wood are used in considerable amounts.

Water consumption (tap water, deionised water, decarbonised water) is included in the working materials. As a consequence, this category bears about 15°% of the total amount of water used.

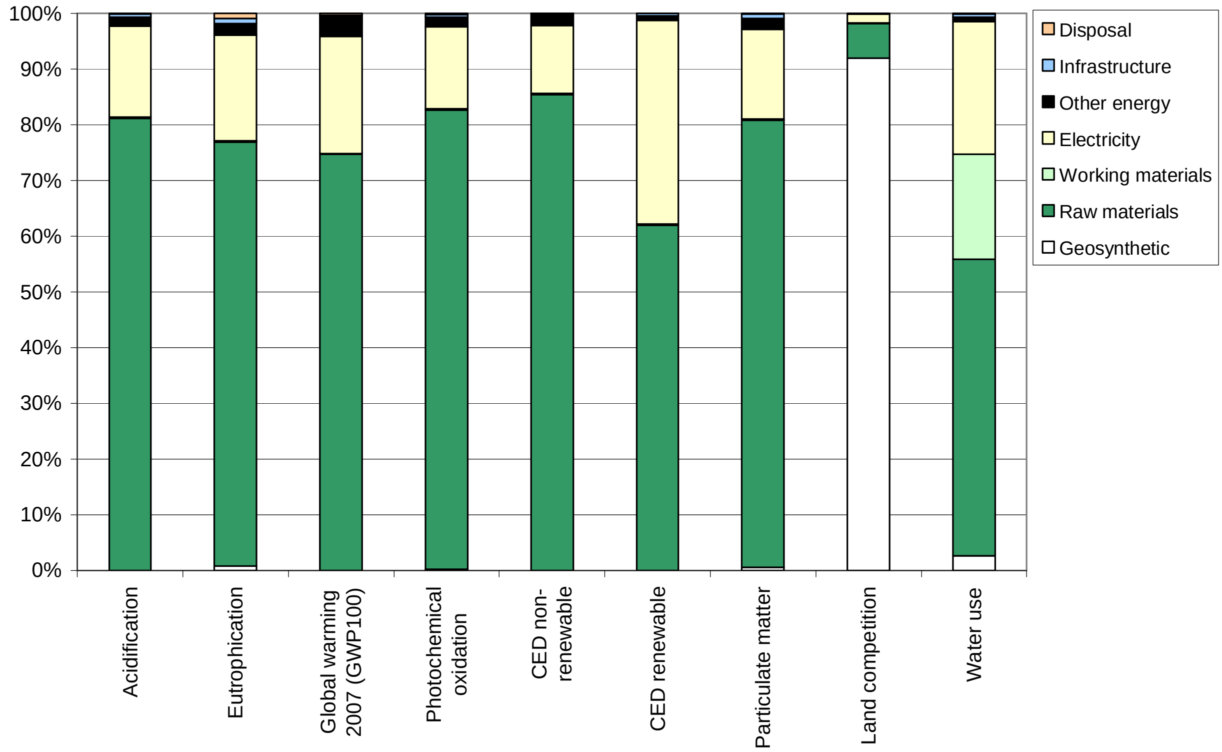

Fig. 2.4: Environmental impacts of the life cycle of 1 kg geosynthetic layer. Geosynthetic includes direct burdens of the geosynthetic production. Raw materials include plastic, extrusion if necessary, and additives, working materials include water (tap and deionised) and lubricating oil, other energy includes thermal energy and fuels, infrastructure covers the construction of the production plant and disposal comprises wastewater treatment and disposal of different types of waste.

2.4.4 Discussion and Data Quality Considerations

The use of geosynthetics leads to lower environmental impacts of filter layer construction in case more than a layer of 8 cm gravel is saved. If 30 cm of gravel are saved, the specific climate change impact of the construction of 1 square meter filter using geosynthetics is about 7 kg CO_2-eq lower compared to the impacts from the construction of an equivalent gravel based filter.

If a thinner gravel based filter is constructed, the environmental impacts of the gravel based filter are significantly reduced. Nevertheless, the sequence of the two cases does not change and the difference is still significant between the cases 1AS2 and 1B.

Filters constructed in Europe may differ in cross section and materials used. Thus, generalised assumptions were necessary to model a filter layer of a typical road. Data about gravel extraction and the use of building machines are based on generic data and knowledge of individual civil engineering experts.

The additional excavation needed for the boundary area (cf. Fig. 2.1 and Fig. 7.2) of case 1A is not considered in the comparison. An additional increase of the excavated volume would cause a further increase of the environmental impacts of case 1A compared to case 1B.

Despite the necessary simplifications and assumptions, the results of the comparison are considered to be significant and reliable.

3 Case 2 – Foundation Stabilisation

3.1 Characterisation of the Alternatives

In road construction the sub-base needs to meet defined requirements for compaction and bearing capacity. Improvements of some soil characteristics may be necessary while building on weak soils. Besides the construction of a conventional road with a non frost sensitive gravel/sand layer (case 2A), soil improvement can be done with geosynthetic (case 2B) or by adding lime, cement or hydraulic binder (case 2C). Both cases 2B and 2C lead to a reduced thickness of the gravel/sand layer.

The average of 3 types of different geosynthetics is used to represent its performance, namely

- extruded stretched grids,
- layed grids, and
- woven / knitted grids.

Polypropylene granulates are used as basic material to manufacture geogrids or wovens used in case 2B. The average weight of the polymer is 250 g/m^2. In alternative to that, also PET grids, with a weight of 260 g/m^2 (30 kN/m in each direction) are used.

The case of a conventional road (2A) is compared to a road reinforced with geosynthetics (2B) and to a cement/lime stabilised road (2C). The example considered is a road class III[2] with the same finished surface level in all cases. The road is built on frost-sensitive soil class F3. In regions where the frost penetration depth does not reach the frost-sensitive soil, this soil needs not being removed. This is considered the standard case 2B. In a sensitivity analysis the frost sensitive soil is removed and replaced by non frost-sensitive soil to meet the class F2 soil criterion (case 2BS1). In case of the cement/lime stabilised road the improvement is achieved by mixing the existing soil with 50 % cement and 50 % lime (case 2C). In a sensitivity analysis stabilisation is achieved by using limestone (case 2CS1) and cement only (case 2CS2). Fig. 3.1 shows the profiles of the three alternatives.

[2] This corresponds to a road with up to 3 million passes (equivalent 10t-axle).

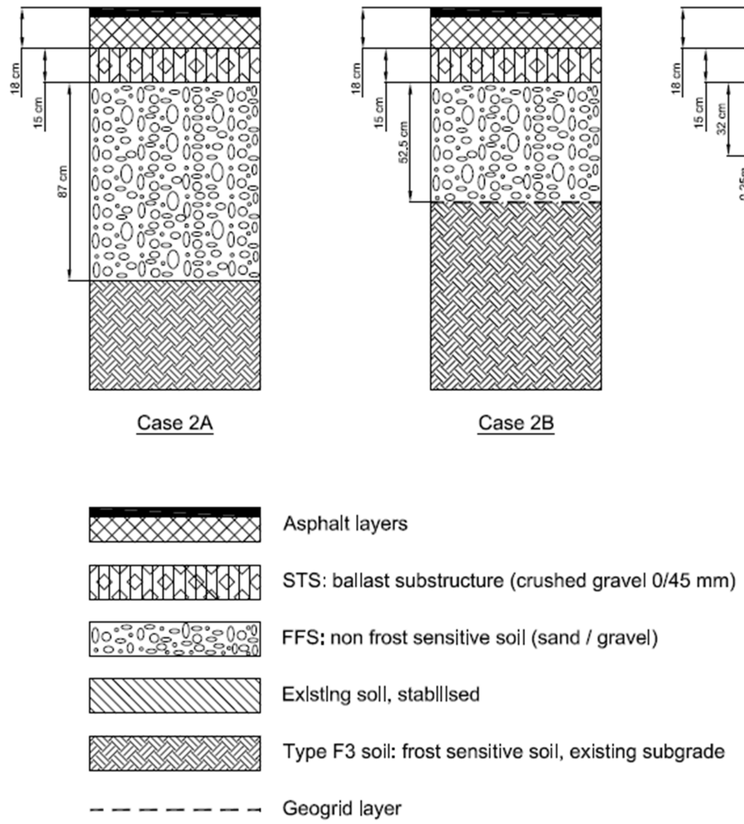

Fig. 3.1: Scheme of the road profiles of a standard road (case 2A, left), a road using reinforcement with geogrid (case 2B, middle) and a road using soil improvement with lime/cement (case 2C, right).

Tab. 3.1 and Tab. 3.2 show specific values of the roads for all three alternatives in their base case and their sensitivity analyses, respectively.

Tab. 3.1: Specification of three alternative road foundations

Parameter	**Unit**	**Case 2A conventional road**	**Case 2B Reinforced with geosyn-thetic**	**Case 2C Stabilised with ce-ment/lime**
road width	m	12	12	12
geogrid	g/m²	-	250 (PP) or 260 (PET)	-
separation and filtration geosynthetic	g/m² (geosynthetic from case 1)	-	150 (PP)	-
stabiliser : cement/quicklime	weight-%	-	-	2.25 / 3.75
existing soil stabilised	cm	-	-	25
grade and subgrade FSS	cm	87	52.2	32
ballast substructure (0/45mm), STS	cm	15	15	15
asphalt layer	cm	18	18	18
- surface layer	cm	4	4	4
- binder course	cm	14	14	14

Tab. 3.2: Specification of alternative road foundations using soil replacement (2BS1), no separation and filtration geosynthetic (2BS1), and quicklime and cement only for stabilisation (Cases 2CS1 and 2CS2, respectively)

Parameter	Unit	2BS1 Reinforced with geosynthetic, soil replacement	2BS2 Reinforced with geosynthetic, no separation geosynthetic, no soil replacement	2CS1 Stabilised with quicklime	2CS2 Stabilised with cement
road width	m	12	12	12	12
geogrid	g/m²	250 (PP) or 260 (PET)	250 (PP) or 260 (PET)	-	-
separation and filtration geosynthetic	g/m² (geosynthetic from case 1)	150 (PP)		-	-
stabiliser: quicklime only	weight-%			7.5 (5 to 10)	-
stabiliser: cement only	weight-%			-	4.5 (3 to 6)
existing soil stabilised	cm			25	25
existing soil removed and disposed (sensitivity analysis)	cm	16.8	-	-	-
non frost-sensitive soil (gravel/sand), FSS	cm	69	52.2		
subgrade	cm	-	-	32	32
ballast substructure (0/45mm), STS	cm	15	15	15	15
asphalt layer	cm	18	18	18	18
- surface layer	cm	4	4	4	4
- binder course	cm	14	14	14	14

The foundation is considered with a life time of 30 years because of the demanding conditions of the weak soil ground. The asphalt layer is assumed to consist of a 4 cm surface layer with a life time of 15 years. The 14 cm binder course has a lifetime of 30 years.

3.2 Functional Unit and Definition of the System

The function of case 2 is the provision of a road class III[3] on a stable foundation. The stability is either reached by using a stabiliser (cement/quicklime), a geogrid or is given without particular measures. The functional unit is thus defined as the construction, and disposal of a road class III with a length of 1 meter, a width of 12 meters and a lifetime of 30 years.

3.3 Life Cycle Inventory

A detailed description of the life cycle inventory of the case 2A, case 2B and case 2C road and the geosynthetic layers is placed in the Annex C.2. A general description of the infrastructure element and the geosynthetic layers is given in the following sections.

[3] Corresponds to a road with up to 3 millions 10t-axle-eq. passes. This could be arterial street, industrial road, pedestrian zone with loading traffic (RStO 01)

3.3.1 LCI of Infrastructure Element

The cases 2A, 2B and 2C differ in the design of the foundation stabilisation. The material and energy consumption which is related to the construction and disposal of the binder course and the surfacing in the pavement are equal in all three cases. Hence, the difference between the three cases lies in the amount of sandy primary gravel and cement that is used in the foundation, the energy consumption that is related to the foundation (material transportation, excavation etc.), and the use of geosynthetics. Recycled gravel is not considered for the foundation, since no onsite recycled gravel is available when building a road for the first time.

Some important key figures of the construction of the case 2A, case 2B and case 2C road are summarized in Tab. 3.3. The information refers to one meter road and a time period of 30 years. The NMVOC emissions are released from the bitumen and the figures regarding the particulate emissions refer to emissions from mechanical processes.

Tab. 3.3: Selected key figures referring to the road construction of one meter for the cases 2A, 2B and 2C (time period = 30 years)

	Unit	Case 2A		Case 2B		Case 2C	
		Total	Thereof foundation stabiliser	Total	Thereof foundation stabiliser	Total	Thereof foundation stabiliser
Bitumen	t/m	0.3	-	0.3	-	0.3	
Gravel	t/m	33.9	-	24.3	-	18.7	6.9
Cement	t/m	-	-	-	-	0.16	0.16
Quicklime	t/m	-	-	-	-	0.26	0.26
Geosynthetic separator layer	m^2/m	-	-	12	12	-	-
Geosynthetic stabiliser layer	m^2/m	-	-	12	12	-	-
Diesel used in building machines	MJ/m	1957	-	1972	-	1969	14.9
Transport, lorry	tkm/m	1711	-	1232	-	994	41.4
Transport, freight, rail	tkm/m	-	-	2.0	2.0	41.4	41.4
Land use	m^2/m	12	12	12	12	12	12
NMVOC	kg/m	2.19	-	2.19	-	2.19	-
Particulates, > 10 µm	g/m	237	-	170	-	131	-
Particulates, > 2.5 µm & < 10 µm	g/m	63	-	45	-	35	-

3.3.2 LCI of Geosynthetic

In total 7 questionnaires concerning the production of geosynthetic layers used in foundation stabilisation are included. The quality of the data received is considered to be accurate. The level of detail is balanced in few cases before modelling an average geosynthetic layer. A detailed description of the life cycle inventory is shown in Annex C.2.4.

Tab. 2.3 shows important key figures of the production of an average geosynthetic layer.

Tab. 3.4: Selected key figures referring to the production of 1 kg geosynthetic layer used in foundation stabilisation

	Unit	Value
Raw materials	kg/kg	1.02
Water	kg/kg	0.50
Lubricating oil	kg/kg	$3.62*10^{-4}$
Electricity	kWh/kg	1.76
Thermal energy	MJ/kg	1.75
Fuel for forklifts	MJ/kg	0.15
Building hall	m^2/kg	$1.41*10^{-5}$

3.4 Life Cycle Impact Assessment

3.4.1 LCIA of Foundation Stabilisation

In this Subchapter the environmental impacts over the full life cycle of 1 meter road class III are evaluated. Three alternative road foundations are analysed, a conventional foundation (case 2A), a foundation reinforced with geosynthetics (case 2B) and a foundation stabilised with cement/lime (case 2C). The life cycle includes the provision of raw materials as well as the construction and disposal phases.

In Fig. 3.2 the environmental impacts over the full life cycle of the road are shown. For each indicator, the case with the highest environmental impacts is scaled to 100 %. The total impacts are divided into the sections road, bitumen, gravel, geosynthetic layer, cement, lime, building machine (includes hot mixing of gravel and bitumen and construction requirements), transports (of raw materials to construction site) and disposal (includes transports from the construction site to the disposal site and impacts of the disposal of the different materials). A significant share of the environmental impacts is equal for all three cases, because the asphalt layers and the ballast substructure are identical. Thus the differences in results are less pronounced as compared to cases 1, 3 and 4.

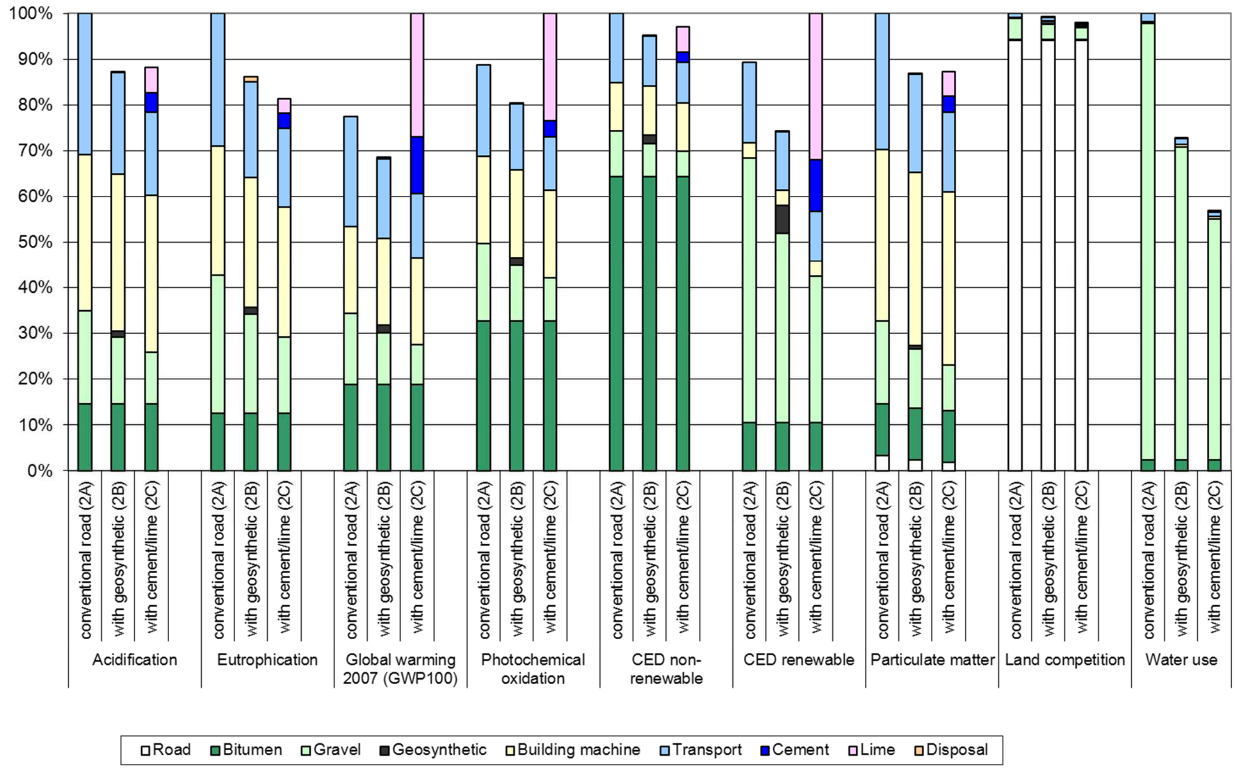

Fig. 3.2: Environmental impacts of the life cycle of 1 m road with different foundations, cases 2A, 2B and 2C. For each indicator, the case with highest environmental impacts is scaled to 100%.

Case 2A causes equal (land competition) or higher (all other impact category indicators) environmental impacts compared to case 2B. Case 2B causes lower impacts compared to case 2C regarding acidification, global warming, photochemical oxidation CED non-renewable and CED renewable. The differences between the cases 2B and 2C are small for the indicators acidification, CED non-renewable and particulate matter. With regard to global warming, case 2C causes 23 % higher impacts compared to case 2A and 32 % higher impacts compared to case 2B, mainly because of the geogenic CO_2 emissions from the clinker and quicklime production. The CED renewable of the alternatives 2A and 2B are lower than the CED renewable of case 2C. Case 2A has a higher water use than the cases 2B and 2C.

The non-renewable cumulative energy demand of the construction and disposal of 1 meter stabilised road with a width of 12 meters and a life time of 30 years is 25’200 MJ-eq in case 2A, 23’900 MJ-eq in case 2B and 24’400 MJ-eq in case 2C. The cumulative greenhouse gas emissions amount to 0.73 t CO_2-eq in case 2A, 0.65 t CO_2-eq in case 2B and 0.95 t CO_2-eq in case 2C. Correspondingly, the cumulative greenhouse gas emissions of 1 km stabilised road are 730 t CO_2-eq in case 2A, 650 t CO_2-eq in case 2B and 950 t CO_2-eq in case 2C.

The most relevant aspects concerning the life cycle of the road are the use of bitumen, building machines, cement and gravel. The provision of bitumen is more important than building machines with respect to photochemical oxidation and CED non-renewable. Gravel is the driving factor with regard to CED renewable and water use and the land use of the road is contributing most to land competition.

Bitumen bears an important share of the overall burdens. Bitumen is made from crude oil. Its impacts are relatively high depending on the indicator. In case of CED non-renewable this is due to the extraction of the resource crude oil. In case of photochemical oxidation SO_2, CH_4 and CO emissions from diesel-electric generating, electricity production, and natural gas venting during onshore production are important. Nevertheless, impacts of the bitumen are exactly the same in all three cases because the same amount is used. The impacts related to the use of building machines are similar too because the highest share of building machines is used for hot mixing of gravel and bitumen which is the same in all three cases.

The main difference lies in the amount of gravel needed, the cement and lime used in case 2C and the geosynthetics used in case 2B. Compared to case 2A about 28 % less gravel is used in case 2B and 45 % less gravel is used in case 2C. The environmental impacts of gravel are mainly caused by building machines and the use of electricity during mining. Furthermore, transport expenditures correlate with the amount of gravel needed, i.e. the more gravel used to build the road the more transports are required.

The use of cement and quicklime has a high influence on the result with regard to global warming and CED renewable. The burdens with regard to GWP stem mainly from the clinker production, namely from geogenic CO_2 emissions from the calcination process and fossil CO_2 emissions from traditional fuels. The use of geosynthetics contributes significantly to the CED renewable (8 %) because of hydropower used in some electricity mixes that provide electricity used in manufacturing.

The disposal of the case 2A and 2C road has no environmental impacts, since the material content is considered as a gravel stock and the environmental impacts from excavation and transport to the place of reuse are allocated to the product where gravel is reused (see Section 1.9.2). The bitumen content is left onsite as well. In case 2B the geosynthetic layer is incinerated, landfilled or recycled. For incineration and landfilling the respective burdens are included. The influence of disposal of the geosynthetics on the overall environmental impacts of the case 2B road is less than 0.7°%.

The share of the geosynthetic layer to the overall impacts of the road is between 0.75 % and 6.1 % with regard to particulate matter and CED renewable, respectively. Neither cement nor quicklime is needed but more gravel is required when applying a geosynthetic stabiliser layer.

A trade off between global warming and other environmental indicators can be identified, since the conventional road and the road reinforced with the geosynthetic layer exhibits lower global warming impacts, but higher impacts on other indicators, such as eutrophication, particulate matter emissions or water use compared to the case where the road is stabilised with a cement/quicklime stabiliser.

3.4.2 Sensitivity Analyses

In a sensitivity analysis, it is analysed how the results change for the alternative road foundation using soil replacement (case 2BS1) and for the alternative using no separation geosynthetic (case 2BS2).

In addition, the use of quicklime instead of a cement/lime mixture as a soil stabiliser is evaluated in case 2CS1, and the use of cement only instead of the cement/lime mixture as a soil stabiliser is evaluated in case 2CS2.

Fig. 3.3 reveals that the result of the case 2B is sensitive, if soil is removed and replaced (case 2BS1). The additional excavation, the additional gravel needed and the additional transport increases the environmental impacts of case 2BS1 by about 10 % compared to case 2B. There is a small decrease of the environmental impact of the case 2BS2 compared to case 2B because no separation geosynthetic is used. This decrease of the environmental impact is lower than 2 %. Furthermore, it could be that a mineral layer must be installed instead of a geosynthetic separation and filtration layer. Differences between environmental impacts from mineral and geosynthetic filter layers can be seen in case 1 and are not evaluated in this case.

Fig. 3.3 shows that using quicklime as stabiliser (case 2CS1) causes the highest environmental impacts with regard to global warming, photochemical oxidation, CED non-renewable and CED renewable. With regard to acidification and eutrophication this scenario causes about the same impacts like the cement stabiliser (case 2CS2) but lower impacts than the geosynthetic stabiliser (case 2B). With regard to land competition, particulate matter and water use the impacts of the quicklime based stabiliser are similar to the impacts of the cement stabiliser. The main driver of the environmental impacts from the quicklime supply chain is the calcination process with high energy consumption and considerable air emissions. Within the calcination process, calcium carbonate reacts to quicklime and geogenic carbon dioxide, which is emitted into air. A reason why applying quicklime causes higher environmental impacts than using cement is the fact that a higher volume of quicklime is required in order to achieve the same stabilising quality as compared to a cement stabilised soil.

Tab. 3.5: Scenario definitions

Scenario name	Definition
2A	Road class III with conventional road foundation (standard case)
2B	Road class III foundation reinforced with geosynthetics (standard case)
2BS1	Road class III reinforced with geosynthetics, frost sensitive soil replaced with non-frost sensitive soil
2BS2	Road class III reinforced with geosynthetics with no separation and filter geosynthetic
2C	Road class III stabilised with cement/lime (standard case)
2CS1	Road class III foundation stabilised with quicklime
2CS2	Road class III foundation stabilised with cement

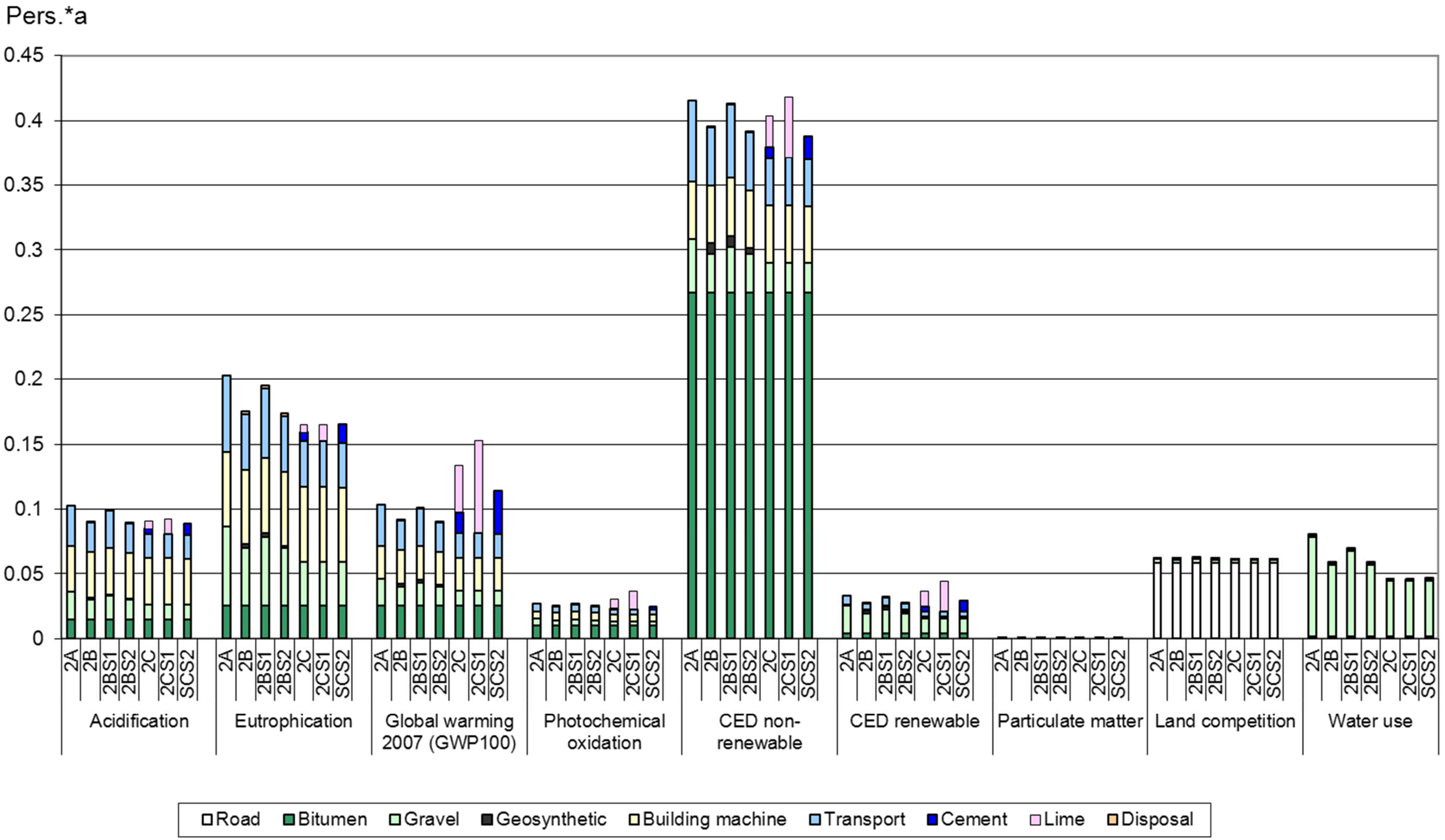

Fig. 3.3: Sensitivity analyses: environmental impacts of the life cycle of 1 m road class III, cases 2A, 2B and 2C. Case 2BS1: soil replacement; case 2BS2: no separation geosynthetic. Case 2CS1: quicklime stabiliser; case 2CS2: cement stabiliser. For each indicator, the results are normalised with the annual world impacts per capita.

3.4.3 Uncertainty Analysis (Monte Carlo Simulation)

To determine the reliability of the results above, a Monte Carlo simulation for the full life cycle of the road is performed. In the Monte Carlo simulation a random value within the uncertainty range specified is taken for every inventory entry. In total 1000 Monte Carlo runs are calculated to form an uncertainty distribution. The life time of the road and the dimensions are not subject to this uncertainty analysis.

Fig. 3.4 shows for each impact category indicator the probability that the environmental impact of case 2B is higher or lower compared to the environmental impact of case 2A. For all indicators the Monte Carlo simulation confirms that case 2B exhibits lower impacts than case 2A.The results are stable for all the indicators with the lowest probability of 68 % for CED renewable.

In general it can be concluded that the more distinct the difference in the standard case is (compare Fig. 3.2) the more reliable is the result that case 2B exhibits lower impacts than case 2A. The differences between cases 2A and 2B are considerable for all the indicators. These clear differences explain the stable result for all the indicators.

With regard to land competition the difference between cases 2A and 2B is very small (less than 1 %). More than 95 % of the land use is due to the land occupation of the road, which is exactly the same in both cases and does not contribute to the uncertainty of the land occupation results. The small difference is thus confirmed stable by the Monte Carlo simulation.

Hence, the road class III with a foundation reinforced with geosynthetic layer leads to lower environmental impacts than the conventional road class III.

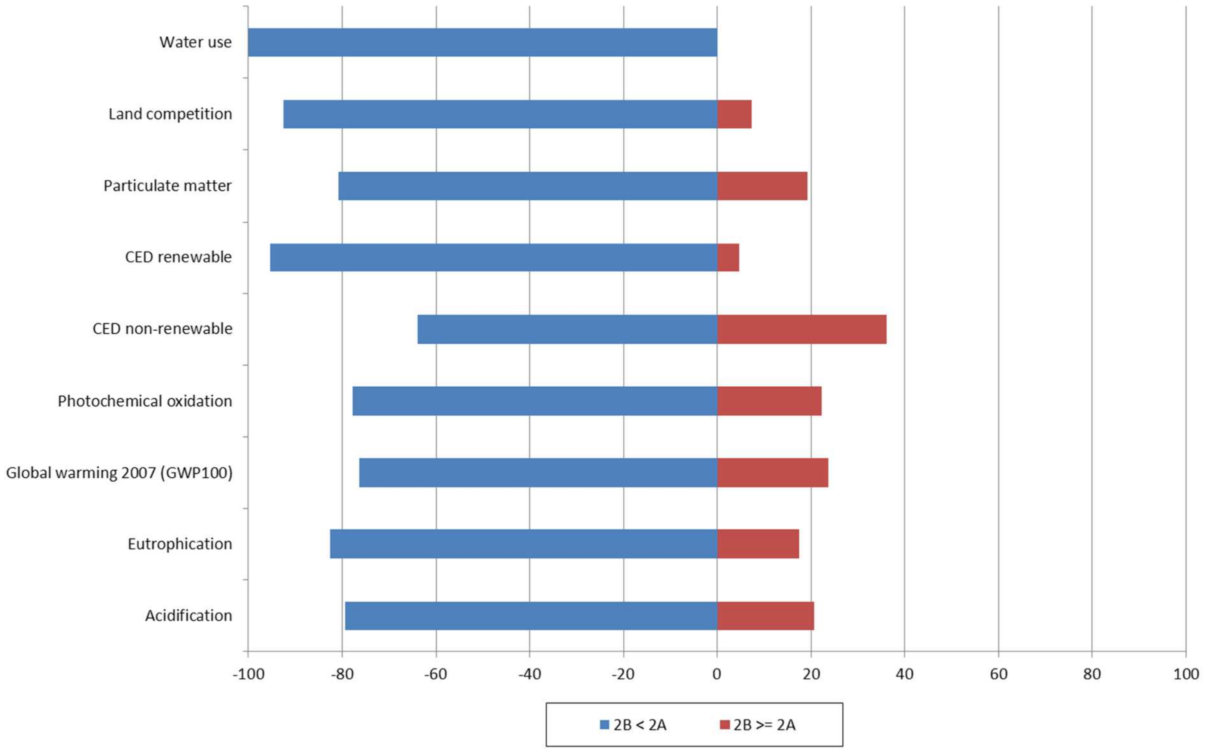

Fig. 3.4: Uncertainty analysis of the life cycle of the road in case 2B and 2A. The figure shows the probability for each impact category indicator that the environmental impact of case 2B is higher or lower compared to the environmental impact of case 2A. The blue bar shows the probability that case 2B performs better, the red bar shows the probability that case 2A performs better. Monte Carlo Simulation, 1000 runs.

Fig. 3.5 shows for each impact category indicator the probability that the environmental impact of case 2B is higher or lower compared to the environmental impact of case 2C. For the indicators water use, land competition, CED renewable, photochemical oxidation and global warming potential the Monte Carlo simulation leads to stable results. For the indicators, particulate matter, CED non-renewable, eutrophication and acidification the uncertainty analysis reveals no stable results. With regard to the indicators particulate matter, CED non-renewable eutrophication and acidification case 2B exhibits higher environmental impacts compared to case 2C in more than 40 % of the runs. This share is considered to be too high to make a clear statement in favour of one of these two cases. In case of the indicators land competition and water use case 2B causes higher environmental impacts than case 2C in more than 90 % of the runs. With regard to land competition the difference between case 2B and 2C is very small too (less than 1 %), but this small difference is confirmed stable by the Monte Carlo simulation. This can be explained by taking into account that more than 95 % of the impacts of this indicator are dominated by the land occupation of the road, which is exactly the same in both cases.

It can be concluded that the uncertainty analysis reveals no clear result for 5 out of 9 indicators. For the indicators CED renewable, photochemical oxidation, land use and global warming potential the uncertainty analysis provides a stable result that confirms the lower environmental impacts of a road class III reinforced with geosynthetics compared to class III road stabilised with cement/lime. For the indicators water use, particulate matter, CED non-renewable, eutrophication and acidification the results do not show a distinct difference between the environmental performance of a road class III reinforced with geosynthetics and with cement/quicklime.

In general one can say that the more distinct the difference in the standard case is (compare Fig. 3.2) the more reliable is the result that case 2B exhibits lower impacts than case 2C. The difference between cases 2B and 2C for the indicators water use, eutrophication, acidification, CED non-renewable and particulate matter is below 7 %. Therefore the uncertainty analysis reveals no reliable result for these indicators.

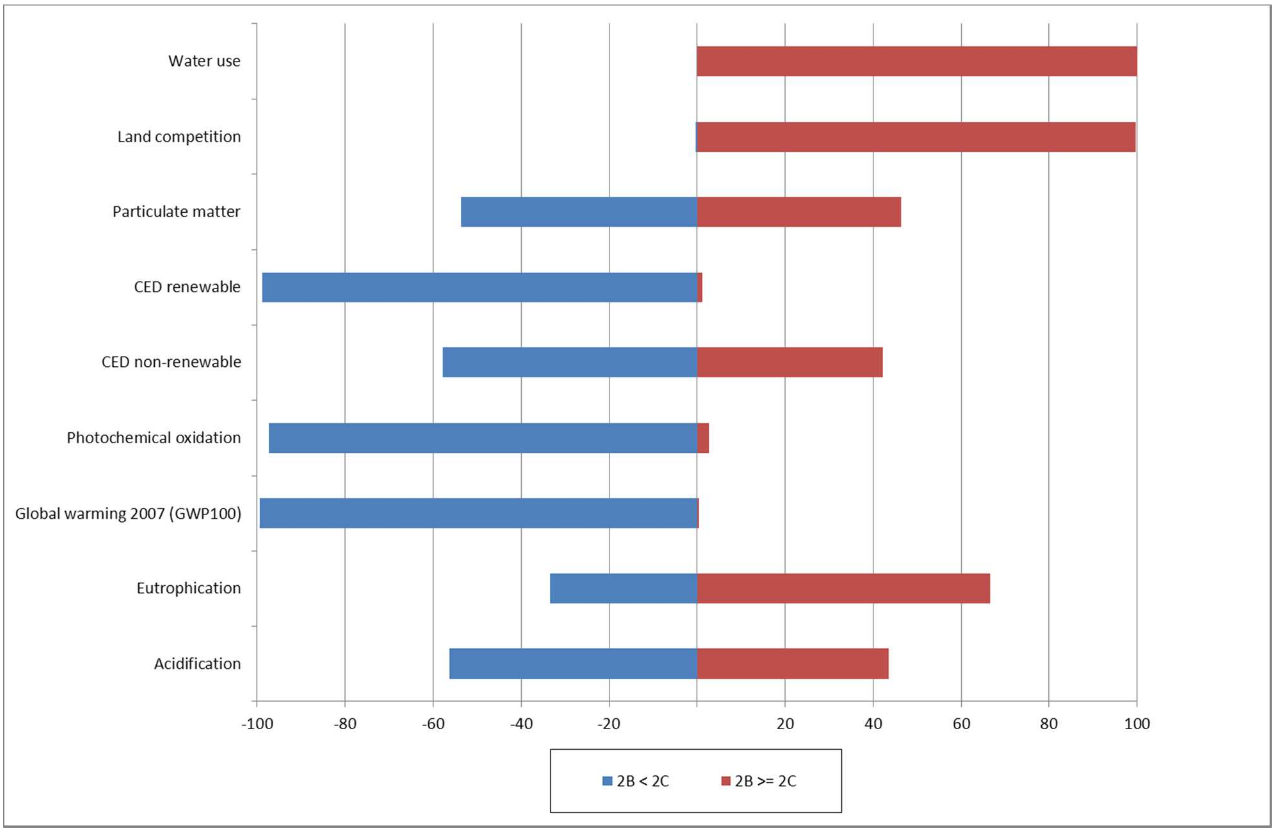

Fig. 3.5: Uncertainty analysis of the life cycle of the road in case 2B and 2C. The figure shows the probability for each impact category indicator that the environmental impact of case 2B is higher or lower compared to the environmental impact of case 2C. The blue bar shows the probability that case 2B performs better, the red bar shows the probability that case 2C performs better. Monte Carlo Simulation, 1000 runs.

3.4.4 Contribution Analysis Geosynthetic Production

In this section the environmental impacts of 1 kg geosynthetic layer are evaluated. Included are the provision and use of raw materials, working materials, energy carriers, infrastructure and disposal processes. The category geosynthetic in Fig. 3.6 comprises the direct burdens of the geosynthetic production. This includes land occupied to produce the geosynthetic as well as process emissions (e.g. NMVOC, particulate and COD emissions) from the production process but not emissions from electricity and fuel combustion.

In Fig. 3.6 the environmental impacts of the geosynthetic layer are shown. The cumulative greenhouse gas emissions amount to 3.4 kg CO_2-eq per kg.

Environmental impacts are mostly dominated by the raw material provision and electricity consumption. Raw material includes plastics, chemicals, printing colours, and other additives. Plastic raw materials are responsible for between 2 % (land competition) and 74 % (CED non-renewable) of the overall impacts, printing colours, chemical and additives for between 9 % (CED non-renewable) and 17 % (land competition).

Country-specific electricity mixes are modelled for each company and thus impacts of electricity consumption depend not only on the amount of electricity needed but also on its mix. The high share of electricity in CED renewable can be explained by the use of hydroelectric power plants in several electricity mixes.

Heating energy and fuel consumption for forklifts are of minor importance. The burdens of infrastructure and working materials are so small that they are not even visible in the graph. With regard to land competition the geosynthetic production plays an important role. The impacts are dominated by the direct land use, i.e. land which is occupied by the manufacturer plant in which the geosynthetic is produced. Indirect land uses, i.e. land occupation stemming from upstream processes, are significantly lower because no land occupation is reported in the inventories of plastic feedstock and no land intensive products as e.g. wood are used in considerable amounts.

Water consumption is included in the working materials. As a consequence, this category bears about 4°% of the total amount of water used.

Compared to the geosynthetic from case 1 the share of electricity is higher in this case. This is because more electricity is required to manufacture the average geosynthetic layer used in case 2 compared to the one used in case 1. Additionally, less cutting wastes are produced and thus less raw materials are needed, which lowers the burdens of raw material provision. However, in terms of climate change impact both geosynthetic layers are very similar.

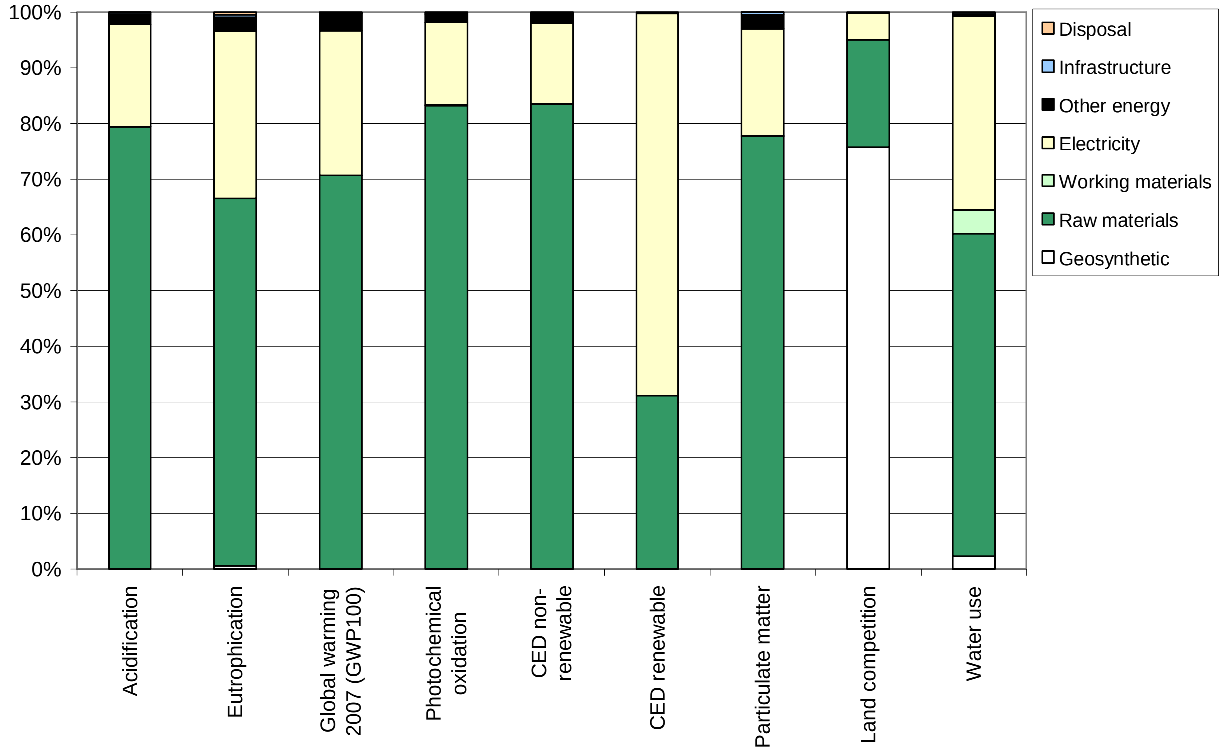

Fig. 3.6: Environmental impacts of the life cycle of 1 kg geosynthetic layer. Geosynthetic includes direct burdens of the geosynthetic production. Raw materials include plastic, extrusion if necessary and additives, working materials include water (tap and deionised) and lubricating oil, other energy includes thermal energy and fuels, infrastructure concerns the production plant and disposal comprises wastewater treatment and disposal of different types of waste.

3.4.5 Discussion and Data Quality Considerations

Compared to a conventional road (case 2A), the use of geosynthetics leads to lower environmental impacts concerning all indicators investigated (case 2B). At least a layer of 25 cm of gravel in a conventional road must be replaced by geosynthetics used in road foundation in order to cause the same or lower environmental impacts regarding all indicators. The comparison between a road stabilised with geosynthetics (case 2B) and a road stabilised with cement/lime (case 2C) is less clear-cut. On the one hand case 2B shows lower climate change impacts, photochemical oxidation impacts and renewable cumulative energy demand. On the other hand acidification and particulate matter impacts as well as non renewable cumulative energy demand are similar and case 2C shows lower eutrophying impacts, land competition and water use. The climate change impact of a road (class III, 12 meters wide, 30 years lifetime) using geosynthetics is about 80 tons CO_2-eq per km lower compared to the impacts from the construction of an equivalent conventional road. This difference is equal to about 11 % of the overall climate change impact of the construction and disposal efforts of an entire road during its 30 years lifetime (excluding traffic emissions). If we compare a road reinforced with geosynthetics to a road stabilised with cement/lime the climate change impact of a class III road reinforced with geosynthetics is about 300 tons CO_2-eq per km lower compared to the impacts of road class III stabilised with cement/lime. This difference is equal to about 30 % of the overall climate change impact of the construction and disposal efforts of an entire road during its 30 years lifetime (excluding traffic emissions).

If quicklime or cement is used as stabiliser instead of a cement/quicklime mixture, the climate change impact is increased compared to a conventional road and compared to a road reinforced with geosynthetics. The use of quicklime further increases the environmental impact for the categories photochemical oxidation and CED renewable

The sensitivity analysis reveals an increase of the environmental impact, if the existing soil has to be replaced and disposed. The increase of the total environmental impact caused by case 2BS1 is about 10 % compared to case 2B. The use of no separation and filtration geosynthetic did not cause considerable changes in the result for all indicators.

Roads constructed in Europe may differ in cross section and materials used. Thus, generalised assumptions were necessary to model a cross section of a typical road. Data about gravel extraction, soil stabilisation and the use of building machines are based on generic data and knowledge of individual civil engineering experts.

Furthermore, the uncertainty analysis shows that results of the comparison of the conventional road and the road reinforced with geosynthetics are reliable with regard to all indicators. The comparison of the road reinforced with geosynthetics and the road stabilised with cement/lime are reliable with regard to the indicators land use, CED renewable, photochemical oxidation and global warming potential. Regarding the other indicators the difference is considerably less significant.

4 Case 3 – Landfill Construction

4.1 Characterisation of the Alternatives

The European Regulation specifies the thickness of gravel for a drainage system in a cap of a hazardous/non-hazardous waste landfill site. The grain size is not defined in particular. A geosynthetic on top of the drainage gravel is often used to prevent moving of fines of the top soil into the drainage, as also a second geosynthetic is used below the drainage as a protection layer to secure that the sealing element was not damaged to the drainage. Instead of the conventional gravel drainage layer a geosynthetic drainage layer is used. In practice both solutions use geosynthetics - on top and below of the drainage layer. All the other layers in a landfill site change neither in thickness nor in material requirements. The profiles of the conventional and geosynthetic alternatives are shown in Fig. 4.1.

The average of 2 types of different geosynthetics are used to represent its' performance, namely

- drainage nets and
- drainage 3D filament.

Polypropylene or polyethylene granulates are used as basic material in case 3B. The average weight of the drainage polymer is 500 g/m^2 (excluding 2 geosynthetic filters). Gravel with a rather uniform grain size of 16-32 mm and a layer thickness of 50 cm is used in case 3A.

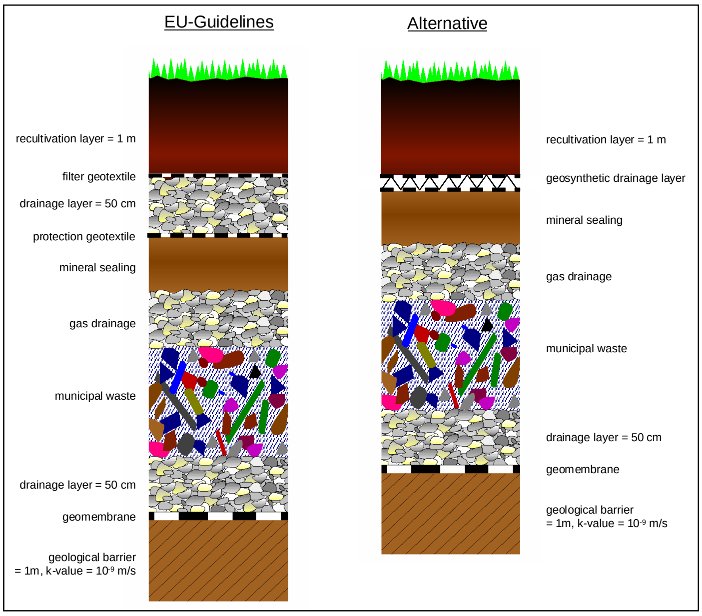

Fig. 4.1: Scheme of the profile of waste landfill site class 2 according to EU guidelines (case 3A, left) and with a geosynthetic as an alternative drainage layer in the cap (case 3B, right)

According to the European Council Directive 1999/31/EC a mineral drainage layer with a thickness of 0.50 m is required. The hydraulic conductivity of the drainage layer (k-value) has not been defined for the drainage layer according to the European Council Directive 1999/31/EC (European Comission 1999). All countries in the European Union have to comply with these requirements/regulation. Each country in the European Union can have an additional regulation which has to fulfil the requirements of the European Union, but is more specific. Additional regulations were introduced in slightly different ways in EU countries. In Germany for example additional requirements for the drainage layer are documented (see German Federal Government 2009). Here the hydraulic conductivity is documented with ≥ 1 mm/s (k-value) and the thickness is defined to be sufficient with ≥ 0.30 m for capping sealing systems. Similar requirements as in Germany are used in the Netherlands since years.[4]

In case that alternative drainage layers are planned to be used, it has to be documented, that a sufficient long term drainage capacity of the product is given. For geosynthetic drainage layers a calculation of the long term drainage capacity has to be carried out.

Several calculations and practical cases over all of Europe have shown that geosynthetic drainage layers with a core weight of an average of 500 g/m² (as an average from different product and production types) documents the suitability of the geosynthetic drainage layer for final capping sealing systems.[5]

Tab. 4.1 shows specific values of the drainage layer for both alternatives.

Tab. 4.1: Characteristics of two alternative landfill drainage constructions

Parameter	Unit	EU-Guidelines	Alternative (geogrid)
Landfill size	m^2	100000	100000
Drainage layer			
- gravel 16/32	cm	50	
- drainage core	g/m^2		500

The typical life time can be assumed to be similar in both cases (100 years).

4.2 Functional Unit and Definition of the System

The function of case 3 is to provide a drainage layer in a landfill cap of hazardous/non-hazardous waste landfill site. The purpose of this drainage layer is to discharge infiltrating rainwater from the surface. The functional unit is defined as the construction and disposal of 1 m^2 surface area drainage layer with a hydraulic conductivity (k-value) of 1 mm/s or more and an equal life time of 100 years.

4.3 Life Cycle Inventory

A detailed description of the life cycle inventory of the case 3A and case 3B cap and the geosynthetic layers is placed in the Annex C.3. A general description of the infrastructure element and the geosynthetic layers is given in the following sections.

The geosynthetic layer modelled in case 1 with the same weight is an appropriate approximation for the geosynthetic on top and below the drainage layer[6].

4.3.1 LCI of Infrastructure Element

Case 3A and case 3B differ in the design of the drainage layer. The material and energy consumption, which is related to the construction and disposal of the other parts of the landfill (e.g. the gas drainage, the mineral sealing and the recultivation layer) are equal in both cases and are not considered in this study. Hence, the difference between the two cases lies in the amount of primary gravel and geosynthetics that is used in the drainage layer and the energy consumption that is related to the drainage layer (material transportation, excavation etc.). The use of recycled gravel is not considered, since usually no onsite recycled

[4] Personal communication, Henning Ehrenberg, on behalf of EAGM, 20.10.2010

[5] Personal communication, Henning Ehrenberg, on behalf of EAGM, 24.9.2010

[6] Personal communication, Henning Ehrenberg, on behalf of EAGM, 29.4.2010

gravel is available when covering a landfill site. In case 3A three process steps are required to build up the drainage layer (filter layer, gravel layer, protection layer) whereas in case 3B only one process step is needed as the protection and filter layer are already glued to the main drainage layer.

Some important key figures of the construction of the case 3A and case 3B drainage layer are summarized in Tab. 4.2. The information refers to one square meter drainage layer, since the hydraulic conductivity is equal in both cases. The life time in both cases is the same (100 years). The figures shown regarding the particulate emissions refer to emissions from mechanical processes.

Tab. 4.2: Selected key figures referring to the construction of one square meter of a case 3A and case 3B drainage layer with a hydraulic conductivity of at least 1 mm/s (lifetime = 100a)

	Unit	Case 3A	Case 3B
Gravel	t/m^2	0.90	-
Geosynthetic filter layer	m^2/m^2	1	-
Geosynthetic protection layer	m^2/m^2	1	-
Geosynthetic drainage core[1]	m^2/m^2	-	1
Diesel used in building machines	MJ/m^2	4.5	3.8
Transport, lorry	tkm/m^2	45.1	0.2
Transport, freight, rail	tkm/m^2	0.1	0.3
Land use	m^2/m^2	1	1
Particulates, > 10 µm	g/m	6.3	-
Particulates, > 2.5 µm & < 10 µm	g/m	1.7	-

[1]The core consists of the drainage layer, geosynthetic filter and protection layer. The latter two are glued on the drainage layer.

4.3.2 LCI of Geosynthetic

In total 3 questionnaires concerning the production of geosynthetic drainage layers used in landfill sites are included. Despite its low number, the responding companies represent a significant market share of this type of geosynthetics. The quality of the data received is considered to be accurate. The level of detail is balanced before modelling an average geosynthetic drainage layer. A detailed description of the life cycle inventory is shown in Annex C.1.4.

Tab. 2.3 shows important key figures of the production of an average geosynthetic drainage layer.

Tab. 4.3: Selected key figures referring to the production of 1 kg geosynthetic drainage layer used in landfill sites

	Unit	Value
Raw materials	kg/kg	1.03
Water	kg/kg	44
Lubricating oil	kg/kg	$8.05*10^{-5}$
Electricity	kWh/kg	1.00
Thermal energy	MJ/kg	0.03
Fuel for forklifts	MJ/kg	0.08
Building hall	m^2/kg	$8.59*10^{-6}$

4.4 Life Cycle Impact Assessment

4.4.1 LCIA of Landfill Construction

In this section the environmental impacts of 1 m^2 drainage layer in a landfill are evaluated. The life cycle includes the provision of raw materials as well as the construction and disposal phases.

In Fig. 4.2 the environmental impacts over the full life cycle of the landfill drainage layer are shown. The environmental impacts of the case with higher environmental impacts (case 3A) are scaled to 100 %. The total impacts are divided into the sections landfill, raw materials (gravel, geosynthetic layers), building machine (construction requirements), transports (of raw materials to construction site) and disposal of the landfill (includes transports from the construction site to the disposal site and impacts of the disposal of the geosynthetic materials).

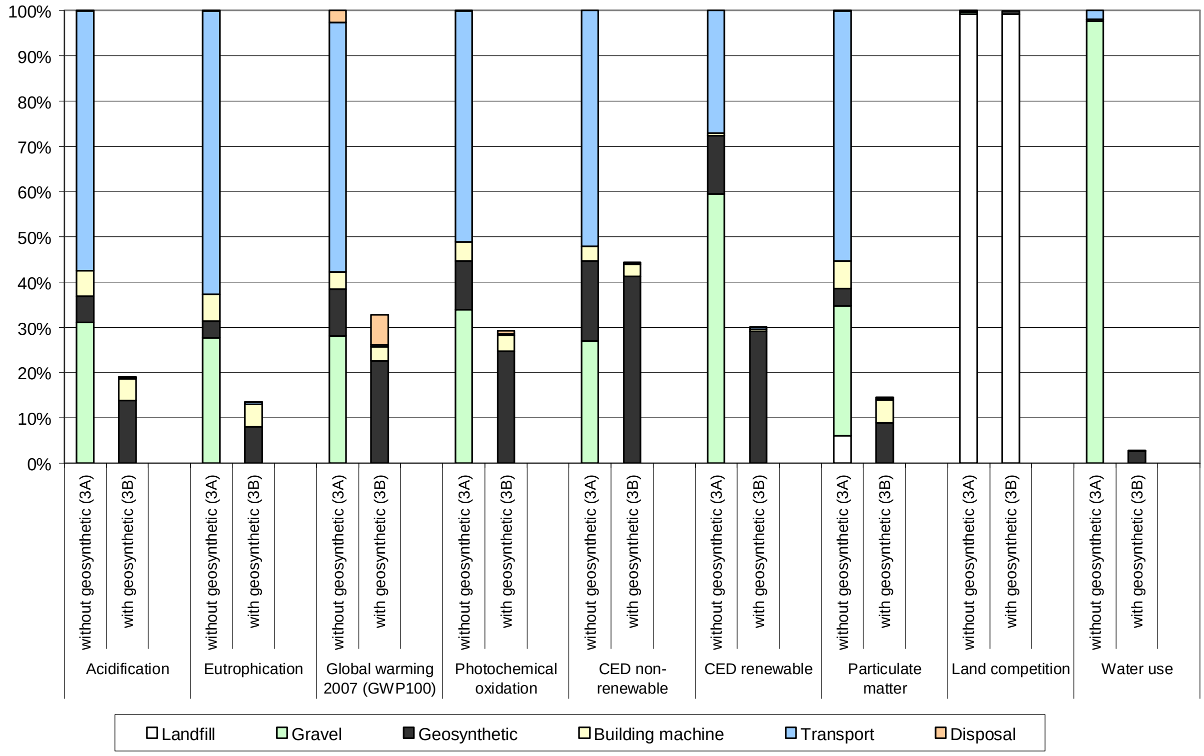

Fig. 4.2: Environmental impacts of the life cycle of 1 m² mineral drainage layer (case 3A) and a geosynthetic drainage layer (case 3B). For each indicator, the case with higher environmental impacts is scaled to 100%.

Case 3B causes lower environmental impacts compared to case 3A in all impact categories considered. The non-renewable cumulative energy demand of the construction and disposal of 1 square meter drainage layer is 194 MJ-eq in case 3A and 86 MJ-eq in case 3B. The cumulative greenhouse gas emissions amount to 10.9 kg CO_2-eq in case 3A and 3.6 kg CO_2-eq in case 3B. Correspondingly, the cumulative greenhouse gas emissions of the drainage layer of a landfill with an area of 30’000 are 320 t in case 3A and 90 t in case 3B respectively.

The most relevant aspects concerning the life cycle of the mineral drainage layer (case 3A) are the extraction and transportation of gravel. Impacts of gravel extraction derive mainly from its mining (high diesel and electricity consumption). A considerably higher amount of material (in particular gravel, see Tab. 4.2) needs to be transported to the construction side in case 3A.

With regard to the life cycle of the geosynthetic drainage core (case 3B), the production of the geosynthetics (including raw material supply) causes the highest burdens in most indicators. The environmental impacts of the drainage layer are about 10 % higher as compared to the impacts of the glued filter and protection layer together. Impacts of the filter and protection layer are discussed in case 1 (Section 2.4.3) and impacts of the drainage layer are discussed below (Section 4.4.4).

The disposal of the drainage layer contributes significantly with regard to global warming only, with a share of 21.7 % and 2.6 % for case 3B and 3A, respectively. This is due to the incineration of plastics in waste incineration, which leads to fossil CO_2 emissions. In both cases, land competition is strongly influenced by the direct land use of the landfill.

The main driving forces for the difference between cases 3A and 3B is the extraction and transportation of gravel used in case 3A. For all indicators except land competition, the impacts of the conventional drainage layer are more than twice as high as compared to the environmental impacts from the geosynthetic drainage layer.

4.4.2 Sensitivity Analysis

In a sensitivity analysis (cases 3AS1 and 3BS1), it is analysed how the results of the drainage layer change, when a Euro5 lorry (>32 t) is used for the transportation of the materials to the construction site instead of an average European lorry (>16 t).

Fig. 4.3 reveals that if a Euro5 lorry with lower exhaust emissions is used for the transportation (cases 3AS1 and 3BS1), the environmental impacts of the geosynthetic based drainage layer are not changed significantly (less than 1 %), whereas the environmental impacts of the conventional drainage layer are decreased between 0.02 % and 37.8 % (land competition and eutrophication, respectively). The higher the share of transportation to the overall results the higher is the influence of using lorries with lower exhaust emissions. In particular regarding acidification, eutrophication, and particulate matter formation high improvements with more than 30 % reduction potential can be achieved, if a Euro5 lorry is used instead of an average one.

This leads to a lower relative difference between the cases. Nevertheless, the sequence of the two cases does not change and the difference is still significant.

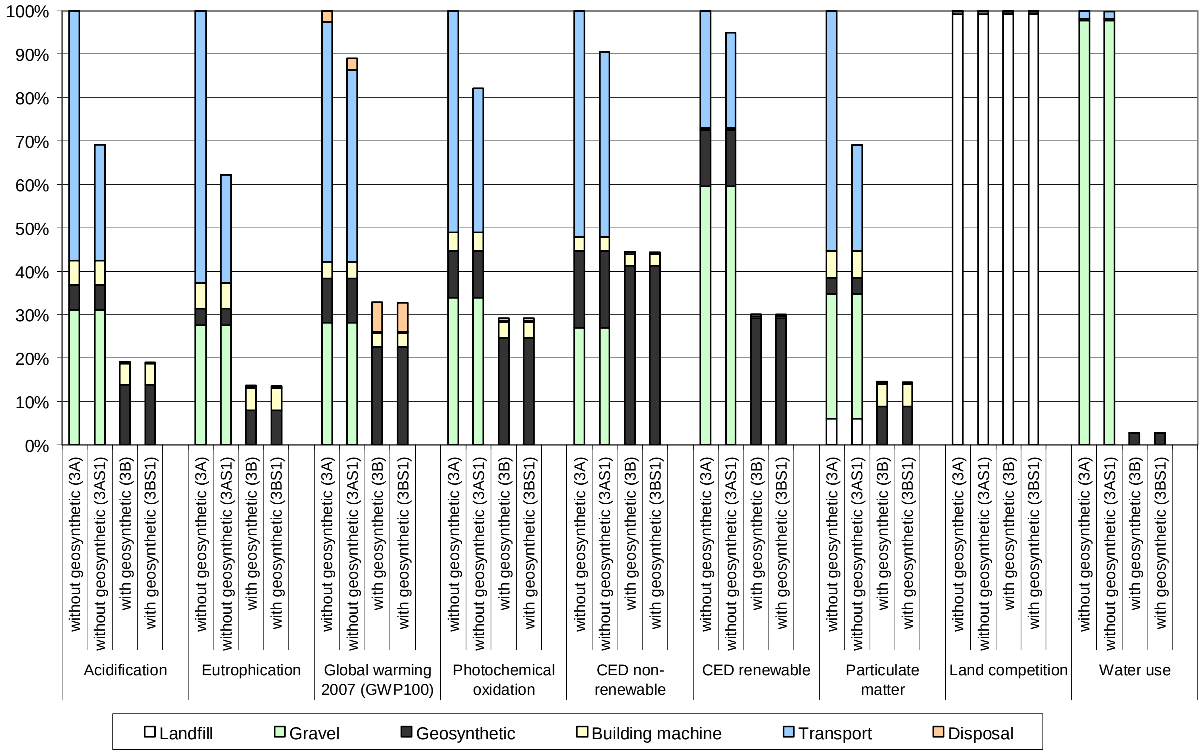

Fig. 4.3: Sensitivity analysis: Environmental impacts of the life cycle of 1 m^2 mineral drainage layer (case 3A) and a geosynthetic drainage layer (case 3B). 3AS1 and 3BS1 refer to the sensitivity analysis with a Euro5 lorry transportation. For each indicator, the case with highest environmental impacts is scaled to 100 %.

4.4.3 Uncertainty Analysis (Monte Carlo Simulation)

In order to determine the reliability of the results above, a Monte Carlo simulation for the full life cycle of the drainage layer is performed. In the Monte Carlo simulation a random value within the uncertainty range specified is taken for every inventory entry. In total 1000 Monte Carlo runs are calculated to form an uncertainty distribution. The life time of the drainage layer and the dimensions are not subject to this uncertainty analysis.

The Monte Carlo Simulation reveals a more than 99.5 % probability that the geosynthetic drainage layer has lower environmental impacts than the mineral drainage layer for all indicators investigated except land competition. Regarding land competition, the probability that geosynthetic drainage layer has lower impacts than the mineral drainage layer is 62 %. Since the difference in land competition between the two alternatives is very small (see Fig. 4.2), they can be considered as equivalent. This becomes clear when taking into consideration that land competition impacts are dominated by the land occupation of the landfill, which is equal in both alternatives.

4.4.4 Contribution Analysis Geosynthetic Drainage Layer

In this section the environmental impacts of 1 kg geosynthetic drainage layer are evaluated. The drainage layer is between the filter and protection layers, which are discussed in Section 2.4.3. The life cycle includes the provision and use of raw materials, working materials, energy carriers, infrastructure and disposal processes. The category geosynthetic in Fig. 4.4 comprises the direct burdens of the geosynthetic production. This includes land occupied to produce the geosynthetic as well as process emissions (e.g. NMVOC, particulate and COD emissions) from the production process but not emissions from electricity and fuel combustion.

In Fig. 4.4 the environmental impacts of the geosynthetic layer are shown. The cumulative greenhouse gas emissions amount to 2.7 kg CO_2-eq per kg.

Environmental impacts are mostly dominated by the raw material provision and electricity consumption. Raw material includes plastics and chemicals. Plastic raw materials are responsible for between 0.1 % (land competition) and 85 % (CED non-renewable) of the overall impacts. The impacts of chemicals are negligibly small.

Country-specific electricity mixes are modelled for each company and thus impacts of electricity consumption depend not only on the amount of electricity needed but also on its mix. The high share of electricity in CED renewable can be explained by the use of hydroelectric power plants in several electricity mixes. And the relatively high share in eutrophication is mainly due to electricity from lignite.

Heating energy and fuel consumption for forklifts are of minor importance. The burdens of infrastructure are so small that they are not even visible in the graph. With regard to land competition the geosynthetic production plays an important role. The impacts are dominated by the direct land use, i.e. land which is occupied by the manufacturer plant in which the geosynthetic is produced. Indirect land uses, i.e. land occupation stemming from upstream processes, are significantly lower because no land occupation is reported in the inventories of plastic feedstock and no land intensive products such as wood are used in considerable amounts.

Water consumption is included in the working materials. As a consequence, this category bears more than 80°% of the total amount of water used.

The share in environmental impacts caused by the use of electricity in the manufacture of the geosynthetic layer used in case 3 is similar to the one used in case 1. Less electricity is required in case 3 but also less raw materials, leading to similar shares as in case 1. Water consumption is obviously higher in this case compared to the other cases. Companies producing a geosynthetic drainage layer use considerably less thermal energy. Furthermore, more infrastructures (buildings) are required in case 3 compared to the other cases.

The case 3 geosynthetic layer causes less greenhouse gas emissions per kilogram compared to the ones used in cases 1, 2 and 4.

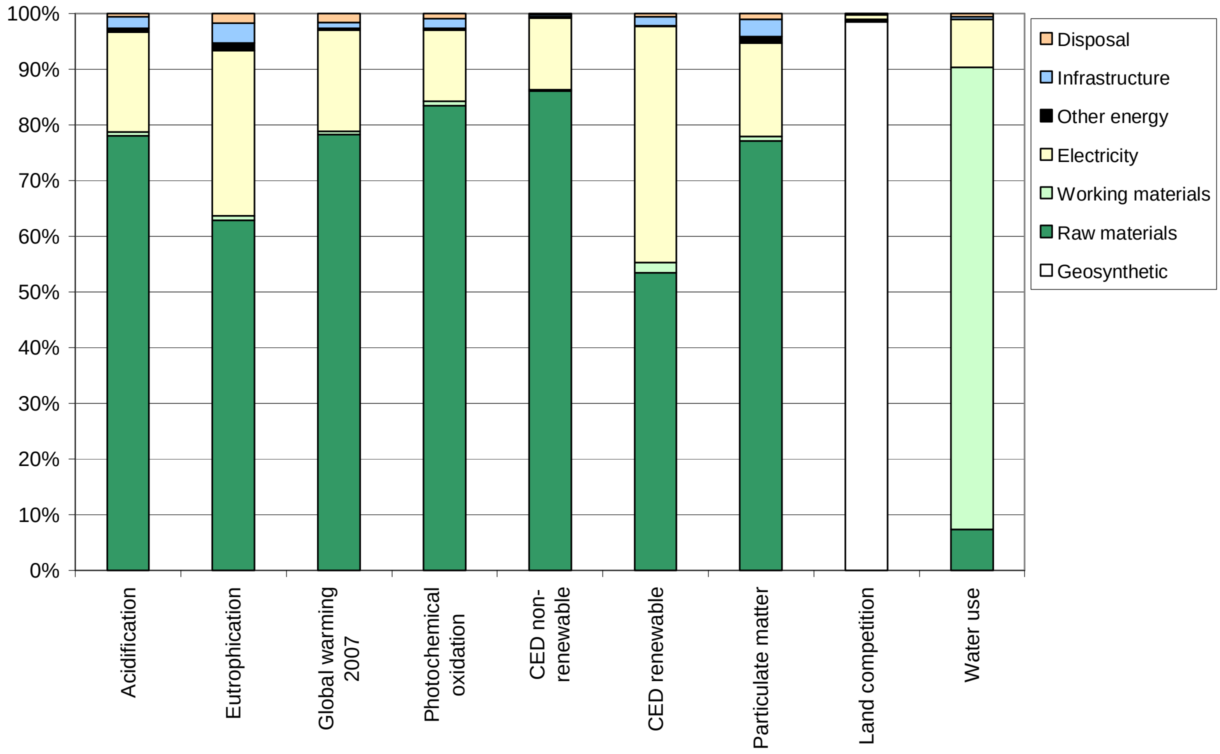

Fig. 4.4: Environmental impacts of the life cycle of 1 kg geosynthetic layer. Geosynthetic includes direct burdens of the geosynthetic production. Raw materials include plastic, extrusion if necessary and additives, working materials include water (tap and deionised) and lubricating oil, other energy includes thermal energy and fuels, infrastructure concerns the production plant and disposal comprises wastewater treatment and disposal of different types of waste.

4.4.5 Discussion and Data Quality Considerations

Compared to a conventional drainage layer in a landfill, the use of geosynthetics leads to lower environmental impacts of drainage layer construction in all indicators investigated, except land competition. The specific climate change impact of the construction of a landfill site's drainage layer (1 m^2 surface area with a hydraulic conductivity (k-value) of 1 mm/s or more and life time of 100 years) using geosynthetics is about 7.8 kg CO_2-eq per m^2 lower compared to a conventional alternative. This difference is equal to about 69 % of the overall climate change impact of the construction and disposal efforts of a conventional drainage layer.

If a Euro5 lorry with lower exhaust emissions than an average fleet lorry is used, the environmental impacts of the geosynthetic drainage layer are not changed significantly, whereas the impacts of the conventional drainage layer are decreased more distinctly with reductions of more than 30 % regarding some indicators. Nevertheless the sequence of the two cases does not change and the difference in environmental impacts is still significant.

Landfills constructed within Europe may differ in cross section and materials used depending on the wastes landfilled. Thus, generalising assumptions are necessary to model a typical drainage layer. Data about gravel extraction and the use of building machines are based on generic data and knowledge of individual civil engineering experts.

Based on the uncertainty analyses, it can be safely stated that the geosynthetics drainage layer solution shows lower environmental impacts than the gravel drainage level. Despite the necessary simplifications and assumptions, the results of the comparison are considered to be significant and reliable.

5 Case 4 – Slope Retention

5.1 Characterisation of the Alternatives

It may be necessary in some cases, especially in the construction of traffic infrastructure, to build-up very steep batters or walls. For such walls, supporting structures are necessary. The retaining walls need to meet defined tensile and shear strengths. Retaining walls reinforced with concrete (case 4A) are compared to soil slopes reinforced with geosynthetics (case 4B). In Fig. 5.1 the retaining wall is 50 meters long and 3 meters high with a steepness of 5:1. In fact, the length of the wall has no influence on the LCA as the functional unit refers to 1 meter standard cross section (see Subchapter 5.2).

The average of 3 types of different geogrids is used to represent its performance, namely

- extruded stretched grids,
- layed grids, and
- woven / knitted grids.

Polyethylene and PET granules are used as basic material in case 4B. In this case a long-term strength of 14 kN/m must be achieved. Back calculated from that and applying the typical reduction factor A1-A4 per raw material the average weight of the polymer is defined as:

- Polyethylene (100kN/m) with 750 g/m²
- PET (35kN/m) with 280 g/m²

The concrete used in case 4A is classified in the strength class B300.

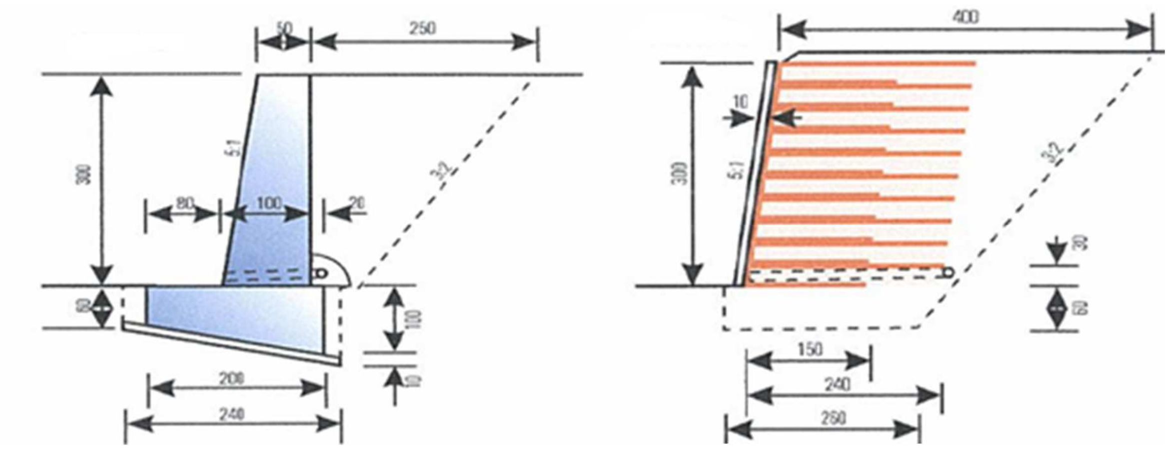

Fig. 5.1: Scheme of retaining walls: the concrete reinforced wall (case 4A, left) versus the geosynthetics reinforced wall (case 4B, right)

Tab. 5.1 shows specific values of the retaining walls for both alternatives. The material on site is used as fill material, wall embankments and cover material in case 4B. A drainage layer made of gravel with a thickness of at least 30 cm[7] behind the concrete lining is necessary. To be consistent with case 4A, a gravel layer thickness of 80 cm is assumed in both cases. Round gravel is used for drainage purposes[8].

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[7] Personal communication Klaus Oberreiter, EAGM, 29.4.2010

[8] Personal communication Nicolas Laidié, EAGM, 29.4.2010

Tab. 5.1: Specification of reinforced concrete wall (case 4A) and geosynthetic reinforced soil supporting structure (case 4B).

Description	Unit	Case 4A	Case 4B	Material
length of the wall	m	50	50	
height of the wall	m	3	3	
excavation fundament	m^3	109		
base compaction	m^2	121	262	On-site material
formwork fundament	m^2	83		Laminated board
cleanness layer	m^2	120		Lean mix concrete
concrete fundament	m^3	80		Concrete, sole plate
reinforcement fundament	kg	2400		Reinforcing steel
formwork wall face work	m^2	153		Laminated board
formwork wall coarse	m^2	150		Laminated board
concrete wall	m^3	105		Structural concrete, with de-icing contact
reinforcement wall	kg	5250		Reinforcing steel
Building gaps	m^2	21		Polystyrene foam slab
insulating coat cold	m^2	154		Bitumen
drainage	m	62	72	Polyethylene HDPE
filter gravel	m^3	10	11	Gravel
frost wall backfilling	m^3	219		Gravel and on-site material
compaction backfilling	m^2	500		Gravel and on-site material
excavation sub-base	m^3		79	On-site material
sub-base fill material	m^3		79	On-site material
form work, support	m^2		153	Laminated board
geosynthetics delivery and laying	m^2		1960	Geosynthetic
wall embankment	m^3		480	On-site material
compaction layers	m^2		1550	Gravel and on-site material
Sprayed-concrete lining	m^2		155	Structural concrete, with de-icing contact
covering material	m^3		45	On-site material

The typical life time is estimated in both cases with 100 years. This is in line with EBGEO (Deutsche Gesellschaft für Geotechnik 2010) and the British Standard “Code of practice for strengthened/reinforced soils and other fills” (British Standard 1995).

5.2 Functional Unit and Definition of the System

The function of the fourth case is to provide a slope retention with a very steep and stable wall. The functional unit is defined as the construction and disposal of 1 m slope retention with a 3 meters high wall, referring to a standard cross-section. Thus, the functional unit is independent of the length of the wall.

5.3 Life Cycle Inventory

A detailed description of the life cycle inventory of the case 4A and case 4B slope retention and the geogrid is placed in the Annex C.2. A general description of the infrastructure element and the geogrid is given in the following sections.

5.3.1 LCI of Infrastructure Element

Some important key figures of the construction of a reinforced concrete wall (case 4A) and a geosynthetic reinforced soil supporting structure (case 4B) are summarized in Tab. 5.2. The information refers to one meter of slope retention infrastructure and a time period of 100 years. Diesel is used in building machines for the excavation of the foundation and the compaction of the ground. The NMVOC emissions shown are released from the bitumen used to seal the concrete wall (case 4A). The use of recycled gravel is not considered, since usually no onsite recycled gravel with specific properties is available when building a slope retention.

Tab. 5.2: Selected key figures referring to the construction of a reinforced concrete wall (case 4A) and a geosynthetic reinforced soil supporting structure (case 4B) (life time = 100a)

	Unit	Case 4A	Case 4B
Concrete, sole plate and foundation	m^3/m	1.60	-
Lean mix concrete	m^3/m	0.24	-
Structural concrete	m^3/m	2.10	0.31
Reinforcing steel	kg/m	153	-
Gravel	t/m	4.3	4.3
Bitumen	kg/m	2.84	-
Three layered laminated board	m^3/m	0.01	-
Geosynthetic	m^2/m	-	39.2
Polystyrene foam slab	kg/m	0.25	-
Polyethylene	kg/m	1.74	2.02
Diesel in building machine	MJ/m	11.6	53.9
Transport, lorry	tkm/m	701	265
Transport, freight, rail	tkm/m	33.2	6.9
Land use	m^2/m	1.0	0.6
NMVOC	g/m	20	-

5.3.2 LCI of Geogrid

In total 6 questionnaires concerning the production of geogrids used in slope retention are included. The quality of the data received is considered to be accurate. The level of detail is balanced before modelling an average geogrid. A detailed description of the life cycle inventory is shown in Annex C.4.4.

Tab. 5.3 summarizes most important key figures for the production of an average geogrid.

Tab. 5.3: Selected key figures referring to the production of 1 kg geogrid used in slope retention.

	Unit	Value
Raw materials	kg/kg	1.02
Water	kg/kg	0.86
Lubricating oil	kg/kg	$7.30*10^{-5}$
Electricity	kWh/kg	0.73
Thermal energy	MJ/kg	1.24
Fuel for forklifts	MJ/kg	0.13
Building hall	m^2/kg	$6.32*10^{-6}$

5.4 Life Cycle Impact Assessment

5.4.1 LCIA of Slope Retention

In this section the environmental impacts of 1 m slope retention with a height of 3 m over the full life cycle are evaluated. The life cycle includes the provision of raw materials as well as the construction and disposal phases.

In Fig. 4.1 the environmental impacts over the full life cycle of the slope retention are shown. The environmental impacts of the case with higher environmental impacts (case 4A) are scaled to 100 %. The total impacts are divided into the sections wall, raw materials (concrete, gravel, geosynthetic layers, reinforcing steel, bitumen, wooden board), building machine (construction requirements), transports (of raw materials to construction site) and disposal of the wall (includes transports from the construction site to the disposal site and impacts of the disposal of the different materials).

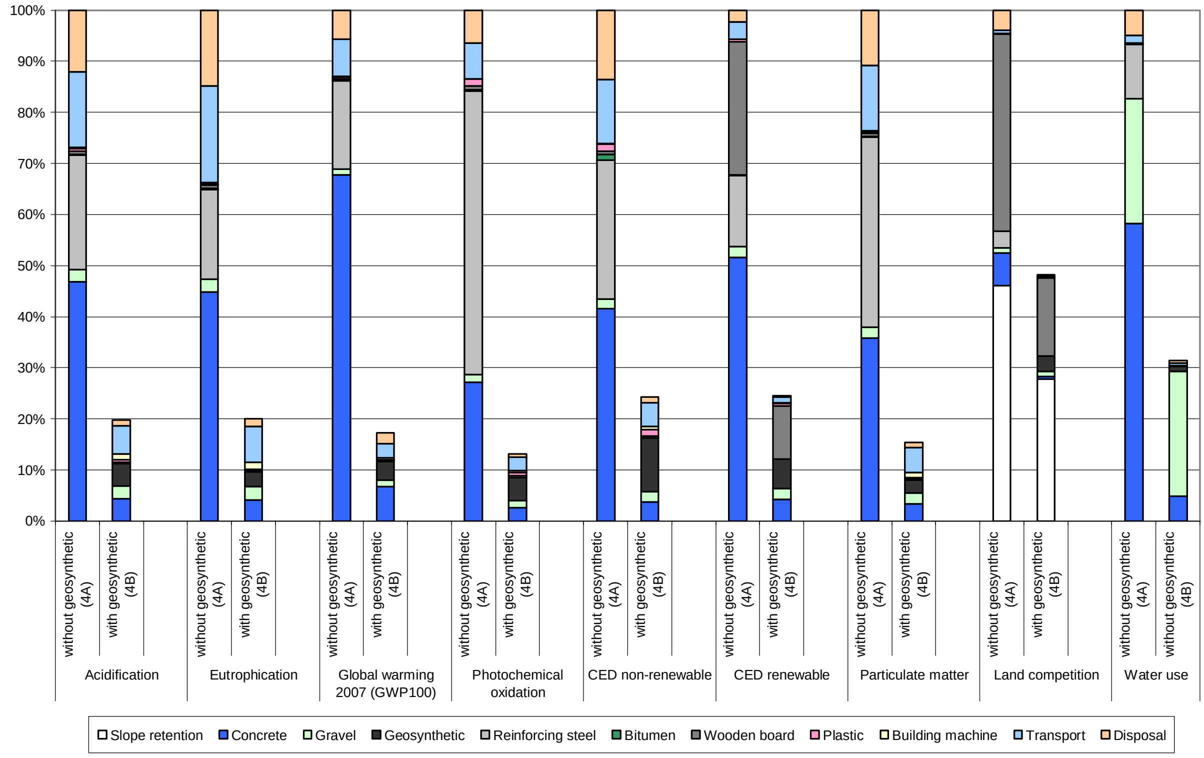

Fig. 5.2: Environmental impacts of the life cycle of 1 m slope retention, cases 4A and 4B. For each indicator, the case with higher environmental impacts is scaled to 100°%.

Case 4B causes lower environmental impacts compared to case 4A in all impact categories considered. The non-renewable cumulative energy demand of the construction and disposal of 1 meter slope retention with a height of 3 meters is 12’700 MJ-eq in case 4A and 3’100 MJ-eq in case 4B. The cumulative greenhouse gas emissions amount to 1.3 t CO_2-eq in case 4A and 0.2 t CO_2-eq in case 4B. Correspondingly, the cumulative greenhouse gas emissions of 300 m slope retention are 400 t in case 4A and 70 t in case 4B, respectively.

The most relevant aspects concerning the environmental impacts of the life cycle of the reinforced concrete retaining wall (case 4A) are concrete, reinforcing steel, transportation and disposal. This order of relevance changes depending on the impact category indicators. The high share of concrete in the global warming indicator can be explained by the production process of clinker. During its calcination process geogenic CO_2 arise. Reinforcing steel consists of 63 % primary steel and 37 % recycled steel. Most environmental impacts of the reinforcing steel arise from the fuel consumption and the emissions during the sinter and pig iron production in the supply chain of the primary steel. Disposal includes the disposal as well as transports from the construction site to the disposal site in case the material is not recycled. Impacts of disposal are dominated by the high amount of concrete which is landfilled. While direct emissions of landfilling concrete are negligible, the construction of the landfill and the transport of concrete to the landfill site are important. The land competition indicator is strongly influenced by the direct land use of the slope retention as well as by the wooden board used in the formworks. Gravel is responsible for a considerable share of the total amount of water used because substantial amounts of water are needed in gravel production.

Concrete, the geosynthetic and transportation mostly cause the highest burdens of the life cycle of the slope retention reinforced with geosynthetics (case 4B). The share of the geogrid to the overall impacts is relatively high because on one hand several layers, and thus a considerable amount of geogrid, are required. On the other hand most materials used in the construction of the slope retention are available on-site and thus do not cause substantial environmental impacts (compare Tab. 5.1). The disposal gains importance in the categories eutrophication and global warming. The global warming impacts of disposal are caused by burning geogrids in waste incineration plants, which leads to fossil CO_2 emissions. Gravel dominates the water use indicator and the direct land use of the slope retention wall during its use is dominating land competition.

The main driving forces for the difference between cases 4A and 4B are the higher amount of concrete used in case 4A as well as the use of reinforcing steel, which additionally leads to higher transport expenditures. With regard to CED renewable and land competition the wooden board additionally increases the difference in total impacts because wood is a renewable resource with a high direct land occupation. Direct land competition is lower for the case 4B because the sprayed concrete lining in case 4B is thinner than the concrete wall in case 4A and the embankment and backfilling area is not considered as occupied land.

The share of the geosynthetic material on the overall environmental impacts is between 3 % and 44 % (water use and CED non-renewable, respectively).

5.4.2 Sensitivity Analysis

In a sensitivity analysis (cases 4AS1 and 4BS1), it is analysed how the results of the slope retention change, when a Euro5 lorry (>32 t) is used for the transportation of the materials to the construction site instead of an average European lorry (>16 t).

Fig. 5.3 reveals that if a Euro5 lorry with lower exhaust emissions is used for the transportation (cases 4AS1 and 4BS1), the environmental impacts of the geosynthetic based slope retention are reduced between 0.1 % and 22.8 % (land competition and eutrophication respectively), whereas the environmental impacts of the conventional slope retention are decreased between 0.2 % and 13.2 % (land competition and eutrophication respectively). The use of a Euro5 lorry leads among others to lower NO_X emissions which influences eutrophication. Land competition is obviously not influenced much by using another type of lorry.

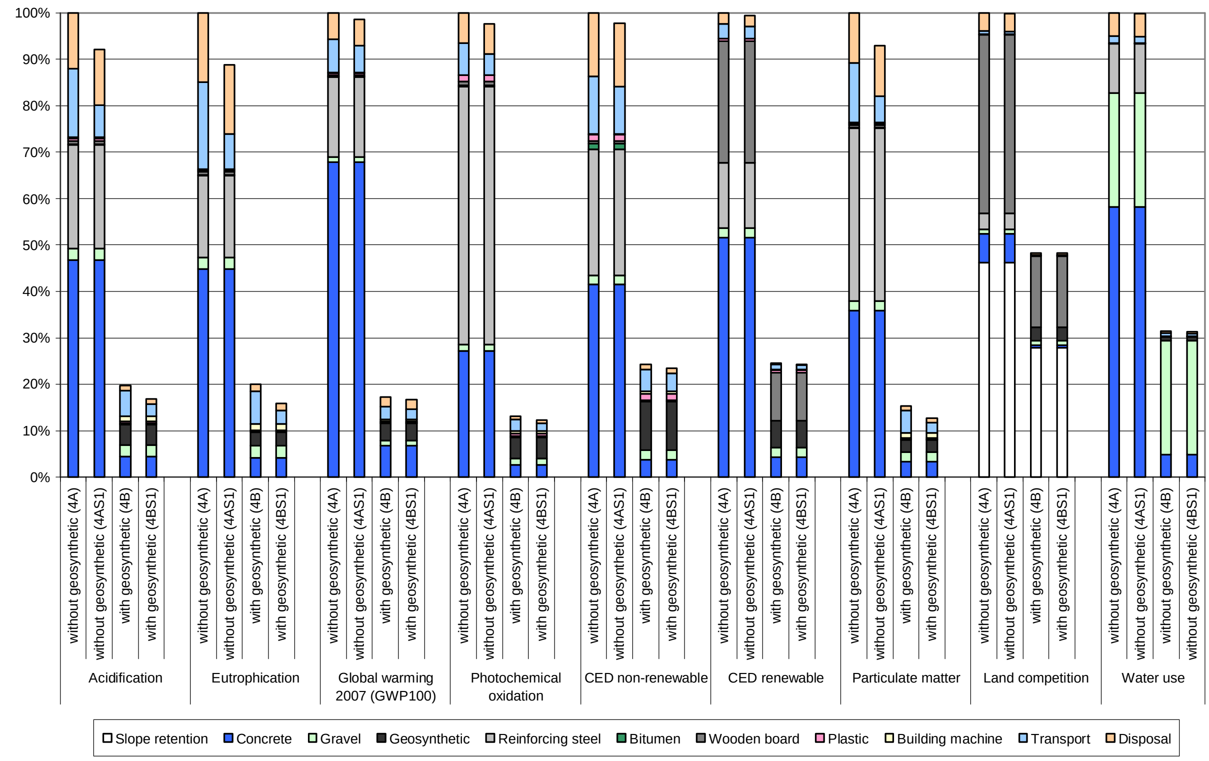

Fig. 5.3: Sensitivity analysis: Environmental impacts of the life cycle of 1 m slope retention, cases 4A and 4B. 4AS1 and 4BS1 refer to the sensitivity analysis with a Euro5 lorry transportation. For each indicator, the case with highest environmental impacts is scaled to 100%.

5.4.3 Uncertainty Analysis (Monte Carlo Simulation)

In order to determine the reliability of the results above, a Monte Carlo simulation of the life cycle of the slope retention alternatives is performed. In the Monte Carlo simulation a random value within the uncertainty range specified is taken for every inventory entry. In total 1000 Monte Carlo runs are calculated to form an uncertainty distribution. The life time of the slope retention and its dimensions are not subject to this uncertainty analysis.

The Monte Carlo simulation shows a probability of 100 % that the environmental impacts of the conventional slope retention are higher compared to the environmental impacts of the geosynthetic slope retention with regard to all indicators.

It can be concluded that it is reliable that the use of geosynthetics instead of a conventional slope retention leads to lower environmental impacts.

5.4.4 Contribution Analysis Geogrid

In this section the environmental impacts of 1 kg geogrid are evaluated. The life cycle includes the provision and use of raw materials, working materials, energy carriers, infrastructure and disposal processes. The category geosynthetic in Fig. 5.4 comprises the direct burdens of the geosynthetic production. This includes land occupied to produce the geosynthetic as well as process emissions (e.g. NMVOC, particulate and COD emissions) from the production process but not emissions from electricity and fuel combustion which are displayed separately.

The environmental impacts of the geogrid are shown in Fig. 5.4. The cumulative greenhouse gas emissions amount to 3.4 kg CO_2-eq per kg.

Environmental impacts are mostly dominated by the raw material provision and electricity consumption. Raw material includes different types of plastics. Country-specific electricity mixes are modelled for each company and thus impacts of electricity consumption depend not only on the amount of electricity needed but also on its mix. The higher share of electricity in CED renewable can be explained by the use of hydroelectric power plants in several electricity mixes. And the relatively high share in eutrophication is mainly due to electricity from lignite.

The share of heating energy and fuel consumption for forklifts is between 0.01 % (land competition) and 2.8 % (global warming) and is thus not considered to be of primary importance.

With regard to land competition the geosynthetic production plays an important role. The impacts are dominated by the direct land use, i.e. land which is occupied by the manufacturer plant in which the geosynthetic is produced. Indirect land uses, i.e. land occupation stemming from upstream processes, are significantly lower because no land occupation is reported in the inventories of plastic feedstock and no land intensive products as e.g. wood are used in considerable amounts.

Water consumption is included in the working materials. As a consequence, this category bears about 5 % of the total amount of water used.

The share of electricity on the overall environmental impacts of the geogrid used in case 4B is smaller as compared to the one used in the other cases. This is because less electricity is required on one hand and because different raw materials are used on the other. Polypropylene (PP) is the basic material in most other cases whereas mainly PET and PE are used in case 4B. According to the PlasticEurope life cycle inventory data used in this study, the supply of 1 kg of PET and PE granules causes higher environmental impacts than the supply of 1 kg PP.

The case 4 geogrid causes similar amounts of greenhouse gas emissions per kg compared to the geosynthetics used in cases 1 and 2.

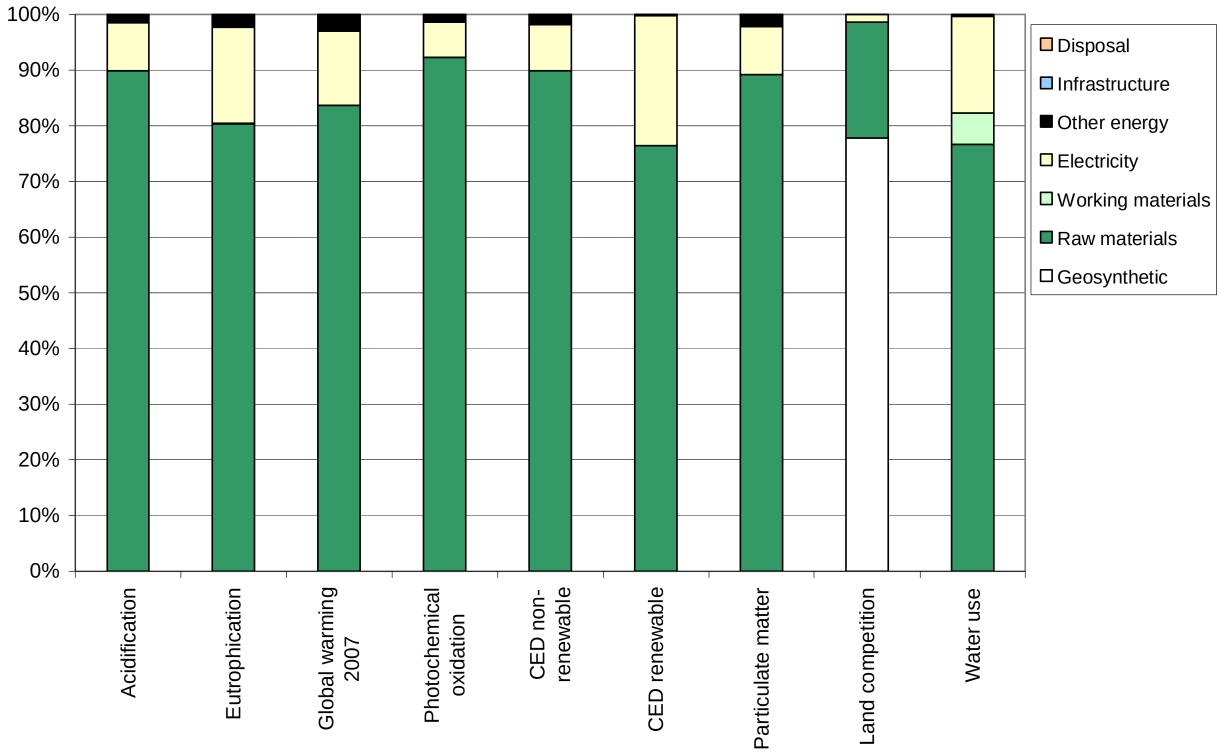

Fig. 5.4: Environmental impacts of the life cycle of 1 kg geogrid. Geosynthetic includes direct burdens of the geosynthetic production. Raw materials include plastic, extrusion if necessary and additives, working materials include water (tap and deionised) and lubricating oil, other energy includes thermal energy and fuels, infrastructure con-

cerns the production plant and disposal comprises wastewater treatment and disposal of different types of waste.

5.4.5 Discussion and Data Quality Considerations

The use of geosynthetics leads to lower environmental impacts of slope retention in all indicators investigated. The specific climate change impact of the construction of the slope retention (1 m slope retention with a 3 meters high wall) using geosynthetics is about 1 ton CO_2-eq per meter lower compared to a conventional alternative. This difference is equal to about 84 % of the overall climate change impact of the construction and disposal efforts of an entire conventional slope retention system during its 100 years lifetime.

If a Euro5 lorry with lower exhaust emissions than an average fleet lorry is used for the transportation of materials, the environmental impacts of both cases are somewhat reduced regarding some indicators. However, this does not affect the overall conclusions of the comparison.

Slope retentions are individual solutions in a particular situation. The height of slope retention walls and the horizontal loads on it may differ, which may lead to differences in thickness and reinforcement. Thus, generalising assumptions were necessary to model a typical slope retention. Data about on-site material used, gravel extraction, concrete and the use of building machines are based on generic data and knowledge of individual civil engineering experts.

Based on the uncertainty assessment it can be safely stated that the geosynthetics reinforced slope retention shows lower environmental impacts than the concrete wall. Despite the necessary simplifications and assumptions, the results of the comparison are considered to be significant and reliable.

6 Overall Conclusions and Recommendations

Geosynthetic materials are used in many different applications in the civil and underground engineering. They are used, among other applications, in filter layer construction, in foundation stabilisation, in landfill construction and in slope retention. In most cases they are used instead of minerals based materials such as concrete, gravel, cement or lime. In this study the environmental performance of four cases of geosynthetics application is compared to the performance of competing construction materials used.

Geosynthetic layers and geogrids can contribute to civil engineering constructions causing significantly lower climate change impacts in all cases considered. The use of geosynthetic layers also leads to lower environmental impacts such as acidification, eutrophication, and to lower cumulative energy demands, compared to conventional solutions.

A **filter layer with geosynthetics** has lower environmental impacts compared to a conventional alternative (gravel). The difference is considerable for all indicators (more than 85 %) and reliable. The difference in the environmental impacts arises mainly because the applied geosynthetic substitutes gravel, which causes considerably higher impacts when extracted and transported to the place of use. At least a layer of 8 cm of gravel must be replaced by geosynthetics used as a filter layer in order to cause the same or lower environmental impacts regarding all indicators.

When comparing the use of **geosynthetics in road construction** in order to reinforce the road foundation (case 2B) and the conventional road construction (case 2A), the environmental impact is reduced for all indicators when using geosynthetics. When road construction using geosynthetics (case 2B) and the road construction with cement/lime stabilised foundation (case 2C) are compared, a trade-off between the cases 2B and 2C can be observed. On the one hand, the use of a cement/lime stabiliser causes higher climate change impacts mainly because of the geogenic CO_2 emissions from the production process of cement and quicklime. On the other hand, the use of a geosynthetic stabiliser shows higher environmental impacts related to eutrophication, particulate matter and water use because of the emissions and the resource consumption related to the production and transportation of the additional amount of gravel required. The use of quick lime only (case 2CS1) causes higher environmental impacts than the use of cement (case 2CS2) for the stabilisation of the road foundation. At least a layer of 25 cm of gravel in a conventional road must be replaced by geosynthetics used in road foundation in order to cause the same or lower environmental impacts regarding all indicators.

The **uncertainty analysis** shows that results are reliable for all indicators when comparing case 2A and 2B and that the results are stable for the indicators photochemical oxidation, global warming, land competition and CED renewable when comparing the case 2B and 2C. Regarding the other indicators the difference is not reliable.

The main driving forces for the difference between the geosynthetic **drainage layer in a landfill site** and the conventional gravel drainage layer is the extraction and transportation of gravel used in the conventional case. For all indicators except land competition, the impacts of the conventional drainage layer are more than twice as high as compared to the impacts from the geosynthetic drainage layer. From the uncertainty analysis it can be concluded that the results are reliable regarding all indicators except land competition.

A geosynthetic **reinforced wall** used for slope retention constitutes a different system compared to a concrete reinforced wall. Nevertheless, both systems provide the same function by enabling the build-up of steep walls. Compared to the conventional slope retention, the geosynthetic reinforced wall substitutes the use of concrete and reinforcing steel, which results between 63 % and 87 % lower environmental impacts. Compared to the use of geosynthetics as foundation stabiliser and separator, the geosynthetic used for slope retention has a considerably higher share in the total environmental impacts of the system between 3 % and 44 %. The Monte Carlo analysis reveales a high confidence in the higher environmental impacts of the conventional slope retention with regard to all indicators.

The main share of the environmental impacts of the manufacture and disposal of **geosynthetic layers** are caused by the raw materials and electricity consumption. However, the share of the environmental impacts in the total share of the four cases considered are small, except in case 4 where it can have an important contribution in some indicators. The variation in environmental impacts of geosynthetics manufacture does not affect the overall results as could be shown with the Monte Carlo simulations. Hence the results shown in this report are valid for the products of any particular manufacturer.

The life cycle assessments of the four cases filter layer, foundation stabilisation, landfill construction and slope retention are defined in a way that they represent commonly applied new constructions. Data about materials, building machines and transport modes used are based on generic data and knowledge of individual civil engineering experts. Despite the necessary simplifications and assumptions, the results of the comparison are considered to be significant and reliable. Nevertheless construction methods may vary from one EU member state to the other. Thus the cases should be perceived as exemplary models of common and frequent applications of geosynthetic materials.

The results of the LCAs do not allow answering the question whether or not constructions based on geosynthetic materials are generally the environmentally preferable option. The specific situation and the particular construction in which the geosynthetic material is being used and the particular alternative options available should be taken into account.

Key parameters influencing the overall environmental performance of foundation stabilisation such as amounts of cement or lime, and of gravel needed, and transport distances should be investigated, when deciding about the environmentally appropriate construction in a particular case.

It is recommended to establish key parameter models for each of the four cases, which allow for an individual assessment of alternatives of any particular construction. This is particularly true for case 4, where actual situations may ask for highly specific technical solutions. In such key parameter models the main determining factors such as amount of gravel, cement, concrete or geosynthetics needed, can be entered to calculate the environmental impacts of the construction alternatives at issue.

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A Annex A: Life Cycle Assessment (LCA) Methodology

The life cycle assessment (LCA) – sometimes also called ecobalance – is a method to assess the environmental impacts of a product[9] encompassing the whole life cycle. . Hence, the environmental impacts of a product are evaluated from cradle to grave, which means from resource extraction to material production, product manufacturing, use of the product up to the disposal of the product and also the production wastes.

The general procedure of conducting an LCA is standardised in ISO 14040 (International-Organization-for-Standardization-(ISO) 2006a) and ISO 14044 (International-Organization-for-Standardization-(ISO) 2006b).

An LCA consists of the following four phases (Figure 1):

1. Goal and Scope Definition
2. Inventory Analysis
3. Impact Assessment
4. Interpretation

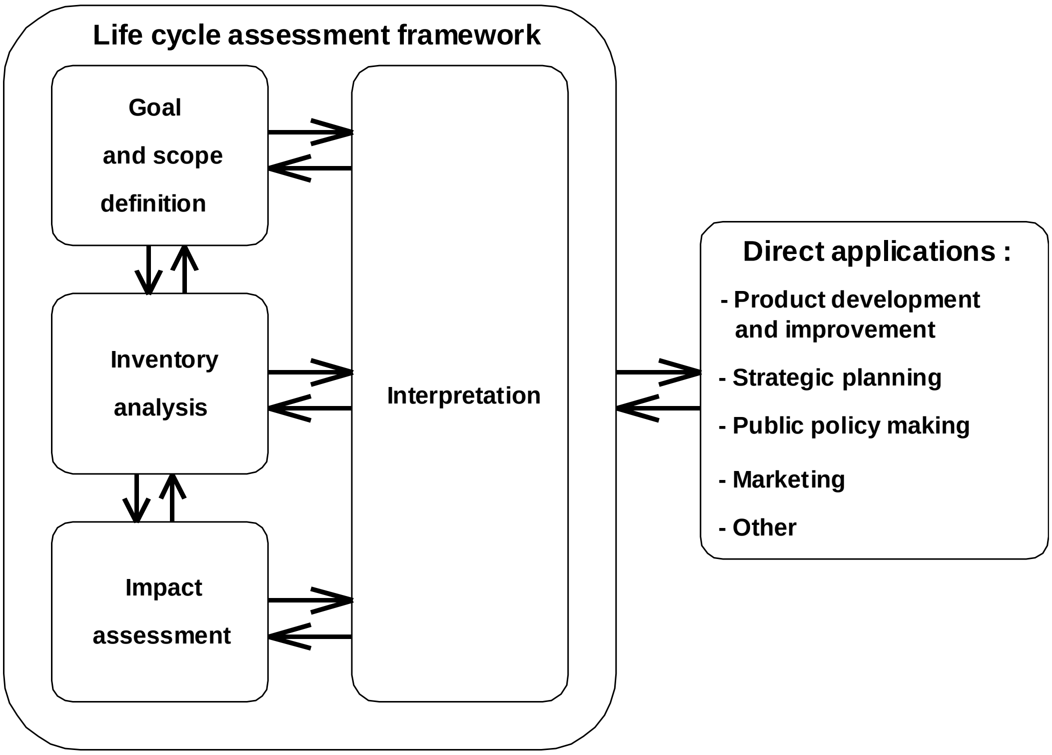

Fig. 7.1 The four phases of the life cycle assessment (LCA) framework according to International Organization for Standardization

The *Goal and Scope Definition* (phase 1) includes a description of the goal of the study and covers the description of the object of investigation. The intended audience is determined. The environmental aspects to be considered in the impact assessment and the interpretation and the functional unit, to which all emissions and resource uses are referred to and which determines the basis for the comparison, are defined.

9 The term product also encompasses services

The elementary flows[10] occuring in a process, the amount of semi-finished products, auxiliary materials and energy of the processes involved in the life cycle are determined and inventoried in the *Inventory Analysis* (phase 2). These data are set in relation to the object of investigation, expressed by the functional unit. The final outcome consists of the cumulative resource demands and the cumulative emissions of pollutants.

The Inventory Analysis provides the basis for the *Impact Assessment* (phase 3). Applying current impact assessment methods, such as climate change impact according to IPCC (2007), on the inventory results leads to impact indicator results that are used and referred to in the interpretation.

The results of the inventory analysis and the impact assessment are analysed and commented in the *Interpretation* (phase 4) according to the initially defined goal and scope of the LCA. Final conclusions are drawn and recommendations stated.

[10] Resource extraction and emission of pollutants

B Annex B: Impact Assessment Result Tables

B.1.1 Case 1

Case 1A	Unit	Filter system	Gravel	Building machine	Geosynthetic	Transport	Disposal	Total
Acidification	kg SO2 eq	0.00E+00	1.64E-02	1.42E-03	0.00E+00	2.48E-02	0.00E+00	4.27E-02
Eutrophication	kg PO4--- eq	0.00E+00	2.81E-03	3.05E-04	0.00E+00	5.43E-03	0.00E+00	8.54E-03
Global warming 2007 (GWP10	kg CO2 eq	0.00E+00	2.99E+00	1.87E-01	0.00E+00	4.60E+00	0.00E+00	7.78E+00
Photochemical oxidation	kg C2H4	0.00E+00	6.33E-04	3.63E-05	0.00E+00	7.40E-04	0.00E+00	1.41E-03
CED non-renewable	MJ-eq	0.00E+00	5.14E+01	2.77E+00	0.00E+00	7.65E+01	0.00E+00	1.31E+02
CED renewable	MJ-eq	0.00E+00	3.08E+00	9.05E-03	0.00E+00	9.36E-01	0.00E+00	4.03E+00
Particulate matter	kg PM10 eq	1.28E-03	7.10E-03	7.58E-04	0.00E+00	1.16E-02	0.00E+00	2.08E-02
Land competition	m2a	3.00E+01	3.68E-01	5.44E-04	0.00E+00	6.83E-02	0.00E+00	3.04E+01
Water use	m3	0.00E+00	9.73E-01	2.54E-04	0.00E+00	1.80E-02	0.00E+00	9.91E-01

Case 1AS1	Unit	Filter system	Gravel	Building machine	Geosynthetic	Transport	Disposal	Total
Acidification	kg SO2 eq	0.00E+00	2.19E-02	1.90E-03	0.00E+00	3.31E-02	0.00E+00	5.69E-02
Eutrophication	kg PO4--- eq	0.00E+00	3.74E-03	4.07E-04	0.00E+00	7.24E-03	0.00E+00	1.14E-02
Global warming 2007 (GWP10	kg CO2 eq	0.00E+00	3.98E+00	2.49E-01	0.00E+00	6.13E+00	0.00E+00	1.04E+01
Photochemical oxidation	kg C2H4	0.00E+00	8.44E-04	4.84E-05	0.00E+00	9.87E-04	0.00E+00	1.88E-03
CED non-renewable	MJ-eq	0.00E+00	6.85E+01	3.69E+00	0.00E+00	1.02E+02	0.00E+00	1.74E+02
CED renewable	MJ-eq	0.00E+00	4.11E+00	1.21E-02	0.00E+00	1.25E+00	0.00E+00	5.37E+00
Particulate matter	kg PM10 eq	1.70E-03	9.46E-03	1.01E-03	0.00E+00	1.55E-02	0.00E+00	2.77E-02
Land competition	m2a	0.00E+00	4.91E-01	7.25E-04	0.00E+00	9.11E-02	0.00E+00	5.83E-01
Water use	m3	0.00E+00	1.30E+00	3.39E-04	0.00E+00	2.40E-02	0.00E+00	1.32E+00

Case 1AS2	Unit	Filter system	Gravel	Building machine	Geosynthetic	Transport	Disposal	Total
Acidification	kg SO2 eq	0.00E+00	1.10E-02	9.49E-04	0.00E+00	1.65E-02	0.00E+00	2.84E-02
Eutrophication	kg PO4--- eq	0.00E+00	1.87E-03	2.03E-04	0.00E+00	3.62E-03	0.00E+00	5.70E-03
Global warming 2007 (GWP10	kg CO2 eq	0.00E+00	1.99E+00	1.24E-01	0.00E+00	3.07E+00	0.00E+00	5.18E+00
Photochemical oxidation	kg C2H4	0.00E+00	4.22E-04	2.42E-05	0.00E+00	4.93E-04	0.00E+00	9.40E-04
CED non-renewable	MJ-eq	0.00E+00	3.43E+01	1.85E+00	0.00E+00	5.10E+01	0.00E+00	8.71E+01
CED renewable	MJ-eq	0.00E+00	2.06E+00	6.03E-03	0.00E+00	6.24E-01	0.00E+00	2.69E+00
Particulate matter	kg PM10 eq	8.51E-04	4.73E-03	5.05E-04	0.00E+00	7.75E-03	0.00E+00	1.38E-02
Land competition	m2a	0.00E+00	2.45E-01	3.62E-04	0.00E+00	4.55E-02	0.00E+00	2.91E-01
Water use	m3	0.00E+00	6.49E-01	1.69E-04	0.00E+00	1.20E-02	0.00E+00	6.61E-01

Case 1B	Unit	Filter system	Gravel	Building machine	Geosynthetic	Transport	Disposal	Total
Acidification	kg SO2 eq	0.00E+00	0.00E+00	7.30E-04	1.65E-03	4.00E-05	2.13E-05	2.44E-03
Eutrophication	kg PO4--- eq	0.00E+00	0.00E+00	1.57E-04	2.12E-04	5.51E-06	6.05E-06	3.80E-04
Global warming 2007 (GWP10	kg CO2 eq	0.00E+00	0.00E+00	9.58E-02	5.58E-01	4.67E-03	1.51E-01	8.10E-01
Photochemical oxidation	kg C2H4	0.00E+00	0.00E+00	1.86E-05	1.04E-04	7.51E-07	2.27E-06	1.25E-04
CED non-renewable	MJ-eq	0.00E+00	0.00E+00	1.42E+00	1.72E+01	7.76E-02	4.72E-02	1.88E+01
CED renewable	MJ-eq	0.00E+00	0.00E+00	4.64E-03	3.02E-01	9.49E-04	8.04E-04	3.09E-01
Particulate matter	kg PM10 eq	0.00E+00	0.00E+00	3.89E-04	5.19E-04	1.18E-05	1.00E-05	9.29E-04
Land competition	m2a	3.00E+01	0.00E+00	2.79E-04	1.10E-01	6.93E-05	3.93E-04	3.01E+01
Water use	m3	0.00E+00	0.00E+00	1.30E-04	2.27E-03	1.83E-05	8.99E-05	2.51E-03

B.1.2 Case 2

Case 2A	Unit	Road	Bitumen	Gravel	Geosynthetic	Building machine	Transport	Cement	Lime	Disposal	Total
Acidification	kg SO2 eq	0	5.85E-01	8.08E-01	0.00E+00	1.37E+00	1.23E+00	0.00E+00	0.00E+00	0.00E+00	3.99E+00
Eutrophication	kg PO4--- eq	0	1.40E-01	3.38E-01	0.00E+00	3.15E-01	3.24E-01	0.00E+00	0.00E+00	0.00E+00	1.12E+00
Global warming 2007 (GWP100)	kg CO2 eq	0	1.80E+02	1.47E+02	0.00E+00	1.79E+02	2.28E+02	0.00E+00	0.00E+00	0.00E+00	7.34E+02
Photochemical oxidation	kg C2H4	0	6.00E-02	3.11E-02	0.00E+00	3.49E-02	3.67E-02	0.00E+00	0.00E+00	0.00E+00	1.63E-01
CED non-renewable	MJ-eq	0	1.62E+04	2.53E+03	0.00E+00	2.66E+03	3.80E+03	0.00E+00	0.00E+00	0.00E+00	2.52E+04
CED renewable	MJ-eq	0	2.77E+01	1.52E+02	0.00E+00	8.70E+00	4.64E+01	0.00E+00	0.00E+00	0.00E+00	2.34E+02
Particulate matter	kg PM10 eq	0.062753	2.19E-01	3.51E-01	0.00E+00	7.29E-01	5.77E-01	0.00E+00	0.00E+00	0.00E+00	1.94E+00
Land competition	m2a	360	6.02E-01	1.81E+01	0.00E+00	5.23E-01	3.39E+00	0.00E+00	0.00E+00	0.00E+00	3.83E+02
Water use	m3	0	1.22E+00	4.78E+01	0.00E+00	2.44E-01	8.91E-01	0.00E+00	0.00E+00	0.00E+00	5.02E+01

Case 2B	Unit	Road	Bitumen	Gravel	Geosynthetic	Building machine	Transport	Cement	Lime	Disposal	Total
Acidification	kg SO2 eq	0	5.85E-01	5.79E-01	4.97E-02	1.38E+00	8.87E-01	0.00E+00	0.00E+00	6.23E-04	3.48E+00
Eutrophication	kg PO4--- eq	0	1.40E-01	2.42E-01	1.65E-02	3.17E-01	2.34E-01	0.00E+00	0.00E+00	1.25E-02	9.62E-01
Global warming 2007 (GWP100)	kg CO2 eq	0	1.80E+02	1.05E+02	1.68E+01	1.81E+02	1.64E+02	0.00E+00	0.00E+00	4.42E+00	6.51E+02
Photochemical oxidation	kg C2H4	0	6.00E-02	2.23E-02	3.12E-03	3.52E-02	2.64E-02	0.00E+00	0.00E+00	6.63E-05	1.47E-01
CED non-renewable	MJ-eq	0	1.62E+04	1.81E+03	4.97E+02	2.68E+03	2.73E+03	0.00E+00	0.00E+00	1.38E+00	2.39E+04
CED renewable	MJ-eq	0	2.77E+01	1.09E+02	1.60E+01	8.77E+00	3.35E+01	0.00E+00	0.00E+00	2.35E-02	1.95E+02
Particulate matter	kg PM10 eq	0.044984	2.19E-01	2.51E-01	1.58E-02	7.34E-01	4.16E-01	0.00E+00	0.00E+00	2.93E-04	1.68E+00
Land competition	m2a	360	6.02E-01	1.30E+01	2.46E+00	5.27E-01	2.44E+00	0.00E+00	0.00E+00	1.15E-02	3.79E+02
Water use	m3	0	1.22E+00	3.43E+01	6.80E-02	2.46E-01	6.42E-01	0.00E+00	0.00E+00	2.63E-03	3.65E+01

Case 2BS1	Unit	Road	Bitumen	Gravel	Geosynthetic	Building machine	Transport	Cement	Lime	Disposal	Total
Acidification	kg SO2 eq	0	5.85E-01	6.90E-01	4.97E-02	1.40E+00	1.12E+00	0.00E+00	0.00E+00	6.23E-04	3.84E+00
Eutrophication	kg PO4--- eq	0	1.40E-01	2.88E-01	1.65E-02	3.21E-01	2.95E-01	0.00E+00	0.00E+00	1.25E-02	1.07E+00
Global warming 2007 (GWP100)	kg CO2 eq	0	1.80E+02	1.25E+02	1.68E+01	1.83E+02	2.07E+02	0.00E+00	0.00E+00	4.42E+00	7.17E+02
Photochemical oxidation	kg C2H4	0	6.00E-02	2.66E-02	3.12E-03	3.56E-02	3.34E-02	0.00E+00	0.00E+00	6.63E-05	1.59E-01
CED non-renewable	MJ-eq	0	1.62E+04	2.16E+03	4.97E+02	2.72E+03	3.45E+03	0.00E+00	0.00E+00	1.38E+00	2.50E+04
CED renewable	MJ-eq	0	2.77E+01	1.29E+02	1.60E+01	8.88E+00	4.23E+01	0.00E+00	0.00E+00	2.35E-02	2.24E+02
Particulate matter	kg PM10 eq	0.053562	2.19E-01	2.99E-01	1.58E-02	7.44E-01	5.25E-01	0.00E+00	0.00E+00	2.93E-04	1.86E+00
Land competition	m2a	360	6.02E-01	1.54E+01	2.46E+00	5.34E-01	3.08E+00	0.00E+00	0.00E+00	1.15E-02	3.82E+02
Water use	m3	0	1.22E+00	4.08E+01	6.80E-02	2.49E-01	8.11E-01	0.00E+00	0.00E+00	2.63E-03	4.32E+01

Case 2BS2	Unit	Road	Bitumen	Gravel	Geosynthetic	Building machine	Transport	Cement	Lime	Disposal	Total
Acidification	kg SO2 eq	0	5.85E-01	5.79E-01	3.00E-02	1.37E+00	8.86E-01	0.00E+00	0.00E+00	6.23E-04	3.45E+00
Eutrophication	kg PO4--- eq	0	1.40E-01	2.42E-01	1.16E-02	3.15E-01	2.34E-01	0.00E+00	0.00E+00	1.25E-02	9.54E-01
Global warming 2007 (GWP100)	kg CO2 eq	0	1.80E+02	1.05E+02	1.01E+01	1.80E+02	1.64E+02	0.00E+00	0.00E+00	4.42E+00	6.43E+02
Photochemical oxidation	kg C2H4	0	6.00E-02	2.23E-02	1.88E-03	3.49E-02	2.64E-02	0.00E+00	0.00E+00	6.63E-05	1.46E-01
CED non-renewable	MJ-eq	0	1.62E+04	1.81E+03	2.90E+02	2.67E+03	2.73E+03	0.00E+00	0.00E+00	1.38E+00	2.37E+04
CED renewable	MJ-eq	0	2.77E+01	1.09E+02	1.24E+01	8.71E+00	3.34E+01	0.00E+00	0.00E+00	2.35E-02	1.91E+02
Particulate matter	kg PM10 eq	0.044984	2.19E-01	2.51E-01	9.52E-03	7.30E-01	4.16E-01	0.00E+00	0.00E+00	2.93E-04	1.67E+00
Land competition	m2a	360	6.02E-01	1.30E+01	1.14E+00	5.23E-01	2.44E+00	0.00E+00	0.00E+00	1.15E-02	3.78E+02
Water use	m3	0	1.22E+00	3.43E+01	4.08E-02	2.44E-01	6.42E-01	0.00E+00	0.00E+00	2.63E-03	3.64E+01

Case 2C	Unit	Road	Bitumen	Gravel	Geosynthetic	Building machine	Transport	Cement	Lime	Disposal	Total
Acidification	kg SO2 eq	0	5.85E-01	4.46E-01	0.00E+00	1.38E+00	7.23E-01	1.68E-01	2.23E-01	0.00E+00	3.52E+00
Eutrophication	kg PO4--- eq	0	1.40E-01	1.87E-01	0.00E+00	3.17E-01	1.93E-01	3.82E-02	3.36E-02	0.00E+00	9.07E-01
Global warming 2007 (GWP100)	kg CO2 eq	0	1.80E+02	8.12E+01	0.00E+00	1.81E+02	1.34E+02	1.18E+02	2.55E+02	0.00E+00	9.49E+02
Photochemical oxidation	kg C2H4	0	6.00E-02	1.72E-02	0.00E+00	3.51E-02	2.17E-02	6.23E-03	4.30E-02	0.00E+00	1.83E-01
CED non-renewable	MJ-eq	0	1.62E+04	1.40E+03	0.00E+00	2.68E+03	2.23E+03	5.25E+02	1.42E+03	0.00E+00	2.44E+04
CED renewable	MJ-eq	0	2.77E+01	8.38E+01	0.00E+00	8.76E+00	2.86E+01	2.96E+01	8.39E+01	0.00E+00	2.62E+02
Particulate matter	kg PM10 eq	0.03467	2.19E-01	1.94E-01	0.00E+00	7.33E-01	3.39E-01	6.85E-02	1.02E-01	0.00E+00	1.69E+00
Land competition	m2a	360	6.02E-01	1.00E+01	0.00E+00	5.26E-01	2.04E+00	7.98E-01	1.78E-01	0.00E+00	3.74E+02
Water use	m3	0	1.22E+00	2.64E+01	0.00E+00	2.46E-01	5.32E-01	3.70E-01	1.87E-01	0.00E+00	2.90E+01

Case 2CS2	Unit	Road	Bitumen	Gravel	Geosynthetic	Building machine	Transport	Cement	Lime	Disposal	Total
Acidification	kg SO2 eq	0	5.85E-01	4.46E-01	0.00E+00	1.37E+00	7.14E-01	3.37E-01	0.00E+00	0.00E+00	3.45E+00
Eutrophication	kg PO4--- eq	0	1.40E-01	1.87E-01	0.00E+00	3.14E-01	1.90E-01	7.63E-02	0.00E+00	0.00E+00	9.07E-01
Global warming 2007 (GWP100)	kg CO2 eq	0	1.80E+02	8.12E+01	0.00E+00	1.79E+02	1.32E+02	2.36E+02	0.00E+00	0.00E+00	8.09E+02
Photochemical oxidation	kg C2H4	0	6.00E-02	1.72E-02	0.00E+00	3.49E-02	2.14E-02	1.25E-02	0.00E+00	0.00E+00	1.46E-01
CED non-renewable	MJ-eq	0	1.62E+04	1.40E+03	0.00E+00	2.66E+03	2.20E+03	1.05E+03	0.00E+00	0.00E+00	2.35E+04
CED renewable	MJ-eq	0	2.77E+01	8.38E+01	0.00E+00	8.70E+00	2.79E+01	5.92E+01	0.00E+00	0.00E+00	2.07E+02
Particulate matter	kg PM10 eq	0.03467	2.19E-01	1.94E-01	0.00E+00	7.28E-01	3.34E-01	1.37E-01	0.00E+00	0.00E+00	1.65E+00
Land competition	m2a	360	6.02E-01	1.00E+01	0.00E+00	5.22E-01	2.00E+00	1.60E+00	0.00E+00	0.00E+00	3.75E+02
Water use	m3	0	1.22E+00	2.64E+01	0.00E+00	2.44E-01	5.23E-01	7.41E-01	0.00E+00	0.00E+00	2.92E+01

B.1.3 Case 3

Case 3A	Unit	Landfill	Gravel	Geosynthetic	Building machine	Transport	Cement	Disposal	Total
Acidification	kg SO2 eq	0.00E+00	1.76E-02	3.30E-03	3.18E-03	3.26E-02	0.00E+00	3.05E-05	5.67E-02
Eutrophication	kg PO4--- eq	0.00E+00	3.14E-03	4.24E-04	6.82E-04	7.13E-03	0.00E+00	7.44E-06	1.14E-02
Global warming 2007 (GWP100)	kg CO2 eq	0.00E+00	3.08E+00	1.12E+00	4.17E-01	6.03E+00	0.00E+00	2.85E-01	1.09E+01
Photochemical oxidation	kg C2H4	0.00E+00	6.48E-04	2.08E-04	8.16E-05	9.76E-04	0.00E+00	1.16E-06	1.91E-03
CED non-renewable	MJ-eq	0.00E+00	5.22E+01	3.44E+01	6.23E+00	1.01E+02	0.00E+00	3.89E-02	1.94E+02
CED renewable	MJ-eq	0.00E+00	2.78E+00	6.05E-01	2.38E-02	1.26E+00	0.00E+00	7.27E-04	4.67E+00
Particulate matter	kg PM10 eq	1.67E-03	7.93E-03	1.04E-03	1.69E-03	1.53E-02	0.00E+00	1.40E-05	2.76E-02
Land competition	m2a	1.00E+02	4.59E-01	2.21E-01	1.28E-03	9.02E-02	0.00E+00	5.08E-05	1.01E+02
Water use	m3	0.00E+00	1.27E+00	4.55E-03	6.28E-04	2.41E-02	0.00E+00	1.28E-04	1.30E+00

Case 3B	Unit	Landfill	Gravel	Geosynthetic	Building machine	Transport	Cement	Disposal	Total
Acidification	kg SO2 eq	0.00E+00	0.00E+00	7.88E-03	2.68E-03	1.95E-04	0.00E+00	1.06E-04	1.09E-02
Eutrophication	kg PO4--- eq	0.00E+00	0.00E+00	9.08E-04	5.75E-04	3.88E-05	0.00E+00	2.99E-05	1.55E-03
Global warming 2007 (GWP100)	kg CO2 eq	0.00E+00	0.00E+00	2.46E+00	3.51E-01	3.62E-02	0.00E+00	7.35E-01	3.58E+00
Photochemical oxidation	kg C2H4	0.00E+00	0.00E+00	4.72E-04	6.88E-05	6.71E-06	0.00E+00	1.11E-05	5.59E-04
CED non-renewable	MJ-eq	0.00E+00	0.00E+00	7.99E+01	5.25E+00	6.22E-01	0.00E+00	2.36E-01	8.60E+01
CED renewable	MJ-eq	0.00E+00	0.00E+00	1.36E+00	2.01E-02	1.80E-02	0.00E+00	4.03E-03	1.40E+00
Particulate matter	kg PM10 eq	0.00E+00	0.00E+00	2.45E-03	1.43E-03	8.79E-05	0.00E+00	4.97E-05	4.01E-03
Land competition	m2a	1.00E+02	0.00E+00	7.19E-01	1.08E-03	9.74E-04	0.00E+00	1.92E-03	1.01E+02
Water use	m3	0.00E+00	0.00E+00	3.47E-02	5.29E-04	2.07E-04	0.00E+00	4.39E-04	3.59E-02

B.1.4 Case 4

Case 4A	Unit	Slope retention	Concrete	Gravel	Geosynthetic	Reinforcing steel	Bitumen	Wood	Plastic	Building machine	Transport	Disposal	Total
Acidification	kg SO2 eq	0.00E+00	1.63E+00	8.45E-02	0.00E+00	7.80E-01	5.52E-03	2.31E-02	1.84E-02	8.19E-03	5.14E-01	4.20E-01	3.48E+00
Eutrophication	kg PO4--- eq	0.00E+00	2.67E-01	1.51E-02	0.00E+00	1.05E-01	8.97E-04	4.13E-03	1.39E-03	1.75E-03	1.12E-01	8.88E-02	5.96E-01
Global warming 2007 (GWP100)	kg CO2 eq	0.00E+00	8.91E+02	1.48E+01	0.00E+00	2.27E+02	1.69E+00	4.15E+00	5.10E+00	1.07E+00	9.50E+01	7.52E+01	1.32E+03
Photochemical oxidation	kg C2H4	0.00E+00	6.09E-02	3.11E-03	0.00E+00	1.24E-01	5.63E-04	1.87E-03	2.92E-03	2.10E-04	1.55E-02	1.45E-02	2.24E-01
CED non-renewable	MJ-eq	0.00E+00	5.28E+03	2.50E+02	0.00E+00	3.45E+03	1.52E+02	7.97E+01	1.71E+02	1.60E+01	1.59E+03	1.73E+03	1.27E+04
CED renewable	MJ-eq	0.00E+00	3.31E+02	1.33E+01	0.00E+00	8.94E+01	2.72E-01	1.67E+02	3.44E+00	6.13E-02	2.08E+01	1.51E+01	6.41E+02
Particulate matter	kg PM10 eq	0.00E+00	6.72E-01	3.81E-02	0.00E+00	6.98E-01	2.06E-03	1.02E-02	5.40E-03	4.35E-03	2.40E-01	2.03E-01	1.87E+00
Land competition	m2a	1.01E+02	1.37E+01	2.20E+00	0.00E+00	7.35E+00	5.80E-03	8.42E+01	1.75E-01	3.30E-03	1.46E+00	8.55E+00	2.18E+02
Water use	m3	0.00E+00	1.45E+01	6.09E+00	0.00E+00	2.63E+00	1.16E-02	3.38E-02	1.26E-02	1.61E-03	3.86E-01	1.23E+00	2.49E+01

Case 4B	Unit	Slope retention	Concrete	Gravel	Geosynthetic	Reinforcing steel	Bitumen	Wood	Plastic	Building machine	Transport	Disposal	Total
Acidification	kg SO2 eq	0.00E+00	1.54E-01	8.45E-02	1.55E-01	0.00E+00	0.00E+00	9.17E-03	1.70E-02	3.79E-02	1.93E-01	3.78E-02	6.88E-01
Eutrophication	kg PO4--- eq	0.00E+00	2.49E-02	1.51E-02	1.74E-02	0.00E+00	0.00E+00	1.64E-03	1.26E-03	8.11E-03	4.21E-02	9.06E-03	1.20E-01
Global warming 2007 (GWP100)	kg CO2 eq	0.00E+00	8.95E+01	1.48E+01	4.78E+01	0.00E+00	0.00E+00	1.65E+00	4.69E+00	4.96E+00	3.57E+01	2.82E+01	2.27E+02
Photochemical oxidation	kg C2H4	0.00E+00	5.75E-03	3.11E-03	1.02E-02	0.00E+00	0.00E+00	7.41E-04	1.41E-03	9.71E-04	5.79E-03	1.50E-03	2.94E-02
CED non-renewable	MJ-eq	0.00E+00	4.80E+02	2.50E+02	1.35E+03	0.00E+00	0.00E+00	3.16E+01	1.68E+02	7.42E+01	5.97E+02	1.45E+02	3.09E+03
CED renewable	MJ-eq	0.00E+00	2.75E+01	1.33E+01	3.69E+01	0.00E+00	0.00E+00	6.64E+01	3.70E+00	2.84E-01	7.66E+00	1.34E+00	1.57E+02
Particulate matter	kg PM10 eq	0.00E+00	6.33E-02	3.81E-02	4.84E-02	0.00E+00	0.00E+00	4.04E-03	5.07E-03	2.02E-02	9.03E-02	1.81E-02	2.87E-01
Land competition	m2a	6.07E+01	1.18E+00	2.20E+00	7.74E+00	0.00E+00	0.00E+00	3.34E+01	2.01E-01	1.53E-02	5.42E-01	7.43E-01	1.07E+02
Water use	m3	0.00E+00	1.21E+00	6.09E+00	2.35E-01	0.00E+00	0.00E+00	1.34E-02	1.16E-02	7.47E-03	1.44E-01	1.13E-01	7.82E+00

C Annex C: Life Cycle Inventory Analyses

How to read the tables with unit process raw data

The **light green fields** describe the name of the product/process, its region (e.g. RER stands for Europe) and the unit data it refers to. It is the output product (the reference output) of the process and always equals '1'. The **yellow fields** show the inputs and outputs of the respective processes. The **grey fields** specify whether it is an input from or an output to nature or technosphere and the compartment to which a pollutant is emitted. For each product, additional descriptive information is given in separate tables.

The location codes (an extended ISO alpha-2 code-set) have the following meaning:

GLO Global
RER Europe
UCTE Union for the Co-ordination of Transmission of Electricity
CH Switzerland

C.1 Case 1 – Filter Construction

We consider two different filter types. Case 1A is a mixed grain filter whereas case 1B is a geosynthetics based filter, which uses geosynthetics as a separator. For each case one LCI dataset of the construction of the filter and one LCI dataset of the disposal of the filter are created. The unit process raw data are shown in Tab. 7.1. The EcoSpold meta information is displayed in Tab. 7.2.

C.1.1 Construction

A filter with an area of 1 m^2 standard cross-section is considered. The total thickness of the case 1A filter is 300 mm, whereas the total thickness of the case 1B road is equivalent to the geosynthetics thickness. The irregular effects on the edges are disregarded (to the advantage of case 1A).

The case 1A filter consists of 300 mm pure gravel. The use of geosynthetics in case 1B reduces the thickness of the filter, because it consists of the geosynthetic only.

The LCI refers to a life time of 30 years which is also the expected life time of the binder course. Direct land use is not included in this LCI because the type of land use under which the filter is being built in is not known.

For the gravel used, a mix of 21 % crushed gravel and 79 % round gravel is considered (according to the corresponding ecoinvent dataset) and the electricity mix and the transport modes are adjusted to the European situation.

During the filter construction, diesel is used for the operation of various building machines. Applying statistical fuel consumption data published by Schäffeler & Keller (2008) and assuming a digging efficiency of 100 m^3/h, the average energy consumption is 4.4 MJ/m^3 digging with a hydraulic excavator (power size between 75 and 130 kW).

For the transportation by lorry of gravel an average distance of 50 km to the construction site is assumed. Geosynthetics are transported typically around 600 km to the place of use.[11] We assume that 400 km is covered by rail and 200 km by lorry.

[11] Personal communication with Henning Ehrenberg , EAGM Project Working Group (31. January 2010)

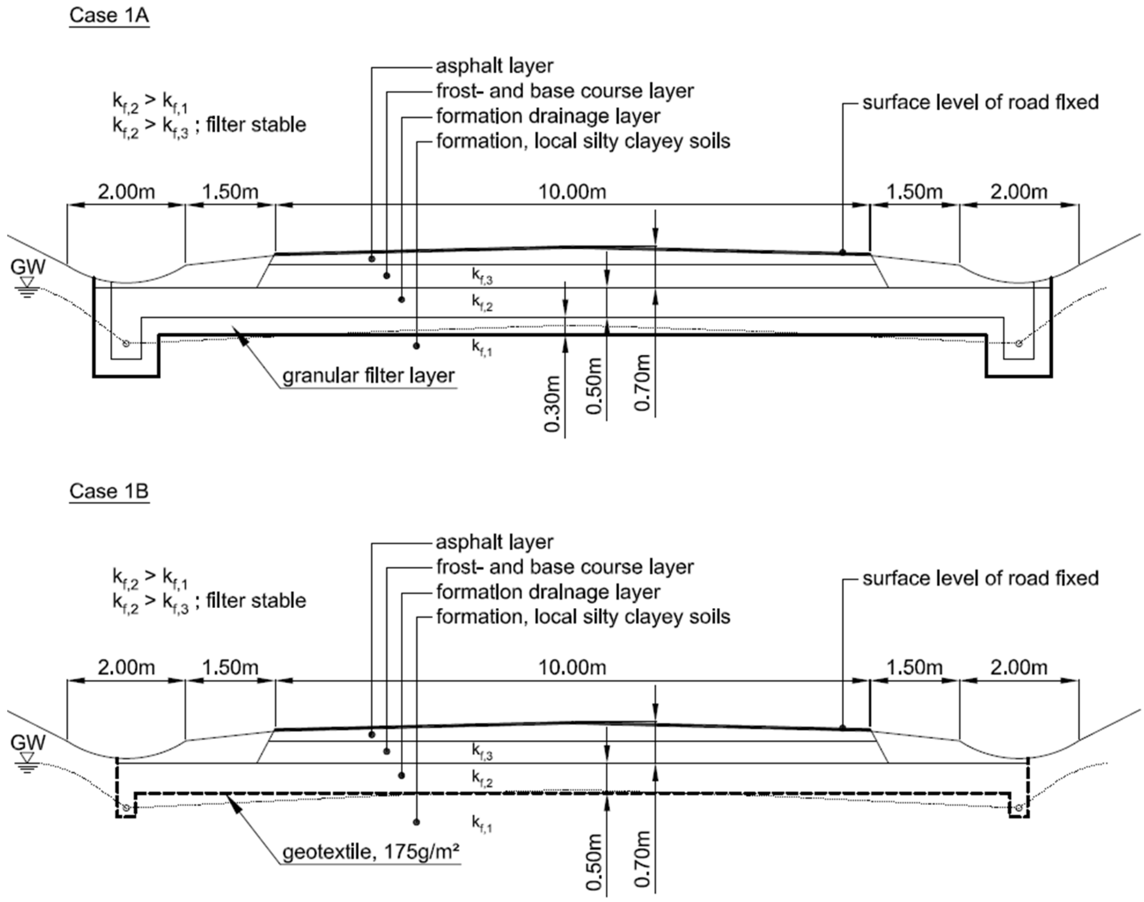

Fig. 7.2: Cross section of the mineral filter (case 1A, top) and geosynthetic filter system (case 1B, bottom)

C.1.2 Disposal

The asphalt and gravel in road infrastructure is usually reused after removal of a road. According to PlasticsEurope (2009) in 2008 16 % of plastics used in construction are recycled, 52 % are sent to landfill, and 32 % are sent to municipal incineration. These shares are applied for the disposal of the geosynthetics. The standard transport distance to the landfill and the municipal waste incinerating plant is 20 km.

C.1.3 Unit process raw data of the infrastructure element

Tab. 7.1: Unit process raw data of cases 1A and 1B

	Name	Location	InfrastructureProcess	Unit	filter layer, gravel, 0.3m, without geotextile	filter layer, geotextile, 175 g/m2	disposal, filter layer, gravel, 0.3m, without geotextile	disposal, filter layer, geotextile, 175 g/m2	life cycle, filter layer, gravel, 0.3m, without geotextile	life cycle, filter layer, geotextile, 175 g/m2	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER	RER	RER	RER	RER	RER			
	InfrastructureProcess				1	1	1	1	1	1			
	Unit				m2	m2	m2	m2	m2	m2			
product	filter layer, gravel, 0.3m, without geotextile	RER	1	m2	1	0	0	0	0	0			
	filter layer, geotextile, 175 g/m2	RER	1	m2	0	1	0	0	0	0			
	disposal, filter layer, gravel, 0.3m, without geotextile	RER	1	m2	0	0	1	0	0	0			
	disposal, filter layer, geotextile, 175 g/m2	RER	1	m2	0	0	0	1	0	0			
	life cycle, filter layer, gravel, 0.3m, without geotextile	RER	1	m2	0	0	0	0	1	0			
	life cycle, filter layer, geotextile, 175 g/m2	RER	1	m2	0	0	0	0	0	1			
	gravel, unspecified, at mine	RER	0	kg	6.90E+2	0	-	-	-	-	1	1.07	(2,1,1,1,1,2);
	c1, geosynthetic, average, road construction	RER	0	m2	-	1.00E+0	-	-	-	-	1	1.05	(3,1,1,1,1,5); uncertainty set to 1.05: 5% cuttings and other
	diesel, burned in building machine	GLO	0	MJ	2.04E+0	1.04E+0	-	-	-	-	1	1.25	(2,3,3,1,1,5); asphalt mixture, compaction, distribution etc.
	transport, lorry >16t, fleet average	RER	0	tkm	3.45E+1	3.50E-2	-	2.94E-3	-	-	1	2.09	(4,5,na,na,na,na); gravel and bitumen: 50 km; geosynthetics: 200 km; disposal: 40 km to recycling plant, 20 km to municial incineration and landfill
	transport, freight, rail	RER	0	tkm	-	7.00E-2			-	-	1	2.09	(4,5,na,na,na,na); geosynthetics: 400 km
	disposal, polypropylene, 15.9% water, to municipal incineration	CH	0	kg	-	-	-	5.60E-2	-	-	1	1.30	(4,1,1,1,1,5); 32 % of geosynthetic
	disposal, polypropylene, 15.9% water, to sanitary landfill	CH	0	kg	-	-	-	9.10E-2	-	-	1	1.30	(4,1,1,1,1,5); 52 % of geosynthetic
	Particulates, > 10 um	-	-	kg	4.83E-3	-	-	-	-	-	1	1.63	(2,3,4,3,1,5); due to loading and tipping of gravel
	Particulates, > 2.5 um, and < 10um	-	-	kg	1.28E-3	-	-	-	-	-	1	2.10	(2,3,4,3,1,5); due to loading and tipping of gravel
technosphere	filter layer, gravel, 0.3m, without geotextile	RER	1	m2	-	-	-	-	1.00E+0	-	1	1.00	(1,1,1,1,1,1); uncertainty set to 1
	filter layer, geotextile, 175 g/m2	RER	1	m2	-	-	-	-	-	1.00E+0	1	1.00	(1,1,1,1,1,1); uncertainty set to 1
	disposal, filter layer, gravel, 0.3m, without geotextile	RER	1	m2	-	-	-	-	1.00E+0	-	1	1.00	(1,1,1,1,1,1); uncertainty set to 1
	disposal, filter layer, geotextile, 175 g/m2	RER	1	m2	-	-	-	-	-	1.00E+0	1	1.00	(1,1,1,1,1,1); uncertainty set to 1

Tab. 7.2: EcoSpold meta information of cases 1A and 1B

ReferenceFunction	Name	filter layer, gravel, 0.3m, without geotextile	filter layer, geotextile, 175 g/m2	disposal, filter layer, gravel, 0.3m, without geotextile	disposal, filter layer, geotextile, 175 g/m2	life cycle, filter layer, gravel, 0.3m, without geotextile	life cycle, filter layer, geotextile, 175 g/m2
Geography	Location	RER	RER	RER	RER	RER	RER
ReferenceFunctio	InfrastructureProcess	1	1	1	1	1	1
ReferenceFunctio	Unit	m2	m2	m2	m2	m2	m2
	IncludedProcesses	This dataset includes material, energy and water consumption as well as infrastructure and land use for the construction of a gravel based filter layer without geosynthetics.	This dataset includes material, energy and water consumption as well as infrastructure and land use for the construction of a filter layer based on a geotextile.	This dataset includs the excavation and disposal of the materials from the dismantling of a gravel based filter layer without geosynthetics.	This dataset includs the excavation and disposal of the materials from the dismantling of a filter layer based on a geotextile, as well as the transportation of the materials to the place of disposal or reuse.	This dataset includes construction and disposal of a gravel based filter layer without geosynthetics.	This dataset includes construction and disposal of a filter layer based on a geotextile.
	GeneralComment	The LCI reflects a filter layer with 0.3 m thickness.	The LCI reflects a filter layer based on geotextile 0.175 kg/m2	The LCI reflects a filter layer with 0.3 m thickness.	The LCI reflects a filter layer based on geotextile 0.175 kg/m2	The LCI reflects a filter layer with 0.3 m thickness.	The LCI reflects a filter layer based on geotextile 0.175 kg/m2
	InfrastructureIncluded	1	1	1	1	1	1
	Category	transport systems	transport systems	transport systems	transport systems	transport systems	transport systems
	SubCategory	road	road	road	road	road	road
TimePeriod	StartDate	2006	2006	2006	2006	2006	2006
	EndDate	2010	2010	2010	2010	2010	2010
	DataValidForEntirePeriod	1	1	1	1	1	1
	OtherPeriodText						
Geography	Text	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.
Technology	Text	Conventional construction with building machines.	Construction of a geosynthethics with building machines.	Excavation by hydraulic excavator, transport by lorry	Excavation by hydraulic excavator, transport by lorry	Conventional construction with building machines.	Construction of a geosynthethics with building machines.
Representativene	Percent	0	0	0	0	0	0
	ProductionVolume	unknown	unknown	unknown	unknown	unknown	unknown
	SamplingProcedure	unknown	unknown	unknown	unknown	unknown	unknown
	Extrapolations	none	none	none	none	none	none
	UncertaintyAdjustments	none	none	none	none	none	none
	Details	07.10.2011	07.10.2011	07.10.2011	07.10.2011	07.10.2011	07.10.2011
	OtherDetails	\\Server\E\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 1\[319-ecospold-filter-construction-case-1-0.2.xlsx]X-Process	\\Server\E\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 1\[319-ecospold-filter-construction-case-1-0.2.xlsx]X-Process	\\Server\E\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 1\[319-ecospold-filter-construction-case-1-0.2.xlsx]X-Process	\\Server\E\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 1\[319-ecospold-filter-construction-case-1-0.2.xlsx]X-Process	\\Server\E\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 1\[319-ecospold-filter-construction-case-1-0.2.xlsx]X-Process	\\Server\E\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 1\[319-ecospold-filter-construction-case-1-0.2.xlsx]X-Process

Tab. 7.3: Unit process raw data of the filter layers in the cases 1AS1 and 1AS2

	Name	Location	InfrastructureProcess	Unit	filter layer, gravel, 0.4m, without geotextile	filter layer, gravel, 0.2m, without geotextile	disposal, filter layer, gravel, 0.4m, without geotextile	disposal, filter layer, gravel, 0.2m, without geotextile	life cycle, filter layer, gravel, 0.4m, without geotextile	life cycle, filter layer, gravel, 0.2m, without geotextile	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER	RER	RER	RER	RER	RER			
	InfrastructureProcess				1	1	1	1	1	1			
	Unit				m2	m2	m2	m2	m2	m2			
product	filter layer, gravel, 0.4m, without geotextile	RER	1	m2	1	0	0	0	0	0			
	filter layer, gravel, 0.2m, without geotextile	RER	1	m2	0	1	0	0	0	0			
	disposal, filter layer, gravel, 0.4m, without geotextile	RER	1	m2	0	0	1	0	0	0			
	disposal, filter layer, gravel, 0.2m, without geotextile	RER	1	m2	0	0	0	1	0	0			
	life cycle, filter layer, gravel, 0.4m, without geotextile	RER	1	m2	0	0	0	0	1	0			
	life cycle, filter layer, gravel, 0.2m, without geotextile	RER	1	m2	0	0	0	0	0	1			
	gravel, unspecified, at mine	RER	0	kg	9.20E+2	4.60E+2	-	-	-	-	1	1.07	(2,1,1,1,1,2;3,1.05);
	diesel, burned in building machine	GLO	0	MJ	2.71E+0	1.36E+0	-	-	-	-	1	1.25	(2,3,3,1,1,5;2,1.05); asphalt mixture, compaction, distribution etc.
	transport, lorry >16t, fleet average	RER	0	tkm	4.60E+1	2.30E+1	-	-	-	-	1	2.09	(4,5,na,na,na,na;5,2); gravel and bitumen: 50 km; geosynthetics: 200 km; disposal: 40 km to recycling plant, 20 km to municial incineration and landfill
	Particulates, > 10 um	-	-	kg	6.44E-3	3.22E-3	-	-	-	-	1	1.63	(2,3,4,3,1,5;18,1.5); due to loading and tipping of gravel
	Particulates, > 2.5 um, and < 10um	-	-	kg	1.70E-3	8.51E-4	-	-	-	-	1	2.10	(2,3,4,3,1,5;19,2); due to loading and tipping of gravel
technosphere	filter layer, gravel, 0.4m, without geotextile	RER	1	m2	-	-	-	-	1.00E+0	-	1	1.00	(1,1,1,1,1,1;9,3); uncertainty set to 1
	filter layer, gravel, 0.2m, without geotextile	RER	1	m2	-	-	-	-	-	1.00E+0	1	1.00	(1,1,1,1,1,1;9,3); uncertainty set to 1
	disposal, filter layer, gravel, 0.4m, without geotextile	RER	1	m2	-	-	-	-	1.00E+0	-	1	1.00	(1,1,1,1,1,1;9,3); uncertainty set to 1
	disposal, filter layer, gravel, 0.2m, without geotextile	RER	1	m2	-	-	-	-	-	1.00E+0	1	1.00	(1,1,1,1,1,1;9,3); uncertainty set to 1

Tab. 7.4: EcoSpold meta information of the filter layers in the cases 1AS1 and 1AS2

ReferenceFunction	Name	filter layer, gravel, 0.4m, without geotextile	filter layer, gravel, 0.2m, without geotextile	disposal, filter layer, gravel, 0.4m, without geotextile	disposal, filter layer, gravel, 0.2m, without geotextile	life cycle, filter layer, gravel, 0.4m, without geotextile	life cycle, filter layer, gravel, 0.2m, without geotextile
Geography	Location	RER	RER	RER	RER	RER	RER
ReferenceFunction	InfrastructureProcess	1	1	1	1	1	1
ReferenceFunction	Unit	m2	m2	m2	m2	m2	m2
	IncludedProcesses	This dataset includes material, energy and water consumption as well as infrastructure and land use for the construction of a gravel based filter layer without geosynthetics.	This dataset includes material, energy and water consumption as well as infrastructure and land use for the construction of a gravel based filter layer without geosynthetics.	This dataset includs the excavation and disposal of the materials from the dismantling of a gravel based filter layer without geosynthetics.	This dataset includs the excavation and disposal of the materials from the dismantling of a gravel based filter layer without geosynthetics.	This dataset includes construction and disposal of a gravel based filter layer without geosynthetics.	This dataset includes construction and disposal of a gravel based filter layer without geosynthetics.
	GeneralComment	The LCI reflects a filter layer with 0.4 m thickness.	The LCI reflects a filter layer with 0.2 m thickness.	The LCI reflects a filter layer with 0.4 m thickness.	The LCI reflects a filter layer with 0.2 m thickness.	The LCI reflects a filter layer with 0.4 m thickness.	The LCI reflects a filter layer with 0.2 m thickness.
	InfrastructureIncluded	1	1	1	1	1	1
	Category	transport systems	transport systems	transport systems	transport systems	transport systems	transport systems
	SubCategory	road	road	road	road	road	road
TimePeriod	StartDate	2006	2006	2006	2006	2006	2006
	EndDate	2010	2010	2010	2010	2010	2010
	DataValidForEntirePeriod	1	1	1	1	1	1
	OtherPeriodText						
Geography	Text	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.
Technology	Text	Conventional construction with building machines.	Conventional construction with building machines.	Excavation by hydraulic excavator, transport by lorry	Excavation by hydraulic excavator, transport by lorry	Conventional construction with building machines.	Conventional construction with building machines.
Representativeness	Percent	0	0	0	0	0	0
	ProductionVolume	unknown	unknown	unknown	unknown	unknown	unknown
	SamplingProcedure	unknown	unknown	unknown	unknown	unknown	unknown
	Extrapolations	none	none	none	none	none	none
	UncertaintyAdjustments	none	none	none	none	none	none
	Details	05.10.2011	05.10.2011	05.10.2011	05.10.2011	05.10.2011	05.10.2011
	OtherDetails	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 1\[319-ecospold-filter-construction-case-1-sensitivity-0.2.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 1\[319-ecospold-filter-construction-case-1-sensitivity-0.2.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 1\[319-ecospold-filter-construction-case-1-sensitivity-0.2.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 1\[319-ecospold-filter-construction-case-1-sensitivity-0.2.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 1\[319-ecospold-filter-construction-case-1-sensitivity-0.2.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 1\[319-ecospold-filter-construction-case-1-sensitivity-0.2.xlsx]X-Process

C.1.4 Geosynthetic layer

In total 13 questionnaires are included in calculating the average life cycle inventory of a geosynthetic layer used in the filter application.

The quality of the data received is considered to be accurate. The level of detail was balanced before modelling an average geosynthetic layer, i.e. information on water consumption, lubricating oil consumption, etc. need to be added for some companies and other information deleted (packaging). In the following the life cycle inventory and assumptions are described.

Raw materials

Some of the companies start the production with polypropylene granules, the others with polypropylene fibres. Three companies provided further data to model the fibre production. Other intermediate goods are modelled with data referring to the extrusion of plastic films from granulates (ecoinvent Centre (2010), based on information derived from PlasticsEurope).

To the authors knowledge it is not possible to produce a geosynthetic layer without plastic wastes (e.g. cutting waste or rejects). Thus, it is not possible that the input material equals the product output. Therefore, an average share of cutting wastes of 4.8°% is added in case 100 % material efficiency is indicated in the questionnaire. This share is calculated using the average of those companies (more than 3) indicating cutting wastes. These wastes are mostly recycled. Due to the allocation approach used in this study (see also Section 1.9.2) no burdens and no credits are allocated to such wastes. Thus, it is not possible that the input material equals the product output.

The UV stabiliser and surface treatment used in the manufacture of the geosynthetic material is modelled as organic chemicals. Master batch is modelled as plastic granulate.

Raw materials need to be transported to the factories. Standard distances as defined in Frischknecht et al. (2004) are used to estimate transportation expenditures, i.e. 100 km by lorry >16t and 600 km by train.

Working materials

To balance the level of detail of the data reported in the questionnaires standard values are included for lubricating oil and water where unknown. These standard values are calculated using the average of those companies indicating water and lubricating oil consumption. However, some companies do not use water in the production. These companies are included in the average. A small part of the questionnaires contain information about packaging material. As the mass contribution of packaging is less than 3 %, packaging material is excluded from the average geosynthetic layer inventory.

Energy consumption

Electricity consumption is modelled with country-specific electricity mixes. In case the production location is unknown, UCTE electricity mix is included. Heating energy is included where known. However, its influence on the environmental impacts of geosynthetic layer production is relatively small. No environmental burdens are allocated to district waste heat, like for instance heat from a waste incineration plant or a cement plant (see Subchapter 1.9). Forklifts working with LPG are modelled with the operation of a natural gas passenger car.

Airborne emissions

It is assumed that 100 % of the electricity consumed is converted to waste heat and that 100 % of the waste heat is released to air. Some companies report carbon emissions. These are assumed to be non methane volatile organic compounds (NMVOC). Data about other airborne emissions are taken from the questionnaires. Not reported emissions are classified as unkown emissions and thus are not included in calculating the average geosynthetic. It is assumed that the manufacturing plants are located in an urban/industrial area. Thus, the pollutants are categorized as emanating in a high population density area.

Emissions to water

Some companies provide information of BOD and COD concentrations in the water effluent. These effluents are modelled with the ecoinvent wastewater treatment tool. The concentration of pollutants in the effluent is comparable to those of the effluent of the ecoinvent process describing the treatment of potato starch. Thus, the potato starch effluent treatment dataset is used to model the wastewater treatment in case no company specific information is available.

Solid waste

Wastes, such as household, plastic and sludge wastes as well as spent lubricating oil, are considered in those cases, where data are provided. Depending on the country, these wastes are either incinerated or landfilled. Material, which is recycled, is neither charged with burdens nor credits (see also Section 1.9.2). Commonly recycled materials are cutting wastes (internal or external recycling) and paper.

Infrastructure and land use

The participating companies provide information on the area of the production site and the number of floors of the buildings. Buildings are assumed to have a lifetime of 80 years.

Selected key figures

Tab. 7.17 summarizes most important key figures of the production of an average geosynthetic layer.

Tab. 7.5: Selected key figures referring to the production of 1 kg geosynthetic layer used in filter application

	Unit	Value
Raw materials	kg/kg	1.05
Water	kg/kg	2.16
Lubricating oil	kg/kg	0.0026
Electricity	kWh/kg	1.14
Thermal energy	MJ/kg	1.49
Fuel for forklifts	MJ/kg	0.09
Building hall	m^2/kg	$2.51 \cdot 10^{-5}$

C.2 Case 2 – Road construction

We consider three different types of a class III road. Case 2A is a conventional road, case 2B is a road, which uses geosynthetics as a stabiliser between the foundation and the subgrade and case 2C is a road stabilised with a cement/quicklime mixture. For each case one LCI dataset of the construction of the road and one LCI dataset of the disposal of the road are created. The unit process raw data are shown in Tab. 7.6. The EcoSpold meta information is displayed in Tab. 7.7.

C.2.1 Construction

A road of class III with 1 m length and 12 m width is considered. The total thickness of the case 2A road is 1200 mm, whereas the total thickness of the case 2B road is 852 mm and the total thickness of the case 2C road is 650 mm.

The foundation stabilisation is not needed for the conventional construction of a class III road, but the foundation layer of sandy gravel is considerably thicker compared to a stabilised foundation.

The foundation stabilisation of the case 2B road is achieved with a geosynthetic. Thereon, a 600 mm foundation layer of sandy gravel is established. The use of geosynthetics in case 2B substitutes the use of cement or quicklime.

The foundation stabilisation of the case 2C road is achieved by mixing cement and lime into the soil within a layer of 250 mm thickness. On top of this improved soil, a foundation layer of 320 mm sandy gravel is created.

Furthermore, all three road types have a 150 mm ballast structure made from gravel and a 180 mm asphalt layer that is made from gravel, sand and 5 % bitumen.

The LCI refers to a road life time of 30 years, which is also the expected life time of the foundation and the geosynthetic layer. The foundation has a short life time of 30 years, because of the demanding conditions of the weak soil ground. The life time of the 140 mm binder course (30 years) and 40 mm surface layer (15 years) are considered to be the same as in the cases 1A and 1B.

With the information above and a bitumen and gravel density of 2.3 t/m^3, the total amount of gravel and bitumen used for the construction of one meter road of cases 2A, 2B and 2C is calculated. For the case 2B 12 m^2 geosynthetics per meter road are required.

For the gravel used, a mix of 21 % crushed gravel and 79 % round gravel is considered (according to the corresponding ecoinvent dataset) and the electricity mix and the transport modes are adjusted to the European situation.

During the road construction, diesel is used for the operation of various building machines. Applying statistical fuel consumption data published by Schäffeler & Keller (2008) and assuming a digging efficiency of 100 m^3/h, the average energy consumption is 4.4 MJ per m^3 digging with a hydraulic excavator (power size between 75 and 130 kW).

Hot mixing practises in central mixing facilities are most common for mixing gravel and bitumen in road construction[12]. According to Frischknecht et al. (1994), the diesel consumption for hot mixing of gravel and bitumen amounts to 9 kg per ton, which equals to an energy consumption of 385 MJ/t. This is in the same order of magnitude like the 260 MJ/t published by Breiter (1983) for the operation of a mixing facility and the 288 MJ/t specified by Daniel Kästli for hot mixing in a central mixing facility[12]. Therefore, we take into account an energy consumption of 300 MJ/t for hot mixing. Furthermore, 0.27 MJ/t are included for the spreading of the foundation material, 0.77 MJ/t are used for the compaction of the foundation, and 17.4 MJ/t are used for the compaction and integration of the pavement (Breiter 1983). The soil stabiliser (cement or quicklime) is mixed with the soil by applying a disc harrow, which mixes 80 m^3 materials per hour.[12] The diesel consumption of the disc harrow is considered with 11.4 MJ/h as reported for a rotary hallow (Nemecek et al. 2007).

The diesel consumption of mounting the geosynthetics is considered with about 1.0 MJ/m^2 as reported by Egloffstein & Burkhard (2006), who assume an 8 hour use of an excavator with a fuel consumption of 461 MJ per hour and a 3 hour use of a wheel loader with a fuel consumption of 500 MJ per hour, having 5000 m^2 of geosynthetics mounted per day.

For the transportation by lorry of bitumen and gravel an average distance of 50 km to the construction site is assumed. For the transportation of cement, a standard distance of 100 km by lorry and 100 km by rail is considered (Frischknecht et al. 2007b). Geosynthetics are typically transported around 600 km to the place of use.[13] We assume that 400 km is covered by rail and 200 km by lorry.

In cases 2A, 2B and 2C the transportation of the materials to the construction site is considered with an average dataset of European rail freight transportation and a dataset of a European fleet average lorry (<16t).

NMVOC emissions in road construction originate from the use of bitumen. In this study, we apply an emission factor of 7.2 kg NMVOC/t bitumen, as published in BUWAL (2000). The particulate matter emissions from the combustion of diesel are included in the dataset of the operation of the building machines, whereas the particulate emissions from mechanical processes and activities are considered separately. According to Spielmann et al. (2007) 7 g large particles (>10 μm) and 1.8 g coarse particles (2.5-10 μm) per ton of gravel moved are emitted due to mechanical processes.

For the case 2B a sensitivity analysis is performed. In the case 2BS1 the frost sensitive soil is excavated and replaced by gravel and in case 2BS2 no separation and filter geosynthetic is used for the construction.

In addition to the case 2C standard scenario with a cement/lime stabiliser, a sensitivity analysis is performed. For the case 2CS1 a stabiliser with quicklime only and for the case 2CS2 a stabiliser with cement only is considered. According to a civil engineering expert, milled quicklime is commonly used as a stabiliser and the amount of 5 – 10 mass percentage quicklime is typically required in order to stabilise weak soil.[12] The same transport distances are considered as for the cement stabiliser. The inventory data of the quicklime stabiliser are also presented in Tab. 7.8.

C.2.2 Disposal

The asphalt and gravel in road infrastructure is usually reused after removal of a road. According to PlasticsEurope (2009) in 2008 16 % of plastics used in construction are recycled, 52 % are sent to landfill, and 32 % are sent to municipal incineration. These shares are applied for the disposal of the geosynthetics.

[12] Personal communication with Daniel Kästli, managing director of the Kästlibau AG (17. September 2010)

[13] Personal communication with Henning Ehrenberg , EAGM Project Working Group (31. January 2010)

The standard transport distance to the landfill and the municipal waste incinerating plant is 20 km. The soil improved with cement is left onsite and not disposed of.

C.2.3 Unit process raw data of the infrastructure element

Tab. 7.6: Unit process raw data of cases 2A, 2B and 2C

	Name	Location	InfrastructureProcess	Unit	road, conventional without geosynthetics	road, reinforced with geosynthetics	road, stabilised with cement/lime	disposal, road, foundation stabilisation, without geosynthetics	disposal, road, foundation stabilisation, with geosynthetics	life cycle, road, foundation stabilisation, without geosynthetics	life cycle, road, foundation stabilisation, with geosynthetics	life cycle, road, foundation stabilisation, with cement/lime	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER	RER	RER	RER	RER	RER	RER	RER			
	InfrastructureProcess				1	1	1	1	1	1	1	1			
	Unit				m	m	m	m	m	m	m	m			
product	road, conventional without geosynthetics	RER	1	m	1	0	0	0	0	0	0	0			
	road, reinforced with geosynthetics	RER	1	m	0	1	0	0	0	0	0	0			
	road, stabilised with cement/lime	RER	1	m	0	0	1	0	0	0	0	0			
	disposal, road, foundation stabilisation, without geosynthetics	RER	1	m	0	0	0	1	0	0	0	0			
	disposal, road, foundation stabilisation, with	RER	1	m	0	0	0	0	1	0	0	0			
	life cycle, road, foundation stabilisation, without	RER	1	m	0	0	0	0	0	1	0	0			
	life cycle, road, foundation stabilisation, with geosynthetics	RER	1	m	0	0	0	0	0	0	1	0			
	life cycle, road, foundation stabilisation, with cement/lime	RER	1	m	0	0	0	0	0	0	0	1			
technosphere	bitumen, at refinery	CH	0	kg	3.04E+2	3.04E+2	3.04E+2	-	-	-	-	-	1	1.22	(2,3,1,1,1,5;3,1.05);
	gravel, unspecified, at mine	RER	0	kg	3.39E+4	2.43E+4	1.87E+4	-	-	-	-	-	1	1.07	(2,1,1,1,1,2;3,1.05);
	c2, geosynthetic, average, road construction	RER	0	m2	-	1.20E+1	-	-	-	-	-	-	1	1.05	(3,1,1,1,1,5;3,1.05); uncertainty
	c1, geosynthetic, average, road construction	RER	0	m2	-	1.20E+1	-	-	-	-	-	-	1	1.05	(3,1,1,1,1,5;3,1.05); uncertainty
	diesel, burned in building machine	GLO	0	MJ	1.96E+3	1.97E+3	1.97E+3	-	-	-	-	-	1	1.25	(2,3,3,1,1,5;2,1.05); asphalt
	transport, lorry >16t, fleet average	RER	0	tkm	1.71E+3	1.23E+3	9.94E+2	-	8.60E-2	-	-	-	1	2.09	(4,5,na,na,na,na;5,2); gravel and
	cement, unspecified, at plant	CH	0	kg	-	-	1.55E+2	-	-	-	-	-	1	1.33	(3,3,1,1,1,5;3,1.05); uncertainty is 33% according to the
	quicklime, milled, loose, at plant	CH	0	kg	-	-	2.59E+2	-	-	-	-	-	1	1.33	(4,1,1,1,1,5;3,1.05); uncertainty is 33% according to the
	transport, freight, rail	RER	0	tkm	-	2.05E+0	4.14E+1			-	-	-	1	2.09	(4,5,na,na,na,na;5,2);
	disposal, polypropylene, 15.9% water, to municipal incineration	CH	0	kg	-	-	-	-	1.64E+0	-	-	-	1	1.30	(4,1,1,1,1,5;6,1.05); 32 % of geosynthetic
	disposal, polypropylene, 15.9% water, to sanitary landfill	CH	0	kg	-	-	-	-	2.66E+0	-	-	-	1	1.30	(4,1,1,1,1,5;6,1.05); 52 % of geosynthetic
emission resource,	Transformation, from unknown	-	-	m2	1.20E+1	1.20E+1	1.20E+1	-	-	-	-	-	1	1.00	(2,5,1,1,na,5;8,2); uncertainty set
	Transformation, to traffic area, road network	-	-	m2	1.20E+1	1.20E+1	1.20E+1	-	-	-	-	-	1	1.00	(2,5,1,1,na,5;8,2); uncertainty set
	Occupation, traffic area, road network	-	-	m2a	3.60E+2	3.60E+2	3.60E+2	-	-	-	-	-	1	1.00	(2,5,1,1,na,5;7,1.5); uncertainty
emission air, unspecified	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	2.19E+0	2.19E+0	2.19E+0	-	-	-	-	-	1	1.58	(2,3,3,3,1,5;16,1.5);
	Particulates, > 10 um	-	-	kg	2.37E-1	1.70E-1	1.31E-1	-	-	-	-	-	1	1.63	(2,3,4,3,1,5;18,1.5); due to
	Particulates, > 2.5 um, and < 10um	-	-	kg	6.28E-2	4.50E-2	3.47E-2	-	-	-	-	-	1	2.10	(2,3,4,3,1,5;19,2); due to loading
technosphere	road, conventional without geosynthetics	RER	1	m	-	-	-	-	-	1.00E+0	-	-	1	1.00	(1,1,1,1,1,1;9,3); uncertainty set to
	road, reinforced with geosynthetics	RER	1	m	-	-	-	-	-	-	1.00E+0		1	1.00	(1,1,1,1,1,1;9,3); uncertainty set to
	road, stabilised with cement/lime	RER	1	m	-	-	-	-	-	-		1.00E+0	1	1.00	(1,1,1,1,1,1;9,3); uncertainty set to
	disposal, road, foundation stabilisation, without geosynthetics	RER	1	m	-	-	-	-	-	1.00E+0	-	1.00E+0	1	1.00	(1,1,1,1,1,1;9,3); uncertainty set to 1
	disposal, road, foundation stabilisation, with	RER	1	m	-	-	-	-	-	-	1.00E+0	-	1	1.00	(1,1,1,1,1,1;9,3); uncertainty set to

Tab. 7.7: EcoSpold meta information of cases 2A, 2B and 2C

ReferenceFunction	Name	road, conventional without geosynthetics	road, reinforced with geosynthetics	road, stabilised with cement/lime	disposal, road, foundation stabilisation, without geosynthetics	disposal, road, foundation stabilisation, with geosynthetics	life cycle, road, foundation stabilisation, without geosynthetics	life cycle, road, foundation stabilisation, with geosynthetics	life cycle, road, foundation stabilisation, with cement/lime
Geography	Location	RER	RER	RER	RER	RER	RER	RER	RER
ReferenceFunctio	InfrastructureProcess	1	1	1	1	1	1	1	1
ReferenceFunctio	Unit	m	m	m	m	m	m	m	m
	IncludedProcesses	This dataset includes material, energy and water consumption as well as infrastructure and land use for the construction of a conventional road class 3.	This dataset includes material, energy and water consumption as well as infrastructure and land use for the construction of a class 3 road with geosynthetic stabilised foundation.	This dataset includes material, energy and water consumption as well as infrastructure and land use for the construction of a class 3 road with cement/lime stabilised foundation.	This dataset includs the excavation and disposal of the materials from the dismantling of a class 3 road cement stabilised foundation, as well as the transportation of the materials to the place of disposal or reuse.	This dataset includs the excavation and disposal of the materials from the dismantling of a class 3 roadwith geosynthetic stabilised foundation, as well as the transportation of the materials to the place of disposal or reuse.	This dataset includes construction and disposal of a conventional road class 3.	This dataset includes construction and disposal of a class 3 road with geosynthetic stabilised foundation.	This dataset includes construction and disposal of a class 3 road with cement/lime stabilised foundation.
	GeneralComment	The LCI reflects a class 3 road of 12 m width and 0.9 m thickness.	The LCI reflects a class 3 road of 12 m width and 0.93 m thickness.	The LCI reflects a class 3 road of 12 m width and 0.93 m thickness.	The LCI reflects a class 3 road of 12 m width and 0.9 m thickness.	The LCI reflects a class 3 road of 12 m width and 0.93 m thickness.	The LCI reflects a class 3 road of 12 m width and 0.9 m thickness.	The LCI reflects a class 3 road of 12 m width and 0.93 m thickness.	The LCI reflects a class 3 road of 12 m width and 0.93 m thickness.
	InfrastructureIncluded	1	1	1	1	1	1	1	1
	Category	transport systems	transport systems	transport systems	transport systems	transport systems	transport systems	transport systems	transport systems
	SubCategory	road	road	road	road	road	road	road	road
TimePeriod	StartDate	2006	2006	2006	2006	2006	2006	2006	2006
	EndDate	2010	2010	2010	2010	2010	2010	2010	2010
	DataValidForEntirePeriod	1	1	1	1	1	1	1	1
	OtherPeriodText								
Geography	Text	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.
Technology	Text	Conventional road construction with building machines.	Construction of a geosynthethics road with building machines.	Construction of a geosynthethics road with building machines.	Excavation by hydraulic excavator, transport by lorry	Excavation by hydraulic excavator, transport by lorry	Conventional road construction with building machines.	Construction of a geosynthethics road with building machines.	Construction of a geosynthethics road with building machines.
Representativene	Percent	0	0	0	0	0	0	0	0
	ProductionVolume	unknown	unknown	unknown	unknown	unknown	unknown	unknown	unknown
	SamplingProcedure	unknown	unknown	unknown	unknown	unknown	unknown	unknown	unknown
	Extrapolations	none	none	none	none	none	none	none	none
	UncertaintyAdjustments	none	none	none	none	none	none	none	none
	Details	05.10.2011	05.10.2011	05.10.2011	05.10.2011	05.10.2011	05.10.2011	05.10.2011	05.10.2011
	OtherDetails	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 2\[319-ecospold-case 2-road-construction-v0.4.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 2\[319-ecospold-case 2-road-construction-v0.4.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 2\[319-ecospold-case 2-road-construction-v0.4.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 2\[319-ecospold-case 2-road-construction-v0.4.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 2\[319-ecospold-case 2-road-construction-v0.4.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 2\[319-ecospold-case 2-road-construction-v0.4.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 2\[319-ecospold-case 2-road-construction-v0.4.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 2\[319-ecospold-case 2-road-construction-v0.4.xlsx]X-Process

Tab. 7.8: Unit process raw data of the cases 2BS1, 2BS2, 2CS1 and 2CS2

	Name	Location	InfrastructureProcess	Unit	road, reinforced with geosynthetics, soil replacement	road, reinforced with geosynthetics, no separation geosynthetic	road, stabilised with quick lime	road, stabilised with cement	disposal, road, foundation stabilisation, without geosynthetics	disposal, road, foundation stabilisation, with geosynthetics	disposal, road, foundation stabilisation, with geosynthetics, without separation	life cycle, road, foundation stabilisation, with geosynthetics, soil replacement	life cycle, road, foundation stabilisation, with geosynthetics, no separation	life cycle, road, foundation stabilisation, with quicklime	life cycle, road, foundation stabilisation, with cement	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER	RER	RER	RER	RER	RER	RER	RER	RER	RER	RER			
	InfrastructureProcess				1	1	1	1	1	1	1	1	1	1	1			
	Unit				m	m	m	m	m	m	m	m	m	m	m			
product	road, reinforced with geosynthetics, soil replacement	RER	1	m	1	0	0	0	0	0	0	0	0	0	0			
	road, reinforced with geosynthetics, no separation geosynthetic	RER	1	m	0	1	0	0	0	0	0	0	0	0	0			
	road, stabilised with quick lime	RER	1	m	0	0	1	0	0	0	0	0	0	0	0			
	road, stabilised with cement	RER	1	m	0	0	0	1	0	0	0	0	0	0	0			
	disposal, road, foundation stabilisation, without geosynthetics	RER	1	m	0	0	0	0	1	0	0	0	0	0	0			
	disposal, road, foundation stabilisation, with geosynthetics	RER	1	m	0	0	0	0	0	1	0	0	0	0	0			
	disposal, road, foundation stabilisation, with geosynthetics, without separation	RER	1	m	0	0	0	0	0	0	1	0	0	0	0			
	life cycle, road, foundation stabilisation, with geosynthetics, soil replacement	RER	1	m	0	0	0	0	0	0	0	1	0	0	0			
	life cycle, road, foundation stabilisation, with geosynthetics, no separation	RER	1	m	0	0	0	0	0	0	0	0	1	0	0			
	life cycle, road, foundation stabilisation, with quicklime	RER	1	m	0	0	0	0	0	0	0	0	0	1	0			
	life cycle, road, foundation stabilisation, with cement	RER	1	m	0	0	0	0	0	0	0	0	0	0	1			
technosphere	bitumen, at refinery	CH	0	kg	3.04E+2	3.04E+2	3.04E+2	3.04E+2	-	-	-	-	-	-	-	1	1.22	(2,3,1,1,1,5;3,1.05);
	gravel, unspecified, at mine	RER	0	kg	2.90E+4	2.43E+4	1.87E+4	1.87E+4	-	-	-	-	-	-	-	1	1.07	(2,1,1,1,1,2;3,1.05);
	c2, geosynthetic, average, road construction	RER	0	m2	1.20E+1	1.20E+1	-	-	-	-	-	-	-	-	-	1	1.05	(3,1,1,1,1,5;3,1.05); uncertainty set to 1.05: 5% cuttings and other excess material
	c1, geosynthetic, average, road construction	RER	0	m2	1.20E+1	0	-	-	-	-	-	-	-	-	-	1	1.05	(3,1,1,1,1,5;3,1.05); uncertainty set to 1.05: 5% cuttings and other excess material
	diesel, burned in building machine	GLO	0	MJ	1.99E+3	1.96E+3	1.97E+3	1.96E+3	-	-	-	-	-	-	-	1	1.25	(2,3,3,1,1,5;2,1.05); asphalt mixture, compaction, distribution etc.
	excavation, skid-steer loader	RER	0	m3	2.02E+0	-	-	-	-	-	-	-	-	-	-	1	1.05	(1,1,1,1,1,1;2,1.05);
	transport, lorry >16t, fleet average	RER	0	tkm	1.56E+3	1.23E+3	1.00E+3	9.83E+2	-	8.60E-2	0.050688	-	-	-	-	1	2.09	(4,5,na,na,na,na;5,2); gravel and bitumen: 50 km; geosynthetics: 200 km; disposal: 40 km to recycling plant, 20 km to municial incineration and landfill
	cement, unspecified, at plant	CH	0	kg	-	-	0	3.11E+2	-	-	-	-	-	-	-	1	1.33	(3,3,1,1,1,5;3,1.05); uncertainty is 33% according to the specification EAGM provided
	quicklime, milled, loose, at plant	CH	0	kg	-	-	5.18E+2	0	-	-	-	-	-	-	-	1	1.33	(4,1,1,1,1,5;3,1.05); uncertainty is 33% according to the specification EAGM provided
	transport, freight, rail	RER	0	tkm	2.05E+0	1.21E+0	5.18E+1	3.11E+1	-	-	-	-	-	-	-	1	2.09	(4,5,na,na,na,na;5,2); geosynthetics: 400 km
	disposal, polypropylene, 15.9% water, to municipal incineration	CH	0	kg	-	-	-	-	-	1.64E+0	9.65E-1	-	-	-	-	1	1.30	(4,1,1,1,1,5;6,1.05); 32 % of geosynthetic
	disposal, polypropylene, 15.9% water, to sanitary landfill	CH	0	kg	-	-	-	-	-	2.66E+0	1.57E+0	-	-	-	-	1	1.30	(4,1,1,1,1,5;6,1.05); 52 % of geosynthetic
emission resource, land	Transformation, from unknown	-	-	m2	1.20E+1	1.20E+1	1.20E+1	1.20E+1	-	-	-	-	-	-	-	1	1.00	(2,5,1,1,na,5;8,2); uncertainty set to 1 as there is no uncertainty concerning the land use of the road.
	Transformation, to traffic area, road network	-	-	m2	1.20E+1	1.20E+1	1.20E+1	1.20E+1	-	-	-	-	-	-	-	1	1.00	(2,5,1,1,na,5;8,2); uncertainty set to 1 as there is no uncertainty concerning the land use of the road.
	Occupation, traffic area, road network	-	-	m2a	3.60E+2	3.60E+2	3.60E+2	3.60E+2	-	-	-	-	-	-	-	1	1.00	(2,5,1,1,na,5;7,1.5); uncertainty set to 1 as there is no uncertainty concerning the land use of the road.
emission air, unspecified	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	2.19E+0	2.19E+0	2.19E+0	2.19E+0	-	-	-	-	-	-	-	1	1.58	(2,3,3,3,1,5;16,1.5);
	Particulates, > 10 um	-	-	kg	2.03E-1	1.70E-1	1.31E-1	1.31E-1	-	-	-	-	-	-	-	1	1.63	(2,3,4,3,1,5;18,1.5); due to loading and tipping of gravel
	Particulates, > 2.5 um, and < 10um	-	-	kg	5.36E-2	4.50E-2	3.47E-2	3.47E-2	-	-	-	-	-	-	-	1	2.10	(2,3,4,3,1,5;19,2); due to loading and tipping of gravel
technosphere	road, reinforced with geosynthetics, soil replacement	RER	1	m	-	-	-	-	-	-	-	1.00E+0	-	-	-	1	1.00	(1,1,1,1,1,1;9,3); uncertainty set to 1
	road, reinforced with geosynthetics, no separation geosynthetic	RER	1	m	-	-	-	-	-	-	-	-	1.00E+0	-	-	1	1.00	(1,1,1,1,1,1;9,3); uncertainty set to 1
	road, stabilised with quick lime	RER	1	m	-	-	-	-	-	-	-	-		1.00E+0	-	1	1.00	(1,1,1,1,1,1;9,3); uncertainty set to 1
	road, stabilised with cement	RER	1	m	-	-	-	-	-	-	-	-	-	-	1.00E+0	1	1.00	(1,1,1,1,1,1;9,3); uncertainty set to 1
	disposal, road, foundation stabilisation, without geosynthetics	RER	1	m	-	-	-	-	-	-	-	-	-	1.00E+0	1.00E+0	1	1.00	(1,1,1,1,1,1;9,3); uncertainty set to 1
	disposal, road, foundation stabilisation, with geosynthetics	RER	1	m	-	-	-	-	-	-	-	1.00E+0	-	-	-	1	1.00	(1,1,1,1,1,1;9,3); uncertainty set to 1
	disposal, road, foundation stabilisation, with geosynthetics, without separation	RER	1	m	-	-	-	-	-	-	-	-	1.00E+0	-	-	1	1.00	(1,1,1,1,1,1;9,3); uncertainty set to 1

Tab. 7.9: EcoSpold meta information of the cases 2BS1, 2BS2, 2CS1 and 2CS2

ReferenceFunction	Name	road, reinforced with geosynthetics, soil replacement	road, reinforced with geosynthetics, no separation geosynthetic	road, stabilised with quick lime	road, stabilised with cement	disposal, road, foundation stabilisation, without geosynthetics	disposal, road, foundation stabilisation, with geosynthetics	disposal, road, foundation stabilisation, with geosynthetics, without separation	life cycle, road, foundation stabilisation, with geosynthetics, soil replacement	life cycle, road, foundation stabilisation, with geosynthetics, no separation	life cycle, road, foundation stabilisation, with quicklime	life cycle, road, foundation stabilisation, with cement
Geography	Location	RER	RER	RER	RER	RER	RER	RER	RER	RER	RER	RER
ReferenceFunction	InfrastructureProcess	1	1	1	1	1	1	1	1	1	1	1
ReferenceFunction	Unit	m	m	m	m	m	m	m	m	m	m	m
	IncludedProcesses	This dataset includes material, energy and water consumption as well as infrastructure and land use for the construction of a class 3 road with geosynthetic stabilised foundation with soil replacement	This dataset includes material, energy and water consumption as well as infrastructure and land use for the construction of a class 3 road with geosynthetic stabilised foundation with no separation geosynthetic.	This dataset includes material, energy and water consumption as well as infrastructure and land use for the construction of a road class 3 stabilised with quicklime.	This dataset includes material, energy and water consumption as well as infrastructure and land use for the construction of a road class 3 stabilised with cement.	This dataset includes the excavation and disposal of the materials from the dismantling of a class 3 road without geosynthetic stabilised foundation.	This dataset includes the excavation and disposal of the materials from the dismantling of a class 3 roadwith geosynthetic stabilised foundation, as well as the transportation of the materials to the place of disposal or reuse.	This dataset includes the excavation and disposal of the materials from the dismantling of a class 3 roadwith geosynthetic stabilised foundation, as well as the transportation of the materials to the place of disposal or reuse.	This dataset includes construction and disposal of a conventional class 3 road without geosynthetic stabilised foundation.	This dataset includes construction and disposal of a class 3 road with geosynthetic stabilised foundation.	This dataset includes construction and disposal of a class 3 road with quicklime stabilised foundation.	This dataset includes construction and disposal of a class 3 road with cement stabilised foundation.
	GeneralComment	The LCI reflects a class 3 road of 12 m width and 0.9 m thickness.	The LCI reflects a class 3 road of 12 m width and 0.93 m thickness.	The LCI reflects a class 3 road of 12 m width and 0.9 m thickness.	The LCI reflects a class 3 road of 12 m width and 0.9 m thickness.	The LCI reflects a class 3 road of 12 m width and 0.93 m thickness.	The LCI reflects a class 3 road of 12 m width and 0.9 m thickness.	The LCI reflects a class 3 road of 12 m width and 0.9 m thickness.	The LCI reflects a class 3 road of 12 m width and 0.93 m thickness.	The LCI reflects a class 3 road of 12 m width and 0.93 m thickness.	The LCI reflects a class 3 road of 12 m width and 0.93 m thickness.	The LCI reflects a class 3 road of 12 m width and 0.93 m thickness.
	InfrastructureIncluded	1	1	1	1	1	1	1	1	1	1	1
	Category	transport systems	transport systems	transport systems	transport systems	transport systems	transport systems	transport systems	transport systems	transport systems	transport systems	transport systems
	SubCategory	road	road	road	road	road	road	road	road	road	road	road
TimePeriod	StartDate	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006	2006
	EndDate	2010	2010	2010	2010	2010	2010	2010	2010	2010	2010	2010
	DataValidForEntirePeriod	1	1	1	1	1	1	1	1	1	1	1
	OtherPeriodText											
Geography	Text	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.
Technology	Text	Construction of a geosynthethics road with building machines.	Construction of a geosynthethics road with building machines.	Construction of a cement/lime stabilised road with building machines.	Construction of a cement/lime stabilised road with building machines.	Excavation by hydraulic excavator, transport by lorry	Excavation by hydraulic excavator, transport by lorry	Excavation by hydraulic excavator, transport by lorry	Construction of a geosynthethics road with building machines.	Construction of a geosynthethics road with building machines.	Construction of a geosynthethics road with building machines.	Construction of a geosynthethics road with building machines.
Representativeness	Percent	0	0	0	0	0	0	0	0	0	0	0
	ProductionVolume	unknown	unknown	unknown	unknown	unknown	unknown	unknown	unknown	unknown	unknown	unknown
	SamplingProcedure	unknown	unknown	unknown	unknown	unknown	unknown	unknown	unknown	unknown	unknown	unknown
	Extrapolations	none	none	none	none	none	none	none	none	none	none	none
	UncertaintyAdjustments	none	none	none	none	none	none	none	none	none	none	none
	Details	05.10.2011	05.10.2011	05.10.2011	05.10.2011	05.10.2011	05.10.2011	05.10.2011	05.10.2011	05.10.2011	05.10.2011	05.10.2011
	OtherDetails	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 2\[319-ecospold-case 2-road-construction-sensitivity-v0.7.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 2\[319-ecospold-case 2-road-construction-sensitivity-v0.7.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 2\[319-ecospold-case 2-road-construction-sensitivity-v0.7.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 2\[319-ecospold-case 2-road-construction-sensitivity-v0.7.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 2\[319-ecospold-case 2-road-construction-sensitivity-v0.7.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 2\[319-ecospold-case 2-road-construction-sensitivity-v0.7.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 2\[319-ecospold-case 2-road-construction-sensitivity-v0.7.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 2\[319-ecospold-case 2-road-construction-sensitivity-v0.7.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 2\[319-ecospold-case 2-road-construction-sensitivity-v0.7.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 2\[319-ecospold-case 2-road-construction-sensitivity-v0.7.xlsx]X-Process	Z:\ESU-Docs\Projekte laufend\319 Ökobilanz Geotex\Berechnungen\Case 2\[319-ecospold-case 2-road-construction-sensitivity-v0.7.xlsx]X-Process

C.2.4 Geosynthetic layer

In total 7 questionnaires are included in calculating the average life cycle inventory of a geosynthetic layer used in foundation stabilisation of a road.

The quality of the data received is considered to be accurate. The level of detail was balanced before modelling an average geosynthetic layer, i.e. information on water consumption, lubricating oil consumption, etc. need to be added for some companies and other information deleted (packaging). In the following the life cycle inventory and assumptions are described.

Raw materials

Some of the companies start the production with plastic granules, the others with intermediate goods (yarns, straps, etc.). The production of such intermediate goods are modelled with data referring to the extrusion of plastic films from granulates (ecoinvent Centre (2010), based on information derived from PlasticsEurope).

To the authors knowledge it is not possible to produce a geosynthetic layer without plastic wastes (e.g. cutting waste or rejects). Thus, it is not possible that the input material equals the product output. Therefore, an average share of cutting wastes of 2.15°% is added in case 100 % material efficiency is indicated in the questionnaire. This share is calculated using the average of those companies (more than 3) indicating cutting wastes. These wastes are mostly recycled. Due to the allocation approach used in this study (see also Section 1.9.2) no burdens and no credits are allocated to such wastes

Additives used in the manufacture of the geosynthetic material are modelled as organic chemicals.

Raw materials need to be transported to the factories. Standard distances as defined in Frischknecht et al. (2004) are used to estimate transportation expenditures, i.e. 100 km by lorry >16t and 600 km by train.

Working materials

To balance the level of detail of the data reported in the questionnaires standard values are included for lubricating oil where unknown. This standard value is calculated using the average of those companies indicating lubricating oil consumption. A small part of the questionnaires contain information about packaging material. As the mass contribution of packaging is less than 3 %, packaging material is excluded from the average geosynthetic material inventory.

Energy consumption

Electricity consumption is modelled with country-specific electricity mixes. In case the production location is unknown UCTE electricity mix is included. Heating energy is included where known. No environmental burdens are allocated to district waste heat, like for instance heat from a waste incineration plant or a cement plant (see Subchapter 1.9). However, its influence on the environmental impacts of geosynthetic material production is relatively small. To balance the level of detail of the questionnaires standard values are included for diesel consumption of forklifts where unknown and where not included in the electricity consumption. These standard values are calculated using the average of those companies (more than 3) indicating diesel consumption.

Airborne emissions

It is assumed that 100 % of the electricity consumed is converted to waste heat and that 100 % of the waste heat is released to air. Some companies report carbon emissions. These are assumed to be non methane volatile organic compounds (NMVOC). Data about further airborne emissions are taken from the questionnaires where provided and measured. Not reported emissions are classified as unkown emissions and thus are not included in calculating the average geosynthetic. It is assumed that the manufacturing plants are located in an urban/industrial area. Thus, the pollutants are categorized as emanating in a high population density area.

Emissions to water

No information on wastewater characteristics is available. Thus, wastewater treatment is modelled with the ecoinvent dataset "treatment, sewage, unpolluted, to wastewater treatment, class 3".

Solid waste

Wastes, such as household, plastic and sludge wastes as well as spent lubricating oil, are considered in those cases, where data are provided. Depending on the country, these wastes are either incinerated or landfilled. Material, which is recycled, is neither charged with burdens nor credits (see also Section 1.9.2). Commonly recycled materials are cutting wastes (internal or external recycling) and paper.

Infrastructure and land use

The participating companies provide information on the area of the production site and the number of floors of the buildings. Buildings are assumed to have a lifetime of 80 years. To balance the level of detail of the questionnaires standard values are included for infrastructure where unknown. These standard values are calculated using the average of those companies (more than 3) indicating infrastructure and land use.

Selected key figures

Tab. 7.17 summarizes most important key figures for the production of an average geosynthetic layer.

Tab. 7.10: Selected key figures referring to the production of 1 kg geosynthetic layer used in foundation stabilisation

	Unit	Value
Raw materials	kg/kg	1.02
Water	kg/kg	0.50
Lubricating oil	kg/kg	$3.62*10^{-4}$
Electricity	kWh/kg	1.76
Thermal energy	MJ/kg	1.75
Fuel for forklifts	MJ/kg	0.15
Building hall	m^2/kg	$1.41*10^{-6}$

C.3 Case 3 – Landfill Construction

We consider two different types of drainage layers in the construction of a landfill. Case 3A is a 500 mm gravel drainage layer; whereas case 3B is a geosynthetic drainage layer with the same hydraulic conductivity of at least 1 mm/s (k-value). Furthermore, both cases include a filter geotextile and a protection textile each. In case 3B, these two textile layers are attached directly to the geosynthetic drainage layer and the three layers are mounted in one step. In contrast, the geotextile layers and the gravel drainage layer in case 3A are mounted in separate steps.

For each case one LCI dataset of the construction of the drainage layer and one LCI dataset of the disposal of the drainage layer are created. The unit process raw data are shown in Tab. 7.11. The EcoSpold meta information is displayed in Tab. 7.12.

C.3.1 Construction

One square meter of a drainage layer in a landfill is considered, since both cases have the same hydraulic conductivity. The case 3A drainage layer consists of a 500 mm layer of round gravel, a protection geotextile below the gravel and a filter geotextile at the top. The case 3B drainage layer consists of three geosynthetic layers with a geosynthetic drainage layer in the middle.

Other layers of the landfill, such as the recultivation layer, the mineral sealing, the gas drainage, etc. are not included in the inventory, but are equal for both alternatives. The inventories refer to a life time of 100 years for both cases.

From the thickness of the gravel drainage layer (500 mm) in case 3A and a gravel density[14] of 1’800 kg/m^3, the total amount of gravel used for the construction of one square meter drainage is calculated.

For the case 3B 1 m^2 geosynthetic drainage is required. And in both cases 1 m^2 of filter geotextile and 1 m^2 of protection geotextile is used. The production of the geosynthetic drainage layer is described in Annex C.3.4. The filter and protection geosynthetics are considered with the geosynthetics from case 1B as described in Annex C.1.4.

For the round gravel used the electricity mix and the transport modes in the corresponding ecoinvent dataset are adjusted to the European situation.

During the road construction, diesel is used for the operation of various building machines. Applying statistical fuel consumption data published by Schäffeler & Keller (2008) and assuming a digging efficiency of 100 m^3/h, the average energy consumption is 4.4 MJ per m^3 digging with a hydraulic excavator (power size between 75 and 130 kW). Furthermore, 0.27 MJ/t are included for the spreading of the foundation material (Breiter 1983).

[14] http://www.verkehrsportal.de/board/index.php?showtopic=46129 (access on 12. April 2010)

The diesel consumption of mounting the filter geotextile and the protection textile in case 3A is considered with about 1.0 MJ/m^2 as reported by Egloffstein & Burkhard (2006), who assume an 8 hour use of an excavator with a fuel consumption of 461 MJ per hour and a 3 hour use of a wheel loader with a fuel consumption of 500 MJ per hour, having 5000 m^2 of geosynthetics mounted per day. The diesel consumption of mounting the geosynthetic drainage layer is considered with the same data, but a lower output of 3000 m^2 per year, resulting in a fuel consumption of 1.73 MJ/m^2 (Egloffstein & Burkhard 2006).

For the gravel transportation by lorry an average distance of 50 km to the construction site is assumed. Geosynthetics are transported typically around 600 km to the place of use.[15] We assume that 400 km is covered by rail and 200 km by lorry.

The particulate matter emissions from the combustion of diesel are included in the dataset of the operation of the building machines, whereas the particulate emissions from mechanical processes and activities are considered separately. According to Spielmann et al. (2007) 7 g large particles (>10 µm) and 1.8 g coarse particles (2.5-10 µm) per ton of gravel moved are emitted due to mechanical processes.

C.3.2 Disposal

The gravel in the drainage layer is reused after removal. According to PlasticsEurope (2009) in 2008 16 % of plastics used in construction are recycled, 52 % are sent to landfill, and 32 % are sent to municipal incineration. These shares are applied for the disposal of the geosynthetics. The standard transport distance to the landfill and the municipal waste incinerating plant is 20 km.

[15] Personal communication with Henning Ehrenberg , EAGM Project Working Group (31. January 2010)

C.3.3 Unit process raw data of the infrastructure element

Tab. 7.11: Unit process raw data of cases 3A and 3B

	Name	Location	InfrastructureProcess	Unit	landfill, mineral sealing (0.5m)	landfill, geosynthethic sealing	disposal, landfill, mineral sealing (0.5m)	disposal, landfill, geosynthethic sealing	life cycle, landfill, mineral sealing (0.5m)	life cycle, landfill, geosynthethic sealing	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER	RER	RER	RER	RER	RER			
	InfrastructureProcess				0	0	0	0	0	0			
	Unit				m2	m2	m2	m2	m2	m2			
product	landfill, mineral sealing (0.5m)	RER	0	m2	1	0	0	0	0	0			
	landfill, geosynthethic sealing	RER	0	m2	0	1	0	0	0	0			
	disposal, landfill, mineral sealing (0.5m)	RER	0	m2	0	0	1	0	0	0			
	disposal, landfill, geosynthethic sealing	RER	0	m2	0	0	0	1	0	0			
	life cycle, landfill, mineral sealing (0.5m)	RER	0	m2	0	0	0	0	1	0			
	life cycle, landfill, geosynthethic sealing	RER	0	m2	0	0	0	0	0	1			
technosphere	gravel, round, at mine	RER	0	kg	9.00E+2	0	-	-	-	-	1	1.07	(2,1,1,1,1,2;3,1.05);
	c3, geosynthetic, average, landfill	RER	0	m2	-	1.00E+0	-	-	-	-	1	1.05	(1,1,1,1,1,1;3,1.05); uncertainty set to 1.05: 5% cuttings and other excess material
	c1, geosynthetic, average, road construction	RER	0	m2	2.00E+0	2.00E+0	-	-	-	-	1	1.05	(1,2,1,1,1,1;3,1.05); uncertainty set to 1.05: 5% cuttings and other excess material
	diesel, burned in building machine	GLO	0	MJ	4.53E+0	3.82E+0	-	-	-	-	1	1.25	(2,3,3,1,1,5;2,1.05);
	transport, lorry >16t, fleet average	RER	0	tkm	4.51E+1	1.70E-1	7.00E-3	1.70E-2	-	-	1	2.09	(4,5,na,na,na,na;5,2); gravel: 50 km; geosynthetics: 200 km; disposal: 40 km to recycling plant, 20 km to municial incineration and landfill
	transport, freight, rail	RER	0	tkm	1.40E-1	3.40E-1	-	-	-	-	1	2.09	(4,5,na,na,na,na;5,2); geosynthetics: 400 km
	disposal, polypropylene, 15.9% water, to municipal incineration	CH	0	kg	-	-	1.12E-1	2.72E-1	-	-	1	1.30	(4,1,1,1,1,5;6,1.05); 32 % of geosynthetic
	disposal, polypropylene, 15.9% water, to sanitary landfill	CH	0	kg	-	-	-	4.42E-1	-	-	1	1.30	(4,1,1,1,1,5;6,1.05); 52 % of geosynthetic
	landfill, mineral sealing (0.5m)	RER	0	m2	-	-	-	-	1.00E+0	-	1	1.00	(2,4,1,1,1,5;3,1.05); uncertainty set to 1
	landfill, geosynthethic sealing	RER	0	m2	-	-	-	-	-	1.00E+0	1	1.00	(2,4,1,1,1,5;3,1.05); uncertainty set to 1
	disposal, landfill, mineral sealing (0.5m)	RER	0	m2	-	-	-	-	1.00E+0	-	1	1.00	(2,4,1,1,1,5;3,1.05); uncertainty set to 1
	disposal, landfill, geosynthethic sealing	RER	0	m2	-	-	-	-	-	1.00E+0	1	1.00	(2,4,1,1,1,5;3,1.05); uncertainty set to 1
resource, land	Transformation, from unknown	-	-	m2	1.00E+0	1.00E+0	-	-	-	-	1	1.00	(2,4,1,1,1,5;8,2); uncertainty set to 1 as there is no uncertainty concerning
emission resource, land	Transformation, to traffic area, road network	-	-	m2	1.00E+0	1.00E+0	-	-	-	-	1	1.00	(2,4,1,1,1,5;8,2); uncertainty set to 1 as there is no uncertainty concerning
	Occupation, traffic area, road network	-	-	m2a	1.00E+2	1.00E+2	-	-	-	-	1	1.00	(2,3,1,1,3,5;7,1.5); uncertainty set to 1 as there is no uncertainty concerning the land use of the
air, unspecified	Particulates, > 10 um	-	-	kg	6.30E-3	-	-	-	-	-	1	1.58	(2,3,3,3,1,5;18,1.5);
	Particulates, > 2.5 um, and < 10um	-	-	kg	1.67E-3	-	-	-	-	-	1	2.10	(2,3,4,3,1,5;19,2);

Tab. 7.12: EcoSpold meta information of cases 3A and 3B

ReferenceFunction	Name	landfill, mineral sealing (0.5m)	landfill, geosynthethic sealing	disposal, landfill, mineral sealing (0.5m)	disposal, landfill, geosynthethic sealing	life cycle, landfill, mineral sealing (0.5m)	life cycle, landfill, geosynthethic sealing
Geography	Location	RER	RER	RER	RER	RER	RER
ReferenceFunctic	InfrastructureProcess	0	0	0	0	0	0
ReferenceFunctic	Unit	m2	m2	m2	m2	m2	m2
	IncludedProcesses	This dataset includes material, and energy consumption as well as infrastructure and land use for the construction of a drainage layer without geosynthetics in a landfill construction.	This dataset includes material, and energy consumption as well as infrastructure and land use for the construction of a geosynthetic drainage layer in a landfill construction.	This dataset includs the excavation and disposal of the materials from the dismantling of a drainage layer without geosynthetics in a landfill construction.	This dataset includs the excavation and disposal of the materials from the dismantling of a geosynthetic drainage layer in a landfill construction.	This dataset includes construction and disposal of a drainage layer without geosynthetics in a landfill construction.	This dataset includes construction and disposal of a geosynthetic drainage layer in a landfill construction.
	GeneralComment	The drainage layer consists of 50 cm gravel.	The drainage layer consists of polypropylene drainage core.	The drainage layer consists of 50 cm gravel.	The drainage layer consists of polypropylene drainage core.	The drainage layer consists of 50 cm gravel.	The drainage layer consists of polypropylene drainage core.
	InfrastructureIncluded	1	1	1	1	1	1
	Category	waste management	waste management	waste management	waste management	waste management	waste management
	SubCategory	landfill	landfill	landfill	landfill	landfill	landfill
TimePeriod	StartDate	2006	2006	2006	2006	2006	2006
	EndDate	2010	2010	2010	2010	2010	2010
	DataValidForEntirePeriod	1	1	1	1	1	1
	OtherPeriodText						
Geography	Text	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.
Technology	Text	Conventional landfill construction with building machines.	Alternative landfill construction with building machines.	Conventional landfill construction with building machines.	Alternative landfill construction with building machines.	Conventional landfill construction with building machines.	Alternative landfill construction with building machines.
Representativene	Percent	0	0	0	0	0	0
	ProductionVolume	unknown	unknown	unknown	unknown	unknown	unknown
	SamplingProcedure	unknown	unknown	unknown	unknown	unknown	unknown
	Extrapolations	none	none	none	none	none	none
	UncertaintyAdjustments	none	none	none	none	none	none
DataGeneratorAn	Person	44	44	44	44	44	44
	DataPublishedIn	2	2	2	2	2	2
	ReferenceToPublishedSource	41	41	41	41	41	41

C.3.4 Geosynthetic drainage layer

In total 3 questionnaires are included in calculating the average life cycle inventory of a geosynthetic drainage layer used in landfill sites. This inventory only includes the geospacer (drainage layer). The geosynthetics which are glued on the geospacer are included in the landfill construction dataset (see Annex C.3.1).

The quality of the data received is considered to be accurate. Is is not necessary to balance the level of detail in this case. In the following the life cycle inventory and assumptions are described.

Raw materials

The production starts with plastic granules. To the authors knowledge it is not possible to produce a geosynthetic layer without plastic wastes (e.g. cutting waste or rejects). Thus, it is not possible that the input material equals the product output. Therefore, an average share of cutting wastes of 2.5°% is added in case 100 % material efficiency is indicated in the questionnaire. This share derives from plastic extrusion process inventories in ecoinvent. These wastes are mostly recycled. Due to the allocation approach used in this study (see also Section 1.9.2) no burdens and no credits are allocated to such wastes.

Additives used in the manufacture of the geosynthetic material are modelled as organic chemicals.

Raw materials need to be transported to the factories. Standard distances as defined in Frischknecht et al. (2004) are used to estimate transportation expenditures, i.e. 100 km by lorry >16t and 600 km by train.

Working materials

The working materials include water and lubricating oil.

Energy consumption

Electricity consumption is modelled with country-specific electricity mixes. In case the production location is unknown UCTE electricity mix is included. Heating energy is included where known. However, its influence on the environmental impacts of geosynthetic material production is relatively small. The emissions of forklifts working with LPG are modelled with the operation of a natural gas passenger car.

Airborne emissions

It is assumed that 100 % of the electricity consumed is converted to waste heat and that 100 % of the waste heat is released to air. No process specific emissions are reported.

Emissions to water

No information on wastewater characteristics is available. Thus, wastewater treatment is modelled with the ecoinvent dataset "treatment, sewage, unpolluted, to wastewater treatment, class 3".

Solid waste

Wastes, such as household, plastic and sludge wastes as well as spent lubricating oil, are considered in those cases, where data are provided. Depending on the country, these wastes are either incinerated or landfilled. Material, which is recycled, is neither charged with burdens nor credits (see also Section 1.9.2). Commonly recycled materials are cutting wastes (internal or external recycling) and paper.

Infrastructure and land use

The participating companies provide information on the area of the production site and the number of floors of the buildings. Buildings are assumed to have a lifetime of 80 years.

Selected key figures

Tab. 7.13 summarizes most important key figures for the production of an average geosynthetic drainage layer.

Tab. 7.13: Selected key figures referring to the production of 1 kg geosynthetic drainage layer used in landfill sites

	Unit	Value
Raw materials	kg/kg	1.03
Water	kg/kg	44
Lubricating oil	kg/kg	$8.05 \cdot 10^{-5}$
Electricity	kWh/kg	1.00
Thermal energy	MJ/kg	0.03
Fuel for forklifts	MJ/kg	0.08
Building hall	m^2/kg	$8.59 \cdot 10^{-6}$

C.4 Case 4 – Slope Retention

In this study a slope retention reinforced with concrete (case 4A) is compared to a slope retention reinforced with geosynthetics (case 4B). The construction of each type as well as its disposal is modelled in separate LCI datasets. The LCI refers to 1 meter and year of slope retention. The life time of the slope retention is assumed to be 100 years. The main specifications of the cases 4A and 4B slope retention are derived from a calculation example published by TenCate Geosynthetics Austria in 2001. The unit process raw data are shown in Tab. 7.15. The EcoSpold meta information is displayed in Tab. 7.16.

C.4.1 Construction

The amounts of different materials used for the entire construction with a length of 50 m are listed in Tab. 7.14. The sprayed concrete lining has a thickness of 10 cm. For the insulating coat, 0.3 l/m^3 bitumen are used per coating and three coatings are applied[16] (bitumen density: 1.025 kg/m^3 as described by Jungbluth (2007)). For round gravel, a density of 1'800 kg/m^3 is assumed.[17] For the formwork, 5.4 kg/m^2 wood are used and a reuse of 5 times is assumed as recommended by KBOB (2009). For polystyrene foam, a density of 40 kg/m^3 is applied. The drainage is made with 1.4 kg/m^2 polyethylene drainage pipes, produced in a plastic extrusion process.

Tab. 7.14: Material consumption for the construction of a 50 m slope retention

Material	Slope retention compound	Unit	Case 4A	Case 4B
Concrete, sole plate and foundation	Concrete foundation	m^3	80	-
Lean mix concrete	Cleanness layer	m^3	12	-
Structural concrete, with de-icing contact	Concrete wall (4A) Sprayed concrete lining (4B)	m^3	105	15.5
Reinforcing steel	Reinforcement foundation Reinforcement wall	kg	7'640	-
Bitumen	Insulating coat	kg	142.1	-
Gravel	Filter gravel Frost wall backfilling	m^3	120	120
On-site material	Sub-base fill material Wall embankment Covering material	m^3		604
Geosynthetic	Geosynthetic layers	m^2	-	1'960
Laminated board	Formwork fundament Formwork wall face work Formwork wall coarse Formwork, support	m^3	0.74	0.29
Polystyrene foam slab	Building gaps PS 15	kg	12.6	-
Polyethylene HDPE	Drainage	kg	86.8	100.8

The material on site is used as backfill material, wall embankments and cover material in case 4B. A drainage layer made of gravel with a thickness of 30 cm[18] behind the concrete lining is necessary. A gravel layer thickness of 80 cm is assumed to be consistent with case 4A, since the depth of frost penetration in Central Europe is about 80 cm. Round gravel is used for drainage purposes[19].

In the construction process, hydraulic excavators are used for the excavation of the foundation and different building machines are used for the ground compaction. Statistical fuel consumption data published by Schäffeler & Keller (2008) combined with a digging efficiency of 100 m^3/h results in an average energy consumption of 4.4 MJ/m^3 material moved with a hydraulic excavator (power category of 75-130 kW). The ground compaction requires 0.17 MJ/m^2 diesel fuel used in building machines such as vibration plates, universal barrels and vibration pounders. This value is derived from the fuel consumption and performance data of manufacturers.[20] The base area, the backfilling area, and each layer of case 4B slope retention are compacted by these building machines. The diesel consumption of mounting the geosynthetics

[16] http://www.schroer-ahlen.de/isolieranstrich.html (access on 12. April 2010)

[17] http://www.verkehrsportal.de/board/index.php?showtopic=46129 (access on 12. April 2010)

[18] Personal communication, Klaus Oberreiter, 29.4.2010

[19] Personal communication, Nicolas Laidié, 29.4.2010

[20] http://www.wackerneuson.com (access on 12. April 2010)

is considered with about 1.0 MJ/m^2 as reported by Egloffstein & Burkhard (2006), who assume an 8 hour use of an excavator with a fuel consumption of 461 MJ per hour and a 3 hour use of a wheel loader with a fuel consumption of 500 MJ per hour, having 5000 m^2 of geosynthetics mounted per day.

Concrete, gravel and laminated board are transported 50 km by lorry to the construction site. Metals and plastics are transported 100 km by lorry and 200 km by rail (Frischknecht et al. 2007b). Geosynthetics are typically transported around 600 km to the place of use.[21] We assume that 400 km is covered by rail and 200 km by lorry.

The foundation base area is under construction during two month and the completed walls have a life time of 100 years. These time periods are used to quantify land transformation and land occupation during construction and operation of the slope retention. Their base area is classified as road embankment land use type.

NMVOC emissions are released from the use of bitumen. In this study, we apply an emission factor of 7.2 kg NMVOC/t bitumen, as published in BUWAL (2000).

C.4.2 Disposal

Gravel used in slope retention is reused after its demolition. According to the statistics in Appendix 5 of Symonds et al. (1999), a share of 70 % landfilling and 30 % recycling of concrete for the European average is considered. The landfilling share of concrete is disposed of in an inert material landfill and transported 30 km. All reinforcing steel is considered to be recycled and the laminated boards are assumed to be reused. According to PlasticsEurope (2009) in 2008 16 % of plastics used in construction are recycled, 52 % are sent to landfill, and 32 % are sent to municipal incineration. These values are applied on the waste treatment of drainage, building gaps and geosynthetic layers. The standard transport distance to the sanitary landfill and the municipal incineration is 20 km.

[21] Personal communication with Henning Ehrenberg , EAGM Project Working Group (31. January 2010)

C.4.3 Unit process raw data of the infrastructure element

Tab. 7.15: Unit process raw data of slope retention, Case 4A and 4B

	Name	Location	InfrastructureProcess	Unit	slope protection, retaining wall, concrete	slope protection, soil, reinforced with geosynthetics	disposal, slope protection, retaining wall, concrete	disposal, slope protection, soil, reinforced with geosynthetics	life cycle, slope protection, retaining wall, concrete	life cycle, slope protection, soil, reinforced with geosynthetics	UncertaintyType	StandardDeviation95%	GeneralComment
	Location				RER	RER	RER	RER	RER	RER			
	InfrastructureProcess				1	1	1	1	1	1			
	Unit				m	m	m	m	m	m			
product	slope protection, retaining wall, concrete	RER	1	m	1	0	0	0	0	0			
	slope protection, soil, reinforced with geosynthetics	RER	1	m	0	1	0	0	0	0			
	disposal, slope protection, retaining wall, concrete	RER	1	m	0	0	1	0	0	0			
	disposal, slope protection, soil, reinforced with geosynthetics	RER	1	m	0	0	0	1	0	0			
	life cycle, slope protection, retaining wall, concrete	RER	1	m	0	0	0	0	1	0			
	life cycle, slope protection, soil, reinforced with geosynthetics	RER	1	m	0	0	0	0	0	1			
technosphere	diesel, burned in building machine	GLO	0	MJ	1.16E+1	5.39E+1	-	-	-	-	1	1.25	(2,3,3,1,1,5;2,1.05); excavation of fundament, compaction of base and layers
	transport, lorry >16t, fleet average	RER	0	tkm	7.01E+2	2.65E+2	1.97E+2	1.61E+1	-	-	1	2.09	(4,5,na,na,na,na;5,2); 20 km to municial incineration and landfill, 30 km to inert material landfill
	transport, freight, rail	RER	0	tkm	3.32E+1	6.92E+0	-	-	-	-	1	2.09	(4,5,na,na,na,na;5,2);
	concrete, sole plate and foundation, at plant	CH	0	m3	1.60E+0	-	-	-	-	-	1	1.07	(2,1,1,1,1,2;3,1.05); fundament
	poor concrete, at plant	CH	0	m3	2.40E-1	-	-	-	-	-	1	1.07	(2,1,1,1,1,2;3,1.05); cleanness layer
	reinforcing steel, at plant	RER	0	kg	1.53E+2	-	-	-	-	-	1	1.07	(2,1,1,1,1,2;3,1.05); reinforcement fundament and wall
	concrete, exacting, with de-icing salt contact, at plant	CH	0	m3	2.10E+0	3.10E-1	-	-	-	-	1	1.07	(2,1,1,1,1,2;3,1.05); concrete wall (B300) and sprayed concrete lining
	bitumen, at refinery	CH	0	kg	2.84E+0	-	-	-	-	-	1	1.30	(4,5,na,na,na,na;3,1.05); insulating coating cold
	gravel, round, at mine	RER	0	kg	4.32E+3	4.32E+3	-	-	-	-	1	1.30	(4,5,na,na,na,na;3,1.05); 80 cm layer (30 cm drainage), minimum frost wall backfilling is 80 cm
	c4, geosynthetic, average, slope retention	RER	0	m2	-	3.92E+1	-	-	-	-	1	1.05	(2,3,1,1,1,1;3,1.05); uncertainty set to 1.05: 5% cuttings and other excess material
	three layered laminated board, at plant	RER	0	m3	1.49E-2	5.89E-3	-	-	-	-	1	1.25	(2,3,3,1,1,5;3,1.05); formwork walls (5 times reused)
	polystyrene foam slab, at plant	RER	0	kg	2.52E-1		-	-	-	-	1	1.09	(2,3,1,1,1,2;3,1.05); building gaps
	polyethylene, HDPE, granulate, at plant	RER	0	kg	1.74E+0	2.02E+0	-	-	-	-	1	1.09	(2,3,1,1,1,2;3,1.05); drainage
	extrusion, plastic pipes	RER	0	kg	1.74E+0	2.02E+0		-	-	-	1	1.09	(2,3,1,1,1,2;3,1.05); drainage
	disposal, polystyrene, 0.2% water, to municipal incineration	CH	0	kg	-	-	8.06E-2	-	-	-	1	1.30	(4,1,1,1,1,5;6,1.05);
	disposal, polystyrene, 0.2% water, to sanitary landfill	CH	0	kg	-	-	1.31E-1	-	-	-	1	1.30	(4,1,1,1,1,5;6,1.05);
	disposal, polyethylene, 0.4% water, to municipal incineration	CH	0	kg	-	-	5.56E-1	6.45E-1	-	-	1	1.30	(4,1,1,1,1,5;6,1.05);
	disposal, polyethylene, 0.4% water, to sanitary landfill	CH	0	kg	-	-	9.03E-1	1.05E+0	-	-	1	1.30	(4,1,1,1,1,5;6,1.05);
	disposal, polyethylene terephtalate, 0.2% water, to municipal incineration	CH	0	kg	-	-	-	9.41E+0	-	-	1	1.30	(4,1,1,1,1,5;6,1.05); 32% of geosynthetics
	disposal, polyethylene terephtalate, 0.2% water, to sanitary landfill	CH	0	kg	-	-	-	1.53E+1	-	-	1	1.30	(4,1,1,1,1,5;6,1.05); 52% of geosynthetics
	disposal, concrete, 5% water, to inert material landfill	CH	0	kg	-	-	6.56E+3	5.16E+2	-	-	1	1.30	(4,1,1,1,1,5;6,1.05);
resource, land	Transformation, from unknown	-	-	m2	1.00E+0	6.00E-1	-	-	-	-	1	1.00	(4,5,na,na,na,na;8,2); uncertainty set to 1 as there is no uncertainty concerning the land use of the slope.
emission resource, land	Transformation, to traffic area, road embankment	-	-	m2	1.00E+0	6.00E-1	-	-	-	-	1	1.00	(4,5,na,na,na,na;8,2); uncertainty set to 1 as there is no uncertainty concerning the land use of the slope.
emission resource, land	Occupation, construction site	-	-	m2a	7.17E-1	6.83E-1	-	-	-	-	1	1.00	(2,4,1,1,1,5;7,1.5); uncertainty set to 1 as there is no uncertainty concerning the land use of the slope.
	Occupation, traffic area, road embankment	-	-	m2a	1.00E+2	6.00E+1	-	-	-	-	1	1.00	(2,4,1,1,1,5;7,1.5); uncertainty set to 1 as there is no uncertainty concerning the land use of the slope.
emission air, unspecified	NMVOC, non-methane volatile organic compounds, unspecified origin	-	-	kg	2.05E-2	-	-	-	-	-	1	1.64	(4,3,3,3,1,5;16,1.5); assumed: 25% of coating is evaporated solvent
technosphere	slope protection, retaining wall, concrete	RER	1	m	-	-	-	-	1.00E+0	-	1	1.00	(1,2,1,1,1,1;9,3); uncertainty set to 1
	slope protection, soil, reinforced with geosynthetics	RER	1	m	-	-	-	-	-	1.00E+0	1	1.00	(1,2,1,1,1,1;9,3); uncertainty set to 1
	disposal, slope protection, retaining wall, concrete	RER	1	m	-	-	-	-	1.00E+0	-	1	1.00	(1,2,1,1,1,1;9,3); uncertainty set to 1
	disposal, slope protection, soil, reinforced with geosynthetics	RER	1	m	-	-	-	-	-	1.00E+0	1	1.00	(1,2,1,1,1,1;9,3); uncertainty set to 1

Tab. 7.16: EcoSpold meta information of slope retention, Cases 4A and 4B

ReferenceFunction	Name	slope protection, retaining wall, concrete	slope protection, soil, reinforced with geosynthetics	disposal, slope protection, retaining wall, concrete	disposal, slope protection, soil, reinforced with geosynthetics	life cycle, slope protection, retaining wall, concrete	life cycle, slope protection, soil, reinforced with geosynthetics
Geography	Location	RER	RER	RER	RER	RER	RER
ReferenceFunctio	InfrastructureProcess	1	1	1	1	1	1
ReferenceFunctio	Unit	m	m	m	m	m	m
	IncludedProcesses	This dataset includes material, energy and water consumption as well as infrastructure and land use for the construction of a concrete retaining wall for slope protection.	This dataset includes material, energy and water consumption as well as infrastructure and land use for the construction of a geogrid reinforced slope protection.	This dataset includs the excavation and disposal of the materials from the dismantling of a concrete retaining wall for slope protection, as well as the transportation of the materials to the place of disposal or reuse.	This dataset includs the excavation and disposal of the materials from the dismantling of a geogrid reinforced slope protection, as well as the transportation of the materials to the place of disposal or reuse.	This dataset includs construction and disposal of a concrete retaining wall for slope protection.	This dataset includs construction and disposal of a geogrid reinforced slope protection.
	GeneralComment	The LCI reflects a concrete retaining wall for slope protection with 3 m height.	The LCI reflects a geogrid reinforced slope protection with 3 m height.	The LCI reflects a concrete retaining wall for slope protection with 3 m height.	The LCI reflects a geogrid reinforced slope protection with 3 m height.	The LCI reflects a concrete retaining wall for slope protection with 3 m height.	The LCI reflects a geogrid reinforced slope protection with 3 m height.
	InfrastructureIncluded	1	1	1	1	1	1
	Category	transport systems	transport systems	transport systems	transport systems	transport systems	transport systems
	SubCategory	road	road	road	road	road	road
TimePeriod	StartDate	2006	2006	2006	2006	2006	2006
	EndDate	2010	2010	2010	2010	2010	2010
	DataValidForEntirePeriod	1	1	1	1	1	1
	OtherPeriodText						
Geography	Text	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.	Data for a situation in Europe.
Technology	Text	Conventional slope protection construction with building machines.	Geogrid reinforced slope protection construction with building machines.	Excavation by hydraulic excavator, transport by lorry	Excavation by hydraulic excavator, transport by lorry	Excavation by hydraulic excavator, transport by lorry	Excavation by hydraulic excavator, transport by lorry
Representativenes	Percent	0	0	0	0	0	0
	ProductionVolume	unknown	unknown	unknown	unknown	unknown	unknown
	SamplingProcedure	unknown	unknown	unknown	unknown	unknown	unknown
	Extrapolations	none	none	none	none	none	none

C.4.4 Geogrid

In total 5 questionnaires are included in calculating the average life cycle inventory of a geosynthetic layer used in slope retention.

The quality of the data received is considered to be accurate. The level of detail was balanced before modelling an average geosynthetic layer, i.e. information on water consumption, lubricating oil consumption, etc. need to be added for some companies and other information deleted (packaging). In the following the life cycle inventory and assumptions are described.

Raw materials

Some of the companies start the production with plastic granules, the others with intermediate goods (yarns, straps, etc.). The production of such intermediate goods are modelled with data referring to the extrusion of plastic films from granulates (ecoinvent Centre 2010), based on information derived from PlasticsEurope).

To the authors knowledge it is not possible to produce a geosynthetic layer without plastic wastes (e.g. cutting waste or rejects). Thus, it is not possible that the input material equals the product output. Therefore, an average share of cutting wastes of 2 % is added in case 100 % material efficiency is indicated in the questionnaire. This share is calculated using the average of those companies (more than 3) indicating cutting wastes. These wastes are mostly recycled. Due to the allocation approach used in this study (see also Section 1.9.2) no burdens and no credits are allocated to such wastes.

Raw materials need to be transported to the factories. Standard distances as defined in Frischknecht et al. (2004) are used to estimate transportation expenditures, i.e. 100 km by lorry >16t and 600 km by train.

Working materials

To balance the level of detail of the data reported in the questionnaires standard values are included for lubricating oil where unknown. This standard value is calculated using the average of those companies indicating lubricating oil consumption. A small part of the questionnaires contain information about packaging material. As the mass contribution of packaging is less than 3 %, packaging material is excluded from the average geosynthetic material inventory.

Energy consumption

Electricity consumption is modelled with country-specific electricity mixes. In case the production location is unknown UCTE electricity mix is included. Heating energy is included where known. However, its influence on the environmental impacts of geosynthetic material production is relatively small. No environmental burdens are allocated to district waste heat, like for instance heat from a waste incineration plant, a cement plant, etc. To balance the level of detail of the questionnaires standard values are included for diesel consumption of forklifts where unknown and not included in the electricity consumption. These standard values are calculated using the average of those companies (more than 3) indicating diesel consumption.

Airborne emissions

It is assumed that 100 % of the electricity consumed is converted to waste heat and that 100 % of the waste heat is released to air. Some companies report carbon emissions. These are assumed to be non methane volatile organic compounds (NMVOC). Data about further airborne emissions are taken from the questionnaires where provided and measured. Not reported emissions are classified as unkown emissions and thus are not included in calculating the average geosynthetic. It is assumed that the manufacturing plants are located in an urban/industrial area. Thus, the pollutants are categorized as emanating in a high population density area.

Emissions to water

No information on wastewater characteristics is available. Thus, wastewater treatment is modelled with the ecoinvent dataset “treatment, sewage, unpolluted, to wastewater treatment, class 3”.

Solid waste

Wastes, such as household, plastic and sludge wastes as well as spent lubricating oil, are considered in those cases, where data are provided. Depending on the country, these wastes are either incinerated or landfilled. Material, which is recycled, is neither charged with burdens nor credits (see also Section 1.9.2). Commonly recycled materials are cutting wastes (internal or external recycling) and paper.

Infrastructure and land use

The participating companies provide information on the area of the production site and the number of floors of the buildings. Buildings are assumed to have a lifetime of 80 years. To balance the level of detail of the questionnaires standard values are included for infrastructure where unknown. These standard values are calculated using the average of those companies (more than 3) indicating infrastructure and land use.

Selected key figures

Tab. 7.17 summarizes most important key figures for the production of an average geosynthetic layer.

Tab. 7.17: Selected key figures referring to the production of 1 kg geosynthetic layer used in slope retention

	Unit	Value
Raw materials	kg/kg	1.02
Water	kg/kg	0.86
Lubricating oil	kg/kg	$7.30*10^{-5}$
Electricity	kWh/kg	0.73
Thermal energy	MJ/kg	1.24
Fuel for forklifts	MJ/kg	0.13
Building hall	m^2/kg	$6.32*10^{-6}$

D Annex D: Critical Review Report