Life Cycle Analysis

for four different ground improvement techniques

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1201072-003

Deltares

Title
Life Cycle Analysis

Client	Project	Reference	Pages
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Keywords
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Summary
BioGrout is a method developed by SmartSoils® Deltares to strengthen soil. It is based on Microbial In situ Calcite Precipitation (MICP). BioGrout 1st generation, using the urease-enzyme, was developed in 2004. In 2008 the development of 2nd generation BioGrout, based on denitrification, was started. These are two innovative techniques for ground improvement.
At current, determining the sustainability including the environmental impact of technologies, products in the construction sector is becoming more important. , This influences decisionmaking on which technologies to use, and also how to develop new technologies. Life Cycle Analysis (LCA) is a tool that is becoming standard in the building sector anc can be used to determine the environmental impact of a technology/product. An LCA can be used for different applications. First of all, it can be used for analyzing the origins of impacts related to a particular product. Secondly, it can compare improvements of a product or it can be useful for the designing of new products. Finally, it can be used to help choosing between a number of comparable products for internal or external communications. Application of LCA's in the field of geoengineering is new.
An LCA of the two BioGrout methods was produced, in order to determine their environmental impact and to investigate which steps in the process have the highest impact and should be improved. Also an LCA is made of two traditional ground improvement techniques, gel injection and jet grouting, in order to compare the two new methods with the traditional methods.
Based on the assumptions made for these LCAs, it can be concluded that BioGrout first generation has the highest environmental impact. As expected this is caused by the waste treatment of the ammonium chloride produced. When more than 95% of the ammonium chloride is recycled, instead of treated, than the environmental impact of the method becomes more comparable with the other three methods. For BioGrout second generation, the highest impact is caused by the production of calcium nitrate, acetic acid and the production of NOx. When waste products can be used as substrates, the environmental impact will be probably reduced very significantly. From these LCA's the gel injection and jet grouting are the most favourable techniques based solely on environmental impact. However, it should be taken into account that currently LCA's are based on the assembly of products and therefore do not take other aspects of soil treatment in account. Therefore, the way the soil in strengthened, in situ or by mix in place, the direct and indirect effects of these two different methods are not included in the LCA's. In addition, the effect of placing cement/gel/calcite in the soil on the microbiology and ecology are not taken into account. These factors also result in an impact on the environment, but are not taken into account in the LCA.
These LCAs should be seen as 'preliminary estimates of the impact on the environment by BioGrout 1st and 2nd generation. It should be used to improve and steer further development of these methods. Because both methods are not yet mature and optimized the LCA's will change during the development and commercialization steps.
Nevertheless, three main conclusions can be drawn:
1) BioGrout is not necessarily an environmentally friendly method; it should be termed a new ground improvement method;
2) The second generation also has an environmental impact that is strongly dependant on the technical state of the art, the process design and local site conditions.

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3) The relative contribution of ground specific issues in performing LCAs are still uncharted territory. There is a need for the development of methods and parameters in order to perform and evaluate LCA's taking the effect of structures made in the soil into account.

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1	Nov. 2009	drs. J.W.M. Salemans		W.R.L. van der Star		ing. M. Hutteman	
		drs. M. Blauw					
2	February 2010	drs. J.W.M. Salemans		W.R.L. van der Star		ing. M. Hutteman	

State
final

Content

List of Tables

List of Figures

1 Introduction

BioGrout is a method developed by SmartSoils® Deltares to strengthen soil. It is based on in situ calcite precipitation (MICP). BioGrout 1st generation, based on urease-enzyme, was developed in 2004. In 2008 the development of 2nd generation BioGrout, based on denitrification, was started. These are two innovative techniques for ground improvement. In order to compare these two methods with each other and with traditional ground improvement techniques on their environmental impact, Deltares has chosen to make a Life Cycle Analysis.
It should be noticed that a LCA is a tool that can give steering to the development of a technique. Because not all components of a method of technique can be included in a LCA (especially new methods), the results should be interpreted carefully. Many assumptions are made with an LCA; these should be read thoroughly before drawing conclusions from the obtained results.
The LCA reported here gives a rough indication about the environmental impact of the four different ground improvement techniques. These can be more specified, because most data that was needed was not included in the SimaPro database and therefore an alternative was used.

1.1 Life Cycle Analysis

The environment is becoming more and more important in the present society. The making of a Life Cycle Analysis (LCA) is a way to investigate the environmental impact of a product. There are four phases with the LCA procedure: the goal and scope definition, the inventory analysis, the impact assessment and the interpretation (Appendix 1). This information is mainly based on [Lit. 1].

A definition of LCA is given in ISO 14040: "*Environmental management – Life cycle assessment – Principles and framework*". Here LCA is defined as the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle". Thus, LCA can be used as a tool to analyze the environmental burden of a (new) product. This environmental burden covers all types of impacts upon the environment. A product can be a physical good as well as a service.
LCA is, as far as possible, quantitative in character. Where this is not possible, qualitative aspects can be taken into account, so that as complete a picture as possible is given of the environmental impacts involved. Qualitative aspects, however, are harder to compare.
An LCA can be used for different applications. First, it can be used for analyzing the origins of problems related to a particular product. Secondly, it can compare improvements of a product or it can be useful for the designing of new products. Finally, it can be used to help choosing between a numbers of comparable products for internal or external communications.
A classic example of the application of an LCA is the comparison between the use of a porcelain cup and plastic cups when using a coffee machine. The results of this LCA could be used to decide between the two options. Because an LCA takes the environmental impacts from the whole life cycle into account, it is important to include for example the energy needed for doing the dishes for the porcelain cup.

1.2 Aim of this project

The aim with this LCA is to determine which parts of the process have the highest environmental impact (mainly for the BioGrout 1 and 2 generation) and what the environmental impact is of BioGrout compared with traditional techniques (jet grouting and gel injection). This LCA should be useful for the further development of BioGrout first and second generation. The LCA was performed with help of PRé Consultants, who supply the LCA-software SimaPro and has reviewed this report.
In 2007 GeoDelft (now Deltares) performed a first LCA on the first generation BioGrout [Lit. 2].

2 Project description

2.1 Goal and scope

The goal of this LCA is to determine the environmental impact of four different soil-strengthening methods: BioGrout – 1st generation (urea hydrolysis process), BioGrout – 2nd generation (denitrification process), jet grouting (traditional) and gel injection (traditional). *Only the environmental impact is taken into account with this LCA, meaning that not the mode of application and other effects are determined*. Besides this, the main goal is to determine which steps of each process have the highest environmental impact, and need to be improved to obtain an environmental friendly method.

First and second generation BioGrout are both new in situ soil-strengthening methods. Both BioGrout methods will be compared with two traditional soil-strengthening methods, to be able to make a comparison between the techniques not only based on cost but also to take into account the environmental impact. The two BioGrout methods will also be compared with each other.
To make a proper comparison, a real case study has been used to determine the environmental impact of the four ground improvement techniques.

2.2 Approach

Life Cycle Analysis (LCA) is a method developed to evaluate the mass balance of inputs and outputs of systems and to organize and convert those inputs and outputs into environmental themes or categories relative to resource use, human health and ecological areas. Several computer programmes are available for making LCA's. For this project, the program SimaPro has been used. This is the most widely used LCA software.

To quickly build and analyze a LCA model, a transparent, high quality and widely accepted inventory data for most commonly used materials and processes is needed. For this LCA the Swiss Ecoinvent database is used, because it is one of the most complete databases and a well-known database.

Until now, LCA's are mainly made for factory processes, thus the development of coffee machines, using paper of cotton towels etc. There is no dedicated LCA for the subsurface and especially not for microbial processes. Therefore certain processes, which occur for the ground improvement techniques, could not be included in this LCA. To include these processes, and thus there impacts, these specific data should be obtained by ourselves. Because these are rough LCA's, the impact of the technique how the soil is strengthened (*in situ* or mix in place), the effect using microbes etc are not taken into account.

2.3 Case study

2.3.1 Problem

The railway station Gouda Goverwelle has been built in the early nineties of the last century. Simultaneously, the railway line between Gouda and Woerden was broadened. The railway line is situated in an area with soft soils (peat and clay). That is why the designers took big deformations into account, especially settlements.

However, after a couple of years the differences in deformation were still considerable. The differences of the settlements were caused by the differences in the widening of the railway. Because of the unfavourable characteristics of the peat, the deformations have not yet come to a rest. Furthermore, the groundwater level is very high and increases even more during severe precipitation. This is why draining of the groundwater is very difficult.

On top of the clay/peat layer an embankment of sand is placed, on which the railway tracks are placed. Because hardly any drainage of groundwater takes place underneath the sand, a high risk of liquefaction exists. When liquefaction occurs, there will be an increase in embankment deformation. These deformations cause an enhancement of vibrations when trains pass. Therefore, track maintenance is continuously needed, and settlements of platforms and tilting of the platform walls are ongoing. Especially during long periods of rain, the deformations are relatively large, because of the poor drainage system. Due to the weather dependence and the short period when the railway track is available for maintenance (when no trains pass), it is very difficult to plan the needed maintenance. These planning problems are considered the main problem.

2.3.2 Solutions

A report [Lit. 3] was made by GeoDelft (since 2008 Deltares) by order of “NS Railinfrabeheer” to provide possible solutions for this problem. The report gives several solutions for the problem. One possible solution is to improve the drainage of water by installing a drainage system at the base of the embankment. This is an effective and inexpensive solution. Furthermore, it is not necessary to excavate the embankment.

However, there is a chance that this solution will not work sufficiently enough. If this is the case, it is also possible to decrease the water level temporarily. This will cause more inconvenience, because of extra settlements.

When problems still occur after the above-mentioned interventions, it is possible to combine these two interventions with local compaction of sand. This too is inconvenient and it is possible that ongoing deformations will undo the positive effects of the sand compaction.

Another solution is to replace the subsoil partially with lightweight filled material containing good drainage characteristics. However, the costs of this alternative are high and there is the chance that compaction will undo the effect.

By preventing horizontal deformations, the vertical deformations can be reduced. An opportunity is using soil retaining structures/methods. However, it is not certain that this will be effective for the complete railway. Another way of preventing horizontal deformations is using a construction, which can take tensile force at the top of the embankment, such as a geogrid.

However, the most expensive, but also the most effective solution is the use of bearing columns. Bearing columns can be combined with drainage and compaction.

Furthermore, it is also possible to take no action. This can be considered as the actual situation. However, this causes a lot of economic damage, due to high amount of maintenance and trains that need to be diverted.

2.3.3 Functional unit

The function of BioGrout first and second generation, jet grout and gel injection is to strengthen the soil. The functional unit can be formulated as the strengthening of a specific type of soil by certain strength for a certain volume. It is also important to specify the ground characteristics because the working of the product depends on these characteristics. It is assumed that all four methods have the same durability. Therefore, the timing is not taken into account in this LCA. When maintenance will be necessary in these years, this must also be considered as an environmental intervention. The use of the case determines the functional unit as follows:

> *The strengthening of 1000 m^3 sand layers beneath the railway track between Gouda and Goverwelle with a grain size of 0.2 mm to at least 1000 kPa.*

3 BioGrout – 1st generation

3.1 System and boundaries

BioGrout is a method developed by SmartSoils® Deltares to strengthen soil, and is based on MICP (microbial in situ carbonate precipitation). MICP can be obtained using different processes in which the activity of bacteria results in the generation of carbonate in a calcium-rich environment [Lit. 4]. The most commonly studied system of MICP at this moment is urea hydrolysis via the enzyme urease in a calcium-rich environment, BioGrout first generation [Lit. 5].

$$\underbrace{CO(NH_2)_2}_{\text{Urea}} + \underbrace{2H_2O}_{\text{water}} \rightarrow \underbrace{2NH_4^{\ +}}_{\text{ammonium}} + \underbrace{CO_3^{\ 2-}}_{\text{carbonate}}$$

$$\underbrace{Ca^{2+}}_{\text{Calcium}} + \underbrace{CO_3^{\ 2-}}_{\text{carbonate}} \rightarrow \underbrace{CaCO_3\ (s)}_{\text{calcium carbonate}}$$

The urease-containing bacterium that is used is *Sporosarcina pasteurii.* The calcium source is calcium chloride.

The removal of the produced ammonium chloride is part of the first generation BioGrout process, as it is required to remove it from the treated soil. There are in general two different processes to treat/use the produced ammonium chloride. One process is to treat the ammonium chloride in a wastewater treatment plant. The other possibility is to recycle the ammonium chloride and reuse it as e.g. fertilizer, for algae production, or to convert it to urea, polyamide, DNA or azo-dyes.

It is possible to reduce the total amount ammonium chloride using reverse osmosis and evaporation [Lit. 6]. However, these methods were not very favourable for ammonium chloride, due to the high-energy requirement and therefore not taken into account in this LCA.

In Figure 3.1 the BioGrout, first generation BioGrout is visualized. The flow diagram, which is based on the above information and mainly used for the LCA, is shown in Figure 3.2.

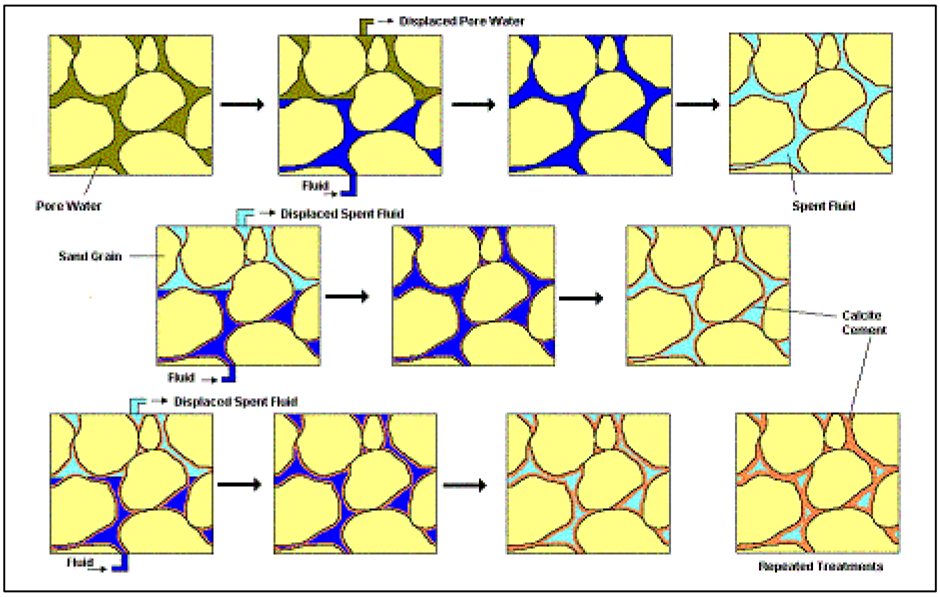

Figure 3.1 The process of BioGrout first generation

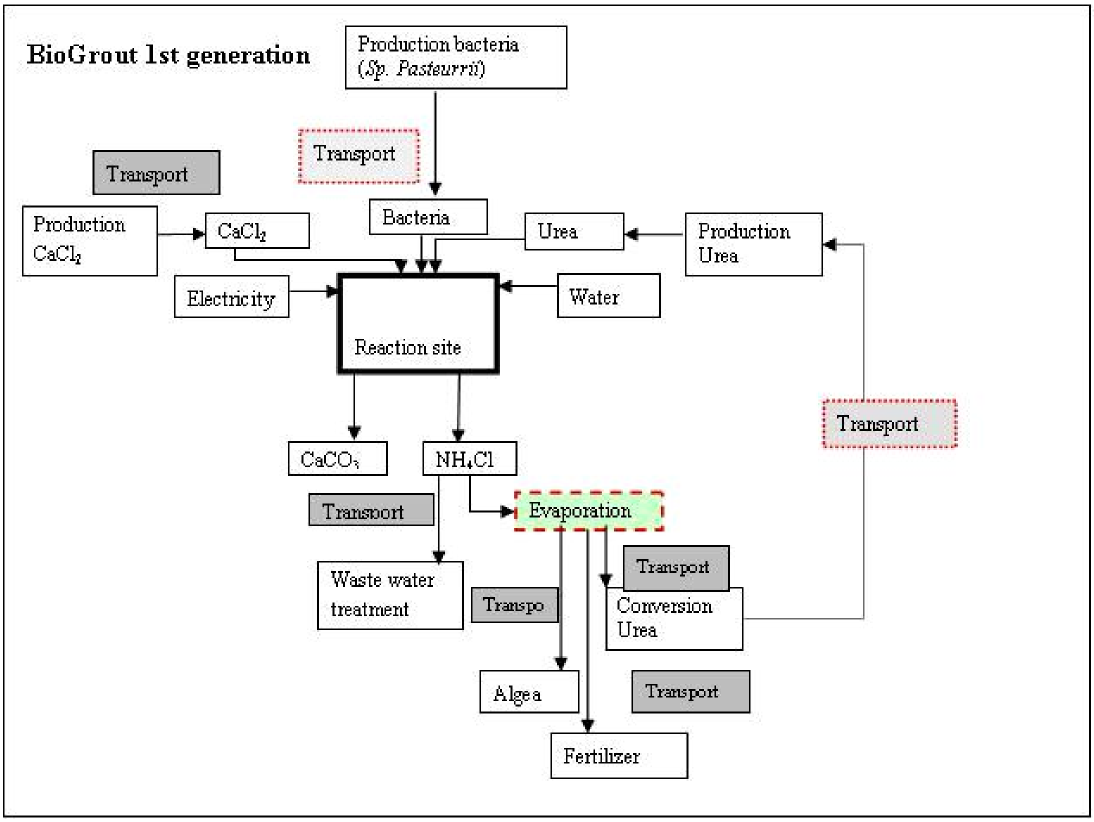

Figure 3.2 Flow diagram of the BioGrout first generation process

The production of the raw materials and bacteria, the energy usage at the production site, the transport of the raw materials to the reaction site is taken into account in the LCA. Ammonium chloride is removed during the BioGrout first generation process and is taken into account.

Two processes are possible for the treatment of ammonium chloride in this LCA; 1) waste water treatment, and 2) recycling of ammonium chloride. How the ammonium chloride is recycled is not taken into account.

The system only has one function and the raw materials will be bought from companies that only produce these materials. Furthermore, if the by-products can be used, the benefits or costs of this process are not taken into account.

3.2 Assumptions

Several assumptions are made for the LCA BioGrout first generation:

- The concentration of substrates calcium chloride and urea is 1.5 M and the output concentration of ammonium chloride is therefore 3 M (assuming 100% conversion).
- The treatment of ammonium chloride is divided into two processes:
  - Recycling: no variations in type of recycling are made. The environmental impact of recycling ammonium chloride is zero, meaning that no positive or negative effect on the environment is taken into account. The positive effect of using wastewater will be included in the LCA of that process, and therefore it cannot be included in the BioGrout process. The positive impact will be taken into account twice then.
  - Wastewater treatment: in a type 3 wastewater treatment facility[1]
    - No transport costs are included;
    - It is assumed that the waste treatment facility will only treat ammonium chloride from the BioGrout process, but in the LCA the complete waste water treatment is included, thus the impact for running a complete facility will be taken into account. The impact will be higher, because also the impact of treating carbon/sulphur sources is included in the impact assessment, which is not an impact from the BioGrout process;
    - It is assumed that 3M ammonium chloride (160.5 kg/m^3) is the outflow concentration. The wastewater treatment unit used during the LCA treats 0.02 kg/m^3 ammonium chloride. However, it is assumed that a treatment plant can treat 0.05 kg $/m^3$ ammonium chloride. In addition, by taking a higher amount, the impact caused by other sources is decreased.
- Bacteria are produced on site. In a large bioreactor, the bacteria will be produced at the same location as the treated soil. Therefore, no transport is included for the raw materials for the production of bacteria.

3.3 Data

Information about the strength of BioGrout first generation and the corresponding amounts of necessary water, urea and calcium chloride and amounts of production of ammonium and

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1. Treatment, sewage, to wastewater treatment, class 3/CHS. Included processes: Infrastructure materials for municipal wastewater treatment plant, transports, dismantling. Land use burdens.
Remark: Wastewater purified in a medium size municipal wastewater treatment plant (capacity class 3), with an average capacity size of 24900 per-captia-equivalents PCE. Geography: Specific to the technology mix encountered in Switzerland in 2000. Well applicable to modern treatment practices in Europe, North America or Japan. Technology: Three stage wastewater treatment (mechanical, biological, chemical) including sludge digestion (fermentation) according to the average technology in Switzerland

chloride are summarized in Table 3.1. These values are based on the treatment of 1000 m^3 sand [Lit. 7] with 1,5M Urea/$CaCl_2$.

Expected strength [kPa]	Produced calcite [kg]	Produced ammonium chloride [kg]	Used calcium-chloride [kg]	Used urea [kg]	Used water [m^3]	Used Bacteria suspension [m^3]
500	121,157	64,754	134,350	72,621	807	100
1000	183,603	98,129	203,596	110,052	1,222	100

Table 3.1 Amounts of raw material and products for BioGrout (1st generation).

In addition, energy usage at the reaction site was taken into account. For BioGrout first generation it the amount of fuel used for pumping and mixing was estimated at 70 m^3 gas (Appendix 2). This includes the removal of the ammonium chloride.

For the transportation of raw materials, it is assumed that calcium chloride and urea are bought in IJmuiden. The amount of kilometres depends on the place where BioGrout 1st generation will be used. For this case study the transport distance is 90 km. For the LCA, it is also important to know the kind of transport that is necessary. This information is summarized in Table 3.2

Raw material	Location	Kind of transport
Calcium chloride	IJmuiden	Truck 40 ton
Urea	IJmuiden	Truck 40 ton

Table 3.2 Location and transport raw material for BioGrout (generation1)

3.4 Input SimaPro

First, the assembly needs to be defined, thus which processes and materials play a role in the LCA and quantify them. This is shown in Figure 3.3 and Figure 3.4. The calcium chloride that is used, is made with the Solvay process. It may be possible that other processes have less impact on the environment, but is assumed that this is not the case. Urea is made of ammonia and calcium dioxide. For this LCA decarbonised water is chosen. The processes that are included in the assembly are the transport of the raw materials, the energy usage, production 100 m^3 bacteria and the treatment of ammonium chloride. The amount of gas is converted from m^3 to kWh by multiplying with 11 (11,6 kWh/m3 (Nuon)). The kind of electricity that is used is electricity of medium voltage[2], produced in the Netherlands. The amount of (tonnes) kilometres (tkm) is based on the distance from IJmuiden to Gouda, which is approximately 90 km. This is multiplied by the total amount of tons material.

2. *Electricity. Medium voltage, production NL, at grid/NL S. Included processes: Included are the electricity production in Netherlands, the transmission network and direct SF6-emissions to air. Electricity losses during medium-voltage transmission and transformation from high-voltage are accounted for. Remark: This dataset describes the transformation from high to medium voltage as well as the transmission of electricity at medium voltage. Geography: Data apply to public and self producers. Geographical classification according to IEA. Assumptions for transmission network, losses and emissions are based on Swiss data. Technology: Average technology used to transmit and distribute electricity. Includes underground and overhead lines, as well as air-, vacuum- and SF6-insulated high-to-medium voltage switching stations. Electricity production according to related datasets*

For the production op bacteria, raw materials, water and electricity are included. The amount of electricity is an estimated value, 24 hours flushing with air and heating up to 30˚C. The transport of the raw materials and of the bacteria is not included in the assembly.

For the removal of ammonium chloride, two different processes can be chosen or a combination of both can be applied in the LCA, recycling or treatment. When the ammonium chloride is recycled, no environmental benefit or impact is taken into account in this LCA. When the ammonium chloride is treated, it is assumed that the impact for 1 m^3 of product 28 kg-N/m^3 is equivalent to 28 kg divided by 0,05 kg-N/m^3 = 560 m^3 of waste stream containing 0,05 kg-N/m^3.   The waste treatment plant normally treats 0.02 kg/m^3 NH_4Cl, but we assume that this value is equivalent to treatment of the BioGrout wastewater at a concentration of 0.05 kg/m^3 with the same operating cost, as the concentrated waste stream probably can be treated with advanced fully autotrophic wastewater treatment technologies (Lit.12).

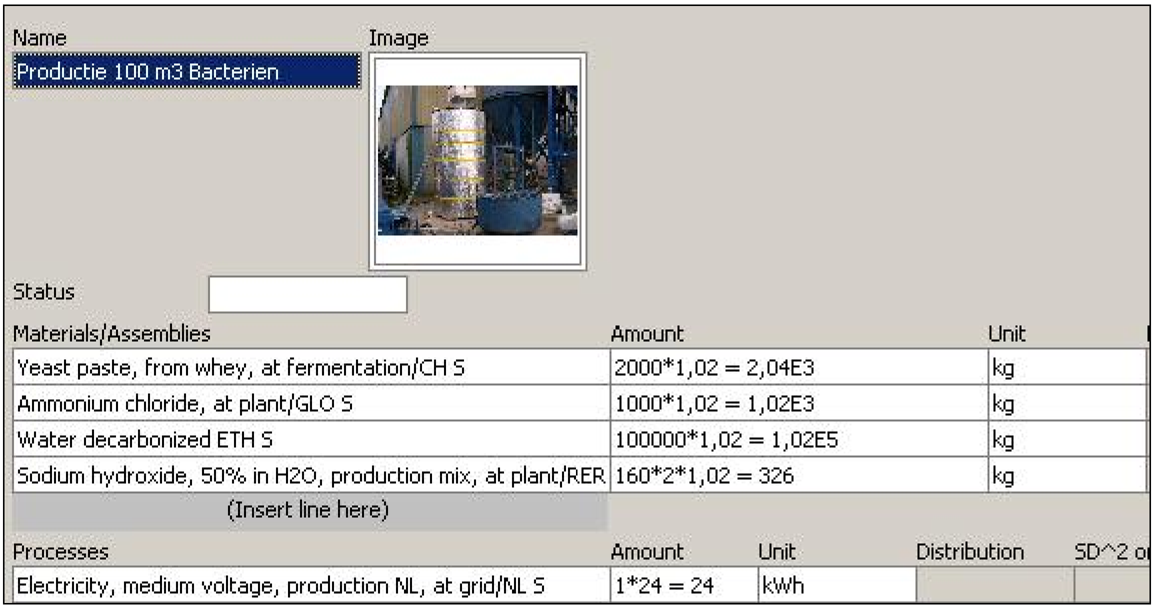


Figure 3.3   Assembly in SimaPro of 100 m3 bacteria

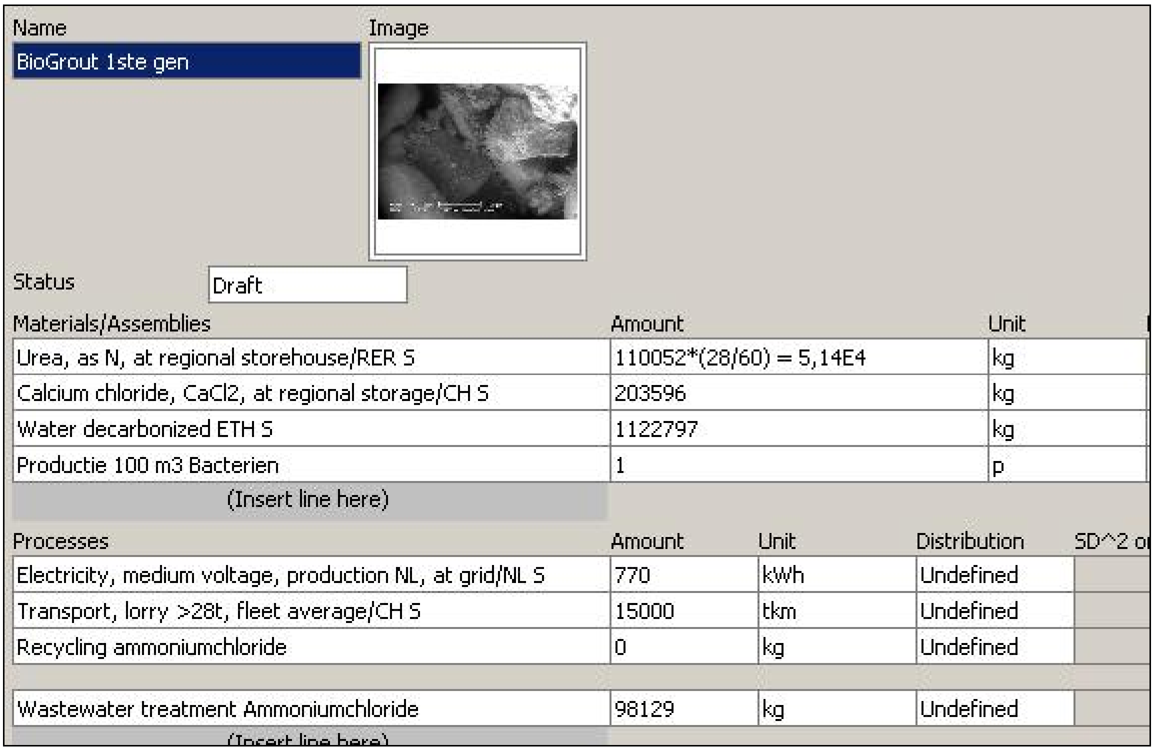


Figure 3.4 Assembly in SimaPro of BioGrout (1st generation)

4 BioGrout – 2nd generation

4.1 System and boundaries

BioGrout second generation is a method developed by SmartSoils® Deltares, which is still in development. The principal is microbial in-situ carbonate precipitation (MICP). Because with the first generation BioGrout, a large volume ammonium chloride is produced and the raw materials (urea and calcium chloride) are relatively expensive, Deltares has started in 2008, to develop the second generation BioGrout. This process is based on denitrification, and might eventually use waste products and produces mainly nitrogen-gas (N_2) (Figure 4.1). The overall reaction is shown below.

$$Ca(CH_3COO)_2 + 1.6Ca(NO_3)_2 \rightarrow$$
$$2.6CaCO_3(s) + 1.44N_2(g) + 1.4\ CO_2(g) + 0.16\ NO_X(g) + 0.5\ C\text{-Biomass}$$

With this process calcium acetate and calcium nitrate are injected in to soil. This causes the growth of denitrifying bacteria. During the denitrification of calcium acetate and nitrate, calcium carbonate is produced, together with nitrogen-gas and carbon dioxide gas. The by-products are emitted into the atmosphere. No by-products are removed. In Figure 4.1 the flow diagram, which is partly used for the LCA, for BioGrout 2nd generation is shown. The green line shows the boundary for the LCA and thus indicates that for this evaluation industrially produced calcium acetate and calcium nitrate are assumed the substrates.
It is possible to eventually use waste streams with high levels of calcium acetate and calcium nitrate are used as base material, but of practical reasons, this step is not included into this LCA yet.

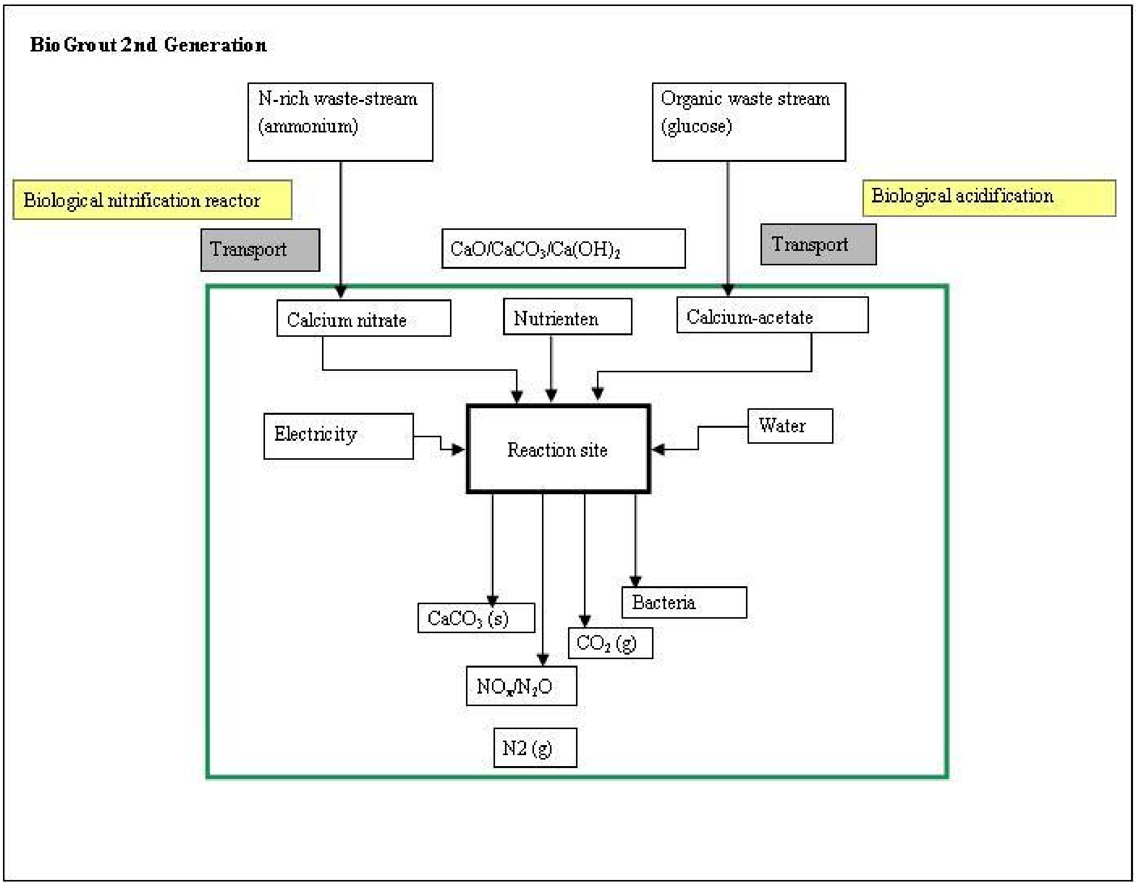


Figure 4.1 Flow diagram of BioGrout 2nd generation process.

The production of the raw materials, the energy usage at the production site, and transport of the raw materials to the reaction site are taken into account in this LCA. Furthermore, the production of output gases is also included. The production of bacteria during the BioGrout 2nd generation process is not included in the LCA.

The boundary between the product system and other product systems is clear for this LCA. The system has one function and the raw materials will be bought from companies that only produce these materials. Furthermore, the by-products are emitted into the atmosphere, or remain in the soil.

4.2 Assumptions

The following assumptions were made for the LCA of BioGrout second generation:

- The reaction has an efficiency of 100%.
- 10% of the total amount produced gas will be N_2O and NO_x rather than N_2.
- The bacteria that are produced in the soil during the injection of calcium nitrate and calcium acetate and are needed for the calcite precipitation do not have an environmental impact.
- No other biomass is produced.
- Eventually waste products will be used for the second generation BioGrout. However, for practical reasons this was not included into this LCA.
- All produced NO_x(g) is emitted into the atmosphere.

- The amount of calcite needed for certain strength is similar for both BioGrout processes.
- The amount of energy and transport used for BioGrout 2nd generation is similar to the BioGrout 1st generation process.

4.3 Data

Information about the strength of BioGrout second generation and the corresponding amounts of needed water, calcium nitrate, calcium acetate, nutrients, and the produced amount of calcite, nitrogen and N_2O/NO_x are summarized in Table 4.1. These values are based on the treatment of 1000 m^3 sand [Lit. 7] with strength of 1MPa.

Expected strength [kPa]	Used calcium acetate [kg]	Used calcium nitrate [kg]	Used water [m^3]	Produced calcite [kg]	Produced N2 [kg]	Produced N_2O/NO_x [kg]	Produced CO_2 [kg]	Prod. Biomass [kg]
1000	167,342	185,113	6,650	183,603	14,222	4,967.6	43,466	10,582

Table 4.1 Amounts of raw material and products for BioGrout (2nd generation).

Nutrients	kg
$(NH_4)_2SO_4$	2636.0
$MgSO_4$	1921.1
KH_2PO_4	5429.5
K_2HPO_4	16215.4

Table 4.2 Amounts of nutrients needed for treatment of 1000 m^3 with a strength of 1Mpa

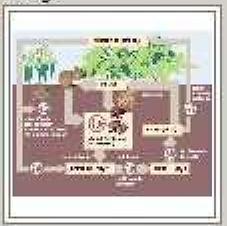
It is assumed that the energy usage for the BioGrout 2nd generation is similar to the first generation BioGrout. Therefore, the amount fuel used is estimated at 70 m^3 gas for the treatment of 1000 m^3 soil.
For the transportation, it is assumed that the amount is the same as for BioGrout 1st generation. Therefore, a truck of 40 ton is used and the raw products are bought in Ijmuiden and transported to Gouda Goverwelle (90 km).

4.4 Input SimaPro

At first, the assembly is defined (Figure 4.2). Because calcium acetate was not included in the database, acetic acid is used for this LCA. The same type of water is used for this LCA, as for BioGrout 1st generation, decarbonized water. For the extra nutrients, which are added, no potassium phosphate was in the database. In stead, sodium phosphate is used for potassium phosphate (KH_2PO_4 and K_2HPO_4), because these products are very similar product.

Name: BioGrout gen2

Image



Status: Temporary

Materials/Assemblies	Amount	Unit
Calcium nitrate, as N, at regional storehouse/RER S	185112,6/4,8 = 3,86E4	kg
Acetic acid, 98% in H2O, at plant/RER S	167342,1*1,02 = 1,71E5	kg
Water, decarbonised, at plant/RER S	6649800	kg
Ammonium sulphate, as N, at regional storehouse/RER S	2636/3,9 = 676	kg
Magnesium sulphate, at plant/RER S	1921,1	kg
Sodium phosphate, at plant/RER S	5429,5+16215,4 = 2,16E4	kg
(Insert line here)		

Processes	Amount	Unit	Distribution	SD^2 o
Electricity, medium voltage, production NL, at grid/NL S	770	kWh	Undefined	
Transport, lorry >28t, fleet average/CH S	15000	tkm	Undefined	
N2-gas output	28444,1	kg	Undefined	
NOx/N2O emission	4967,6	kg	Undefined	
CO2 emission	43466,2	kg	Undefined	

Figure 4.2 Assembly in SimaPro of BioGrout 2^{nd} generation

5 Jet grouting

5.1 System and boundaries

Jet grouting is a soil stabilization technique in which a grout is injected into the soil [Lit. 8]. The grout consists of cement, water, in some cases air and if necessary additives. The injection occurs with rotating and drilling rods. Triple rods make it possible to provide separate flows of air, water and grout to the jet nozzle holder. Once the rod is deep enough in the soil, the jet nozzle holder will inject the grout under pressure, which will cut through the soil. At this way, the original soil will be mixed and partially displaced by a mixture of grout and soil parts. First, the rod will drill into the soil. Then the rod will come up and at the same time will inject the grout. Multiple columns can be made next to each other (Figure 5.1). The use of air depends on the goal of the jet grouting. The excess of the mixture will come up along the rod and is called the spoil. This spoil must be removed from the surface level.

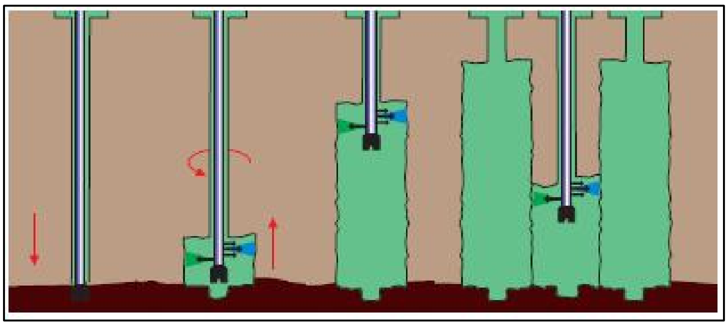


Figure 5.1 The process of jet grouting (from Keller Funderingstechnieken B.V. [Lit. 8])

Jet grouting can be used for stabilization or sealing and the process is shown Figure 5.2.

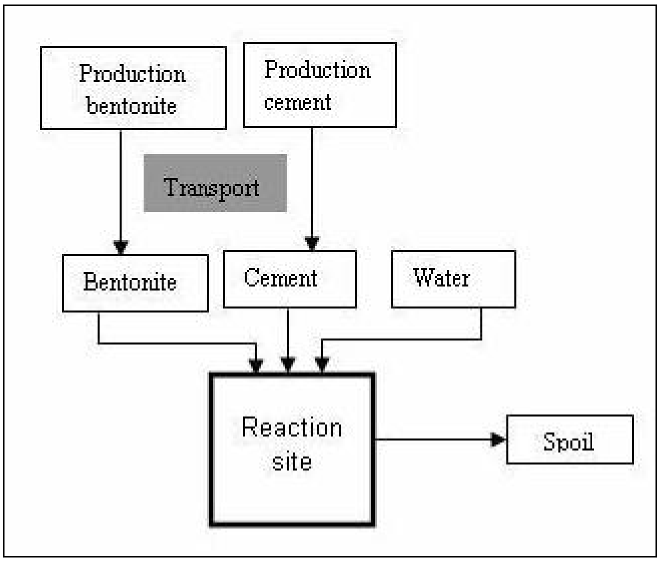


Figure 5.2 The flow diagram of the jet grouting process

The production of the raw materials, the energy usage at the production site and the transport of the raw materials to the reaction site are taken into account in the LCA. Furthermore, the production of the residues is included. A removal step for jet grout is included in the process because the spoil of jet grout needs to be treated at a soil remediation facility, because of the high pH-value. It is assumed that 10% of the total amount of products injected into the soil will be spoil and has to be treated. Various tests on the regeneration of sand from the spoil have not yet lead to a more effective way of recycling.

The boundary between the product system and other product systems is clear for all methods. The system only has one function, which is strengthening soil, and the raw materials will be bought from companies that only produce these materials.

5.2 Assumptions

The following assumptions have been used in the LCA for jet grouting:

- 10 % of the used raw material and soil will be spoil.
- No transport is included for the disposal of the spoil.
- The spoil will be treated as cement mortar
- The values of the raw materials of jet grout are based on a case of Visser & Smit bouw. This project is called: *Jetgrouten de Verademing te Den Haag*. For this case, the following information is used:
    - Cement:
        - 200 kg CEM III per m^3 mixture
        - density CEM III = 2.90 kg/dm^3
        - 200/2.90 = 69 dm^3 = 0.069 m^3 cement per m^3 mixture
    - Bentonite:
        - 40 kg bentonite per m^3 mixture
        - density bentonite = 2.15 kg/dm^3
        - 40/2.15 = 18.6 dm^3 = 0.019 m^3 bentonite per m^3 mixture
    - Water:
        - 1 m^3 mixture - 0.069 m^3 - 0.019 m^3 = 9.12 m^3 water per m^3 mixture
        - Density water = 1.0 kg/ dm^3
        - 12 kg water per m^3 mixture
    - Velocity of pump is 600 l/m
    - The diameter of the grout column is 1.5 meter, so the surface of the grout column is equal to $\pi*0.75^2$. The total amount of l per m^3 is then 600/ $(\pi*0.75^2)$ = 340 l/m^3. This value is rounded to 350 l/m^3. So a total of 350,000 litre mixture is used for the treatment of 1000 m^3 soil.
    - Per litre mixture 0,2 kg cement, 0,04 kg bentonite and 0,012 kg water is used. So the total amounts of raw materials are 70,000 kg cement, 14,000 kg bentonite and 320,000 kg water.
- For the energy usage for jet grout it is assumed that the pump is the most important material because the pump of jet grout needs to be a pump with much more capacity. Other material is available at both reaction sites. For the energy calculation of jet grout, information from Volker and Staal Funderingen is used:
    - Total volume jet grout: 350,000 litre
    - Pump with capacity of 400 kW and 500 litre/min
    - 350,000/500 = 700 min = 12 hours
    - Thus total energy usage = 12 * 400 = 5,000 kWh
- The complete volume (1000 m^3) is covered with jet grout columns. In practice, it is likely that the columns will only be needed in the middle of the trajectory or that columns will overlap.

5.3 Data

Table 5.1 shows the amount of raw materials needed for jet grouting 1000 m^3 soil. The values are based on a case of Visser & Smit Bouw (Jetgrouten, d*e verademing te Den Haag)*. It is assumed that 350 l mixture per m^3 is used and that 1000 m^3 soil will be completely covered with jet grout columns. Information about the transport process of jet grout is shown in. It is assumed that the pumps of jet grout and gel injection have the most impact on the energy costs.

Strength [MPa]	**Cement CEMIII [kg]**	**Water [kg]**	**Bentonite [kg]**
1300	70.000	320.000	14.000

Table 5.1 Amounts of raw material necessary for jet grouting 1000 m^3 soil

Raw material	**Location**	**Kind of transport**
Cement	Luik	Truck 40 ton
Bentonite	IJmuiden	Truck 40 ton

Table 5.2 Locations and transport of raw materials for jet grouting

Material	**Energy usage**	**Specification**
Mixing machine	-	3000 rpm
High Pressure Pump	400 kW	P = max 600 bar Q = max 500 l/min
Drill	-	7/14 rpm

Table 5.3 Equipment and energy usage for production of jet grouting.

5.4 Input in SimaPro

The assembly part of jet grout is shown in Figure 5.3. Cement CEM III and bentonite are used. The processes that are included are the transport of the raw materials and the energy usage. The transport distance for cement from Luik to Gouda is 230 km, the amount of material is 70 ton. The distance for bentonite is 90 km from IJmuiden to Gouda and the amount is 14 ton. The energy usage is estimated at 5,000 kWh. This value is based on the energy usage of the injection pump.

Name: Jetgrout

Image

Status: Draft

Materials/Assemblies	Amount	Unit
Blast furnace slag cement, at plant/CH S	70000	kg
Bentonite, at mine/DE S	14000	kg
Water, decarbonised, at plant/RER S	320000	kg
(Insert line here)		

Processes	Amount	Unit	Distribution	SD^2 c
Transport, lorry >28t, fleet average/CH S	17000	tkm	Undefined	
Electricity, medium voltage, production NL, at grid/NL S	5000	kWh	Undefined	
Waste treatment cement-spoil	4040	kg	Undefined	

Figure 5.3 Assembly in SimaPro of jet grout

6 Gel injection

6.1 System and boundaries

Gel injection is also a method that uses grout injection to strengthen the soil. The grout mixture consists of sodium silicate, a hardener and water. Sodium silicates are combinations of an alkali metal oxide and silica. The general formula is represented as: $xSiO_2$: Na_2O, where x is the molar ratio (moles SiO_2/moles Na_2O). The hardener can be organic (e.g. monodur process, carboxylic acids and synthetic resin) or inorganic (sodium aluminate). By mixture of sodium silicate with the hardener, a polymerisation reaction will start. Depending on the type and percentage of hardener, a soft or more solid gel will be produced. After dispersion in the silicate solution, it slowly hydrolyses and after a predetermined time, this causes the liquid to "set" in the form of a white mass of silica gel.
Injected into the soil in liquid form, the grout's low viscosity allows it to penetrate into the spaces between the soil grains. It then solidifies in-situ, conferring on the ground formation the required permeability and cohesion stabilization [Lit. 9]. The flow diagram of gel injection is shown in Figure 6.1.

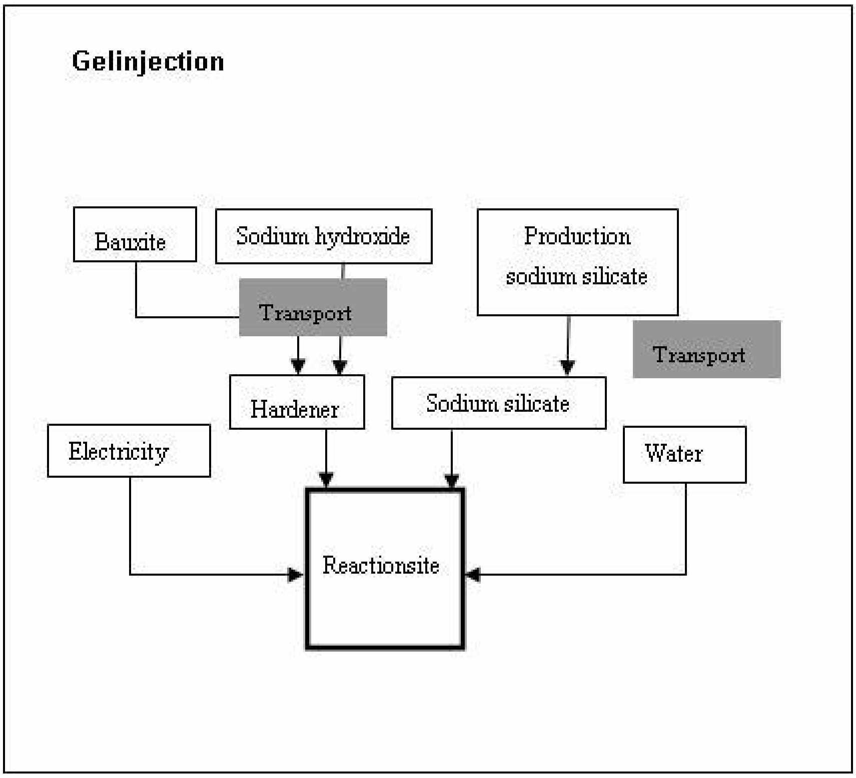


Figure 6.1 The flow diagram of the gel injection process

The production of raw materials, the energy usage at the production site and the transport of the raw materials to the reaction site are taken into account in the LCA. A removal step for gel injection is not included in the process because no by-product is produced with gel injection; the gel injection itself is inert, thus not harmful for the environment. The production of the equipment used at the reaction site, such as an injection pump, is not included.
The boundary between the product system and other product systems is clear. The system only has one function and the raw materials will be bought from companies that only produce

these materials. Due to no production of by-product, no waste treatment process is included in the LCA.

6.2 Assumptions

The following assumptions are used in the LCA for gel injection:

- The produced gel in the soil is inert and has therefore no environmental impact.
- The values of the raw materials of gel injection are based on an offer (see below) and [Lit. 10]. The offer describes the treatment of 133 m^3 soil and is made by Groen & Bregman Bouw B.V. The offer indicates that 400 l mixture per m^3 is used. From [Lit. 10] can be derived that a typical composition of a hard gel is:
  - 64 volume % sodium silicate
  - 20 volume % water
  - 16 volume % hardener

  Furthermore, it is assumed that the hardener is sodium aluminate ($NaAlO_2$). Sodium aluminate is not included in one of the SimaPro libraries and thus sodium hydroxide (NaOH) and bauxite (the raw materials of sodium aluminate) are included in the calculations. It is assumed that 2 tons of bauxite are needed for 1 ton aluminium oxide (Al_2O_3) and that the following reaction occurs:

  $$Al_2O_3 + NaOH \rightarrow NaAlO_2 + 2H_2O$$

  The density of sodium silicate and sodium aluminate are respectively 1.38 kg/dm^3 and 1,5 kg/dm^3. This leads to the total amount of 350,000 kg sodium silicate and 96,000 kg hardener. The amount of hardener can be converted to 1200 kmol and at this way; the amounts of aluminium oxide and sodium hydroxide can be calculated at 120,000 kg and 50,000 kg. The necessary amount of bauxite is thus 240,000 kg.
- No energy values are included in the production of sodium aluminate from sodium hydroxide and bauxite.
- For the energy usage for gel injection, it is assumed that the pump is the most important equipment because the pump needs to be a pump with much more capacity. Other material is available at both reaction sites. For the energy calculation of gel injection, information from Volker and Staal Funderingen is used:
  - Total volume gel injection: 400,000 litre
  - Pump with capacity of 4 kW and 25 litre/min
  - 400,000/25 = 16,000 min = 270 hours
  - Thus total energy usage = 270 * 4 = 1,000 kWh

6.3 Data

In Table 6.1 to Table 6.3 the data is shown for the gel injection process. The volume percentages of the raw materials are based on [Lit. 10]. The expected strength for this type of hardgel is between 1000 and1500 kPa. No methylesters are included in the databases of SimaPro. Therefore, sodium aluminate as hardener is used. Sodium aluminate is made from sodium hydroxide and bauxite, two materials that are defined in the ecoinvent database.

	Sodium silicate	Sodium aluminate	Water
Volume percentage	64	16	20
Amount [l]	256.000	64.000	80.000
Amount [kg]	350.000	96.000	80.000

Table 6.1 Amount of raw materials necessary for gel injection process of 1000 m^3 soil.

Raw material	Location	Kind of transport
Sodium silicate	Eijsden	Truck 40 ton
Sodium aluminate	Munchen	Truck 40 ton

Table 6.2 Locations and transport of raw materials for gel injection.

Equipment	Energy usage	Specification
Mixing machine	--	--
Injection pump	4 kW	P = max 70 bar Q = max 25 l/min

Table 6.3 Equipment and energy usage for production of gel injection.

6.4 Input in SimaPro

The assembly phase of gel injection is shown in

Figure 6.2, the production of hardener, and the assembly for the gel injection Figure 6.3.

Name: Production 96000kg Hardener

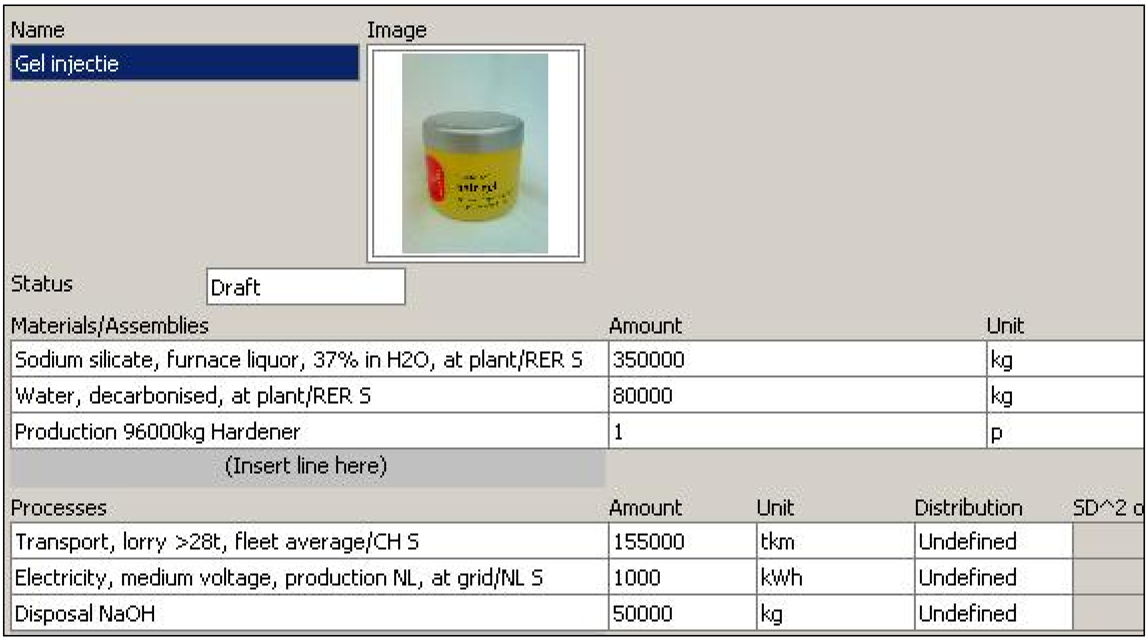
Image

Status:

Materials/Assemblies	Amount	Unit
Bauxite, at mine/GLO S	240000	kg
Sodium hydroxide, 50% in H2O, production mix, at plant/RER	50000*2 = 1E5	kg

Figure 6.2 Assembly of the production of 96,000 kg hardener for gel injection process.

For the production of hardener, energy-use and transport are not included.



Name: Gel injectie

Image

Status: Draft

Materials/Assemblies	Amount	Unit
Sodium silicate, furnace liquor, 37% in H2O, at plant/RER S	350000	kg
Water, decarbonised, at plant/RER S	80000	kg
Production 96000kg Hardener	1	p
(Insert line here)		

Processes	Amount	Unit	Distribution	SD^2 o
Transport, lorry >28t, fleet average/CH S	155000	tkm	Undefined	
Electricity, medium voltage, production NL, at grid/NL S	1000	kWh	Undefined	
Disposal NaOH	50000	kg	Undefined	

Figure 6.3 Assembly in SimaPro of gel injection

The processes that are included are transport of the raw materials and the energy usage. The distance from Eijsden to Gouda is 220 km, from Munchen to Gouda 820 km. The amount of hardener that needs to be transported is 96,000 kg. The amount of sodium silicate that needs to be transported from Eijsden is 350,000 kg. This leads to a total of 155,000 tkm. The energy usage is estimated at 1,000 kWh. This value is only based on the energy usage of the injection pump. As in the jet grout case, it is chosen to use the mixed electricity value of the Netherlands.

7 Method description

7.1 General

SimaPro contains different methods for evaluation of the impact (Appendix 3). The basis structure of impact assessment methods in SimaPro consist of characterization, damage assessment, normalization, weighting, which are described below. According to ISO standards (ISO 14040), the last three steps are optional. That is the reason why these steps are not available in all methods.
Damage assessment is the grouping of a number of impact category indicators into damage categories. A necessary condition is that the impact categories have the same unit to be able to add the different categories. The damage assessment step is included in eco indicator 99 and EPS 2000. The CML method does not include normalization and weighting. However, it is interesting to look at these aspects. That is why impact method Eco-Indicator 99 is chosen in SimaPro.

7.1.1 Eco-indicator 99

The results from the LCA are obtained with the impact assessment method Eco-indicator 99 (Guinee, 2004). The Eco-indicator 99 is both a science based impact assessment method for LCA and a pragmatic ecodesign method. It offers a way to measure various environmental impacts, and shows a result in a single score. The Eco-indicator 99 is a state of the art impact assessment method for LCA, with many conceptual breakthroughs. The method is also the basis for the calculation of eco-indicator scores for materials and processes. These scores can be used as a user-friendly design for environment tool for designers and product managers to improve products. The impact assessment method is now widely used by life cycle assessment practitioners around the world. The methodology is highly compatible with ISO 14042 requirements.

The following characteristics and constraints should be kept in mind when the Eco-indicator 99 method is applied in a LCA:

- All emissions and all forms of land-use are assumed to occur within Europe. The damages for most impact categories are also assumed to occur in Europe, with the following exceptions:
  - The damages from ozone layer depletion and greenhouse effects are occurring on a global scale, as European emissions are influencing the global problem and not just the European.
  - The damages from some radioactive substances are also occurring on a global scale.
  - The damages to Resources are occurring on a global scale.
  - The damages from some persistent carcinogenic substances are also modelled in regions adjoining Europe.
- The method models emissions as if they are emitted at the present time.
- The method is based on a specific definition, for instance definitions that include human welfare or the preservation of cultural heritages, the methodology is not complete or valid.
- There are special rules for modelling the effect of land use, pesticides and fertilizers.

- The results of the damage models must be seen as marginal results, they reflect the increase of the damage when one functional unit is added to the occurring damage level. In addition, the normalisation levels are based on the marginal method.

7.2 General Framework

With LCA, there are three fields of scientific knowledge and reasoning:

2 Technosphere, the description of the life cycle, the emissions from processes, the allocation procedures as far as that are based on causal relations.
3 Ecosphere, the modelling of changes (damages) that are inflicted on the "environment".
4 Valuesphere: the modelling on the perceived seriousness of such changes (damages) as well as the management of modelling choices that are made in Techno- and Ecosphere.

These spheres are partially overlapping, but they have different characters. With these three spheres, the basic three-stage approach is constructed:

- The life cycle model is constructed in Technosphere→ result the inventory table
- Ecosphere modelling is used to link the inventory table to three damage categories.
- Valuesphere modelling is used to weight the three endpoints to a single indicator, and to model the value choices in the Ecosphere.

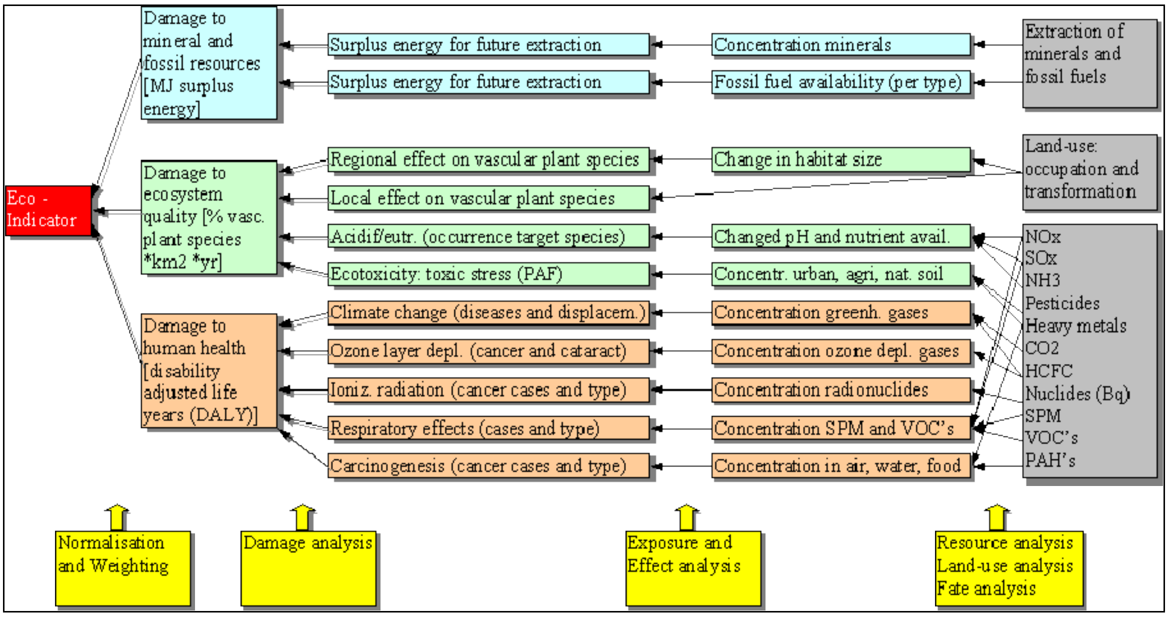


Figure 7.1 General representation of the methodology

In Figure 7.1, the yellow boxes refer to procedures; the other boxes refer to (intermediate) results.

Of course, it is very important to pay attention to the uncertainties in the methodology that is used to calculate the indicators. We distinguish two types:

1 Uncertainties about the correctness of the models used
2 Data uncertainties

The first type of uncertainties include value choices like the choice of the time horizon in the damage model, or the question whether we should include an effect even if the scientific proof that the effect exists is incomplete. The data uncertainties refer to difficulties in measuring or predicting effects. This type of uncertainties is relatively easy to handle and can be expressed as a range or a standard deviation. Uncertainties about the correctness of the model are very difficult to express as a range. To make some general perspectives, three “Archetypes’ have been created, three versions of the damage models which are based on the different perspectives of three groups of persons. This subdivision is based on the Cultural Theory [Lit. 11].
A simplified characterisation, using just three criteria of these versions is shown in the table below.

Archetype	Time perspective	Manageability	Required level of evidence
H (Hierarchist)	Balance between short and long term	Proper policy can avoid many problems	Inclusion based on consensus
I (Individualist)	Short term	Technology can avoid may problems	Only proven effects
E (Egalitarian)	Very long term	Problems can lead to catastrophes	All possible effects

Table 7.1 LCA Archetypes for perspective

In the individualist version, only proven cause-effect relations are included. In the hierarchical version, facts that are backed up by scientific and political bodies with sufficient recognition are included. The hierarchical attitude is rather common in the scientific community and among policy makers. A precautionary principle is used in the egalitarian version. It is tried to leave nothing out and if in doubt, it is included. This version is the most comprehensive version. However, it also has the largest data uncertainties.
The concept of the Cultural Theory is also applied on the weighting phase. In order to analyze the influence of the perspectives, a number of respondents were asked questions about how to weight the damage models and standard questions that should reveal their perspective. Although the sample size was rather small, statistical significant differences were found between the weights given by respondents and perspective they seemed to adhere to.

The main results of this report are obtained with the hierarchical version and the average weighting factors (H/A). The hierarchical version is used as the default method because this is recommended by the makers of Eco-indicator 99. The reason for this is that most models are implicitly or explicitly based on the hierarchical perspective. The other two perspectives can be used as a sensitivity analysis. Because only small sampling sizes were used to come to the different weighting models, it is recommended to use the averaged weighting factors.

The results of the Eco indicator method are given in Eco-indicatorpoints (Pts). The absolute value of an Eco indicator point is 1 thousandth of the annual environmental impacts of an averaged European.

7.3 Damage categories

In the Eco-indicator 99 the following definition for the term “environment” is used :

A set of biological, physical and chemical parameters influenced by man that are conditions to the functioning of man and nature. These conditions include Human Health, Ecosystem Quality and sufficient supply of Resources.

From this definition, it follows that there are three damage categories:

- Human Health, contains the idea that all human beings, in present and future, should be free from environmentally transmitted illnesses, disabilities or premature deaths;
- Ecosystem Quality, contains the idea that non-human species should not suffer from disruptive changes of their populations and geographical distribution;
- Resources, contains the idea that the nature’s supply of non-living goods, which are essential to the human society, should be available also for future generations.

It is possible to select other damage categories, such as material welfare, happiness, equality, safety etc. However, these are very complex to define or model, because in general products can have an intended positive effect as well as a negative (environmental effect).

7.3.1 Damage category Human Health

The health of any human individual, being a member of the present or a future generation, may be damaged either by reducing its duration of life by a premature death, or by causing a temporary permanent reduction of body functions. The environmental sources for such damages are mainly:

- infectious diseases, respiratory disease, forced displacement (climate change),
- cancer (ionising radiation)
- Cancer and eye damage (ozone layer depletion)
- respiratory diseases and cancer (toxic chemicals in air, drinking water and food)

The unit for the damage category Human Health is DALY (disability-adjusted life years).

7.3.2 Damage category Ecosystem Quality

Important difference with Human Health is that we are not concerned with the individual organism, plan or animal. The species diversity is used as an indicator for Ecosystem Quality: percentage of species that are threatened or that disappear from a given area during a certain time.

- Ecotoxicity: PAF (Potentially Affected Fraction) of species in relation to the concentration of toxic substances. This focuses on terrestrial and aquatic organisms.
- Acidification and eutrophication: for acidification NO_x, SO_x and NH_3 deposition effects and for eutrophication nutrients are nitrogen (N) and phosphors (P). It is not possible to determine whether damage was caused by nutrients or acidity, therefore these are combined. The basis is: targeted species that should occur on

a specific type of ecosystem if there would have been no man-made changes in the nutrient level or the acidity.

- Land use: This category covers the consequences of human land use. A distinction can be made between different kinds of land use. Land competition describes the use of land in terms of being temporarily unavailable. Function and the loss of biodiversity belong to the second group of impact categories. The loss of life support covers the problems of the effect on life support function resulting from interventions, such as the destruction or alteration of land. The loss of biodiversity describes the effects on biodiversity resulting from interventions such as the use of biotic resources or the destruction of land. Four different models are needed:
  - Local effect of land occupation
  - Local effect of land conversion
  - Regional effect of land occupation
  - Regional effect of land conversion

7.3.3 Damage category Resources

Only mineral resources and fossil fuels are modelled. The use of agricultural and silvicultural biotic resources and the mining of resources such as sand and gravel, are considered to be adequately covered by the effects on land use.
Eco-indicator 99 does not consider the quantity of resources as such, but rather the qualitative structure if resources, thus the concentration of a resource as the main element of resource quality.

7.3.4 Used impact categories for the assessments

Acidification
Impacts of acidifying pollutants can have impacts on soil, groundwater, surface waters, biological organisms, ecosystems and materials. SO_2, NO_x and NH_x are the most abundant acidifying pollutants.

Carcinogens
This category covers the effect of emissions of carcinogenic substances to air, water and soil.

Climate change (Greenhouse)
Climate change is defined as the effect of human emissions on the heat radiation absorption of the atmosphere. Most of these emissions enhance the absorption, causing the temperature at the earth's surface to rise. This is commonly known as the 'greenhouse effect'. The most abundant naturally occurring greenhouse gas is water vapor, followed by carbon dioxide, methane and nitrous oxide. Human-made chemicals that act as greenhouse gasses include chlorofluorocarbons (CFCs), hydrochloroflurocarbons (HCFs) and hydrofluorocarbons (HFCs) (www.encarta.com).

Ecotoxicity
The ecotoxicity describes the impacts of toxic substances on ecosystems. Ecosystems can be divided into three sub categories; aquatic, terrestrial and sediment ecosystems. There is also a separation between freshwater aquatic ecotoxicity and marine aquatic ecotoxicity and between freshwater sediment ecotoxicity and marine sediment ecotoxicity. *Soil chronic/acute*

Eutrophication
Eutrophication covers all impacts of excessively high environmental levels of macronutrients. The most important nutrients are nitrogen (N) and phosphors (P). The problem of nutrient enrichment is that it may cause a shift in species composition, which is undesirable. Furthermore, it can elevate biomass production in both aquatic and terrestrial ecosystems and high nutrient concentrations can make surface waters unacceptable as a source of drinking water.

Land use
This category covers the consequences of human land use. A distinction can be made between different kinds of land use. Land competition describes the use of land in terms of being temporarily unavailable. Function and the loss of biodiversity belong to the second group of impact categories. The loss of life support covers the problems of the effect on life support function resulting from interventions, such as the destruction or alteration of land. The loss of biodiversity describes the effects on biodiversity resulting from interventions such as the use of biotic resources or the destruction of land.

Ozone depletion
Stratospheric ozone depletion refers to the thinning of the stratospheric ozone layer as a result of human caused emissions. The ozone layer protects life on earth from ultraviolet radiation. Human activity has caused the ozone layer to break down by releasing pollutants into the earth's atmosphere leading to the so-called 'hole' in the ozone layer. Halogens in the atmosphere, also known as CFCs, are responsible for much of the damage that has been done to the ozone layer.

Resources
The EDIP/UMIP resources only method only reports resources. Opposite to the default method, resources are given in individual impact categories.

Respiratory organics
Respiratory effects resulting from summer smog, due to emissions of organic substances to air are included in this category.

Respiratory inorganics
Respiratory effects resulting from winter smog, due to emissions of dust, sulphur and nitrogen oxides to air.

8 Results

This chapter shows the results that are obtained with SimaPro 7.1.8, with the impact assessment method Eco-indicator 99. First, the single score for the four ground improvement methods are shown. Then a comparison is made between the methods. The results are absolute results, and the shown red arrows are relative results for each different LCA. The interpretation phase displays the results of the consistency and completeness check and the contribution and sensitive analysis, for each method. No perturbation and uncertainty analysis are included because no adequate software is available. Furthermore, it is assumed that it is not necessary to perform these checks in this first exploration of the environmental impacts of BioGrout.
The results shown are the processes at the moment now. In another chapter, possible changes in LCA, BioGrout first and second generation, will be shown.

8.1 Single score

8.1.1 BioGrout 1st generation

The network is shown with 100% wastewater treatment. The values left under in the boxes, are the absolute impact values. How thicker the red arrow, the higher the impact is of that process. The wastewater treatment induced the highest impact for the BioGrout first generation process.

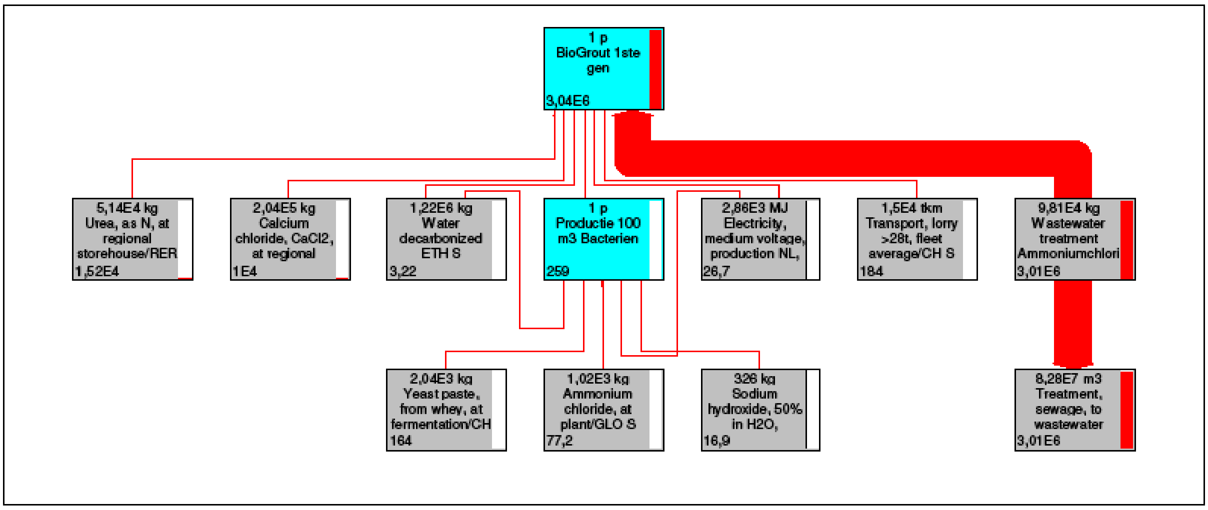


Figure 8.1 Network for BioGrout 1st gen., with 100% wastewater treatment ammonium chloride.

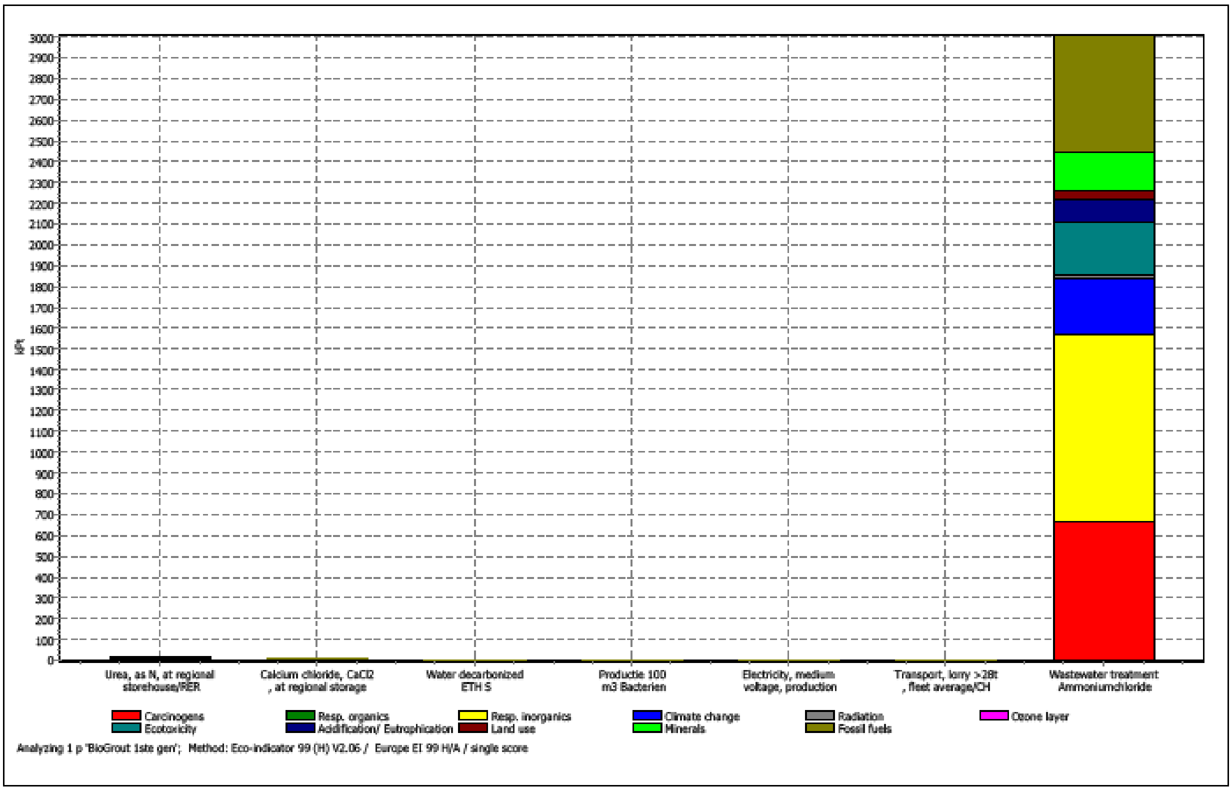


Figure 8.2 Single score for the BioGrout process 1st generation (Eco-indicator 99 H/A)

Figure 8.2 shows the impact for the different impact categories for the various processes of the BioGrout 1st generation process. The wastewater treatment has the highest impact, mainly in the category respiratory inorganics.

8.1.2 BioGrout 2nd generation

Figure 8.3 shows the network for BioGrout 2nd generation. The values left under in the boxes, are the absolute impact values. The red arrows are relative indicators, how thicker the red arrow, the higher the impact is of that process. The production of acetic acid has the highest impact for this process.

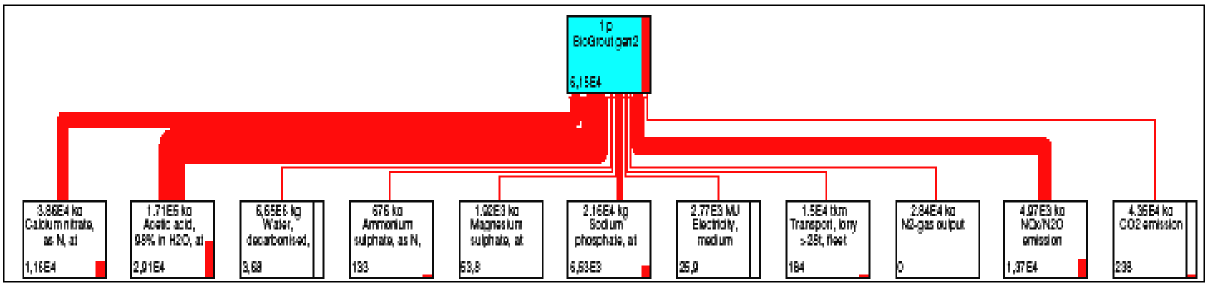


Figure 8.3 Network for BioGrout 2nd generation

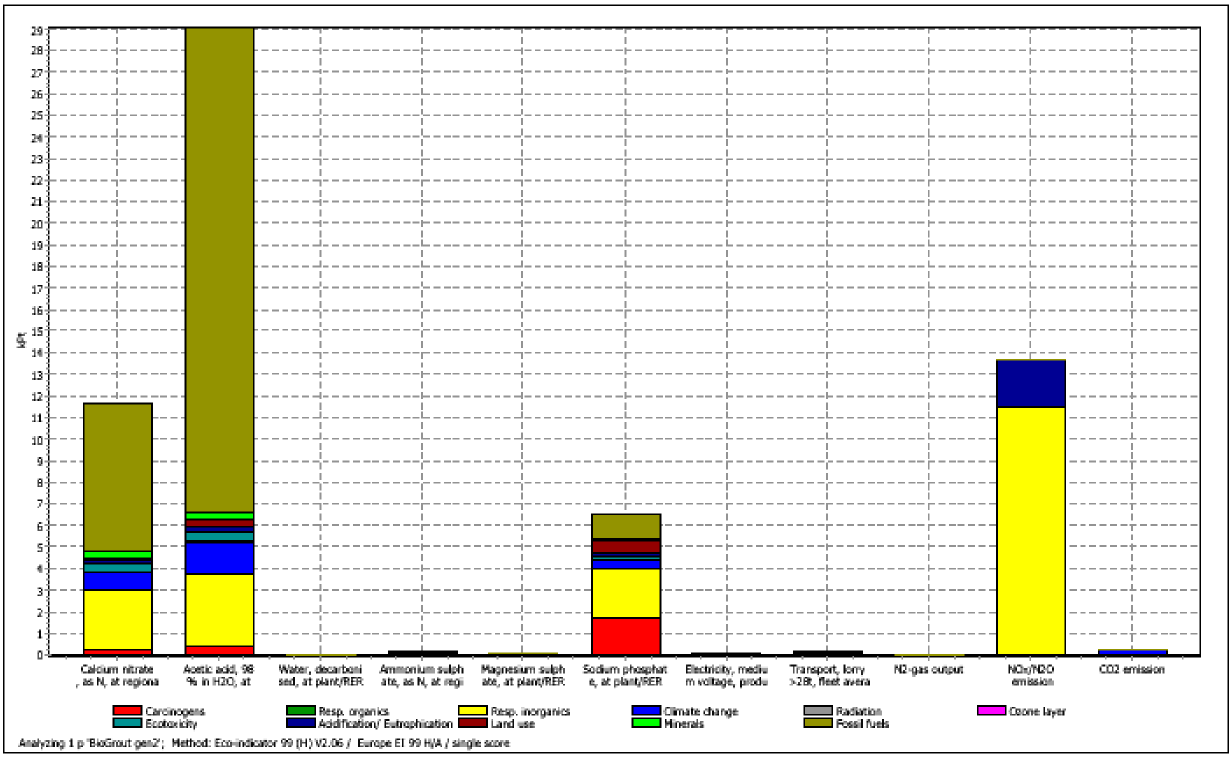


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Figure 8.4 Single score for the BioGrout process 2nd generation (Eco-indicator 99 H/A).

The single score figure (Fig. 8.4) shows the absolute environmental impacts for each process. The different impact categories are also indicated for each process. The main impact is caused by the production of acetic acid, with main impact on the fossil fuel use.

8.1.3 Jet Grouting

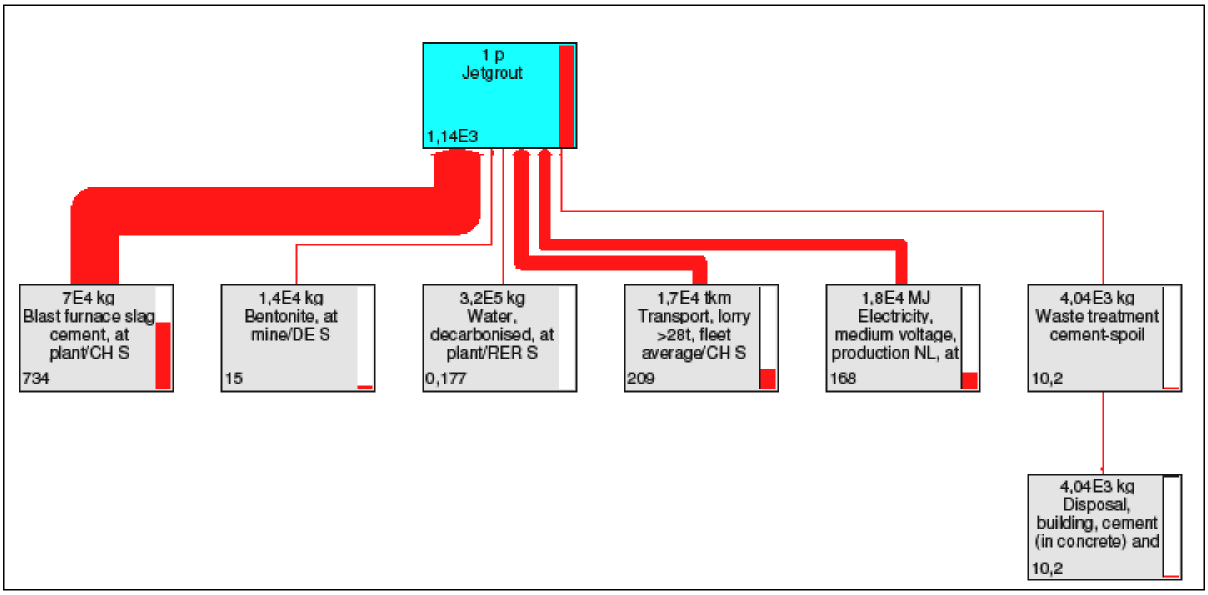

Figure 8.5 Network for jet grouting process

Figure 8.5 shows the network for the jet grout process. The values left under in the boxes are quantitative values for the environmental impact of each process. The red arrows show the relative amount of environmental impact for each process. The production of cement has the highest impact.

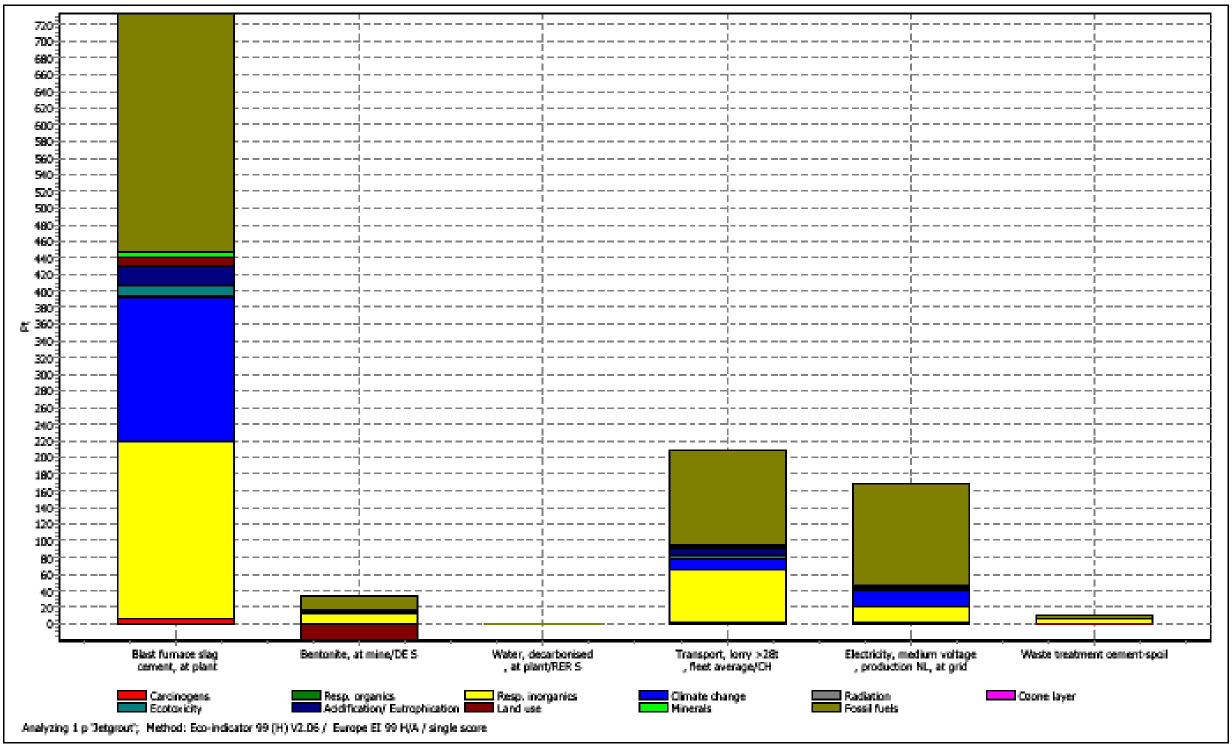

Figure 8.6 Single score for the Jet grout process (Eco-indicator 99 H/A).

Figure 8.6 shows the environmental impact for each process for jet grouting, including the impact categories. This figure shows that the production of cement has the highest impact for jet grouting, with the largest impact by the use of fossil fuels and respiratory inorganics as largest

8.1.4 Gel injection

Figure 8.7 shows the network for the gel injection. The values left under in the boxes are quantitative values for the environmental impact of each process. The red arrows show the relative amount of environmental impact for each process. The production of sodium silicate has the highest impact.

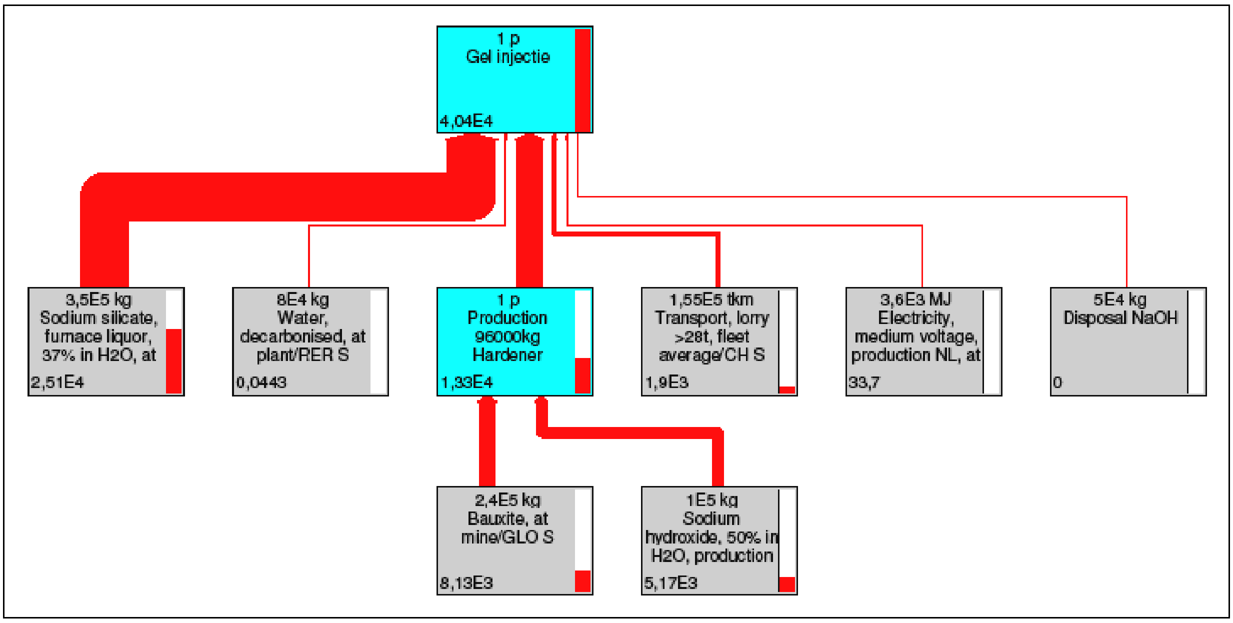

Figure 8.7 Network for gel injection process

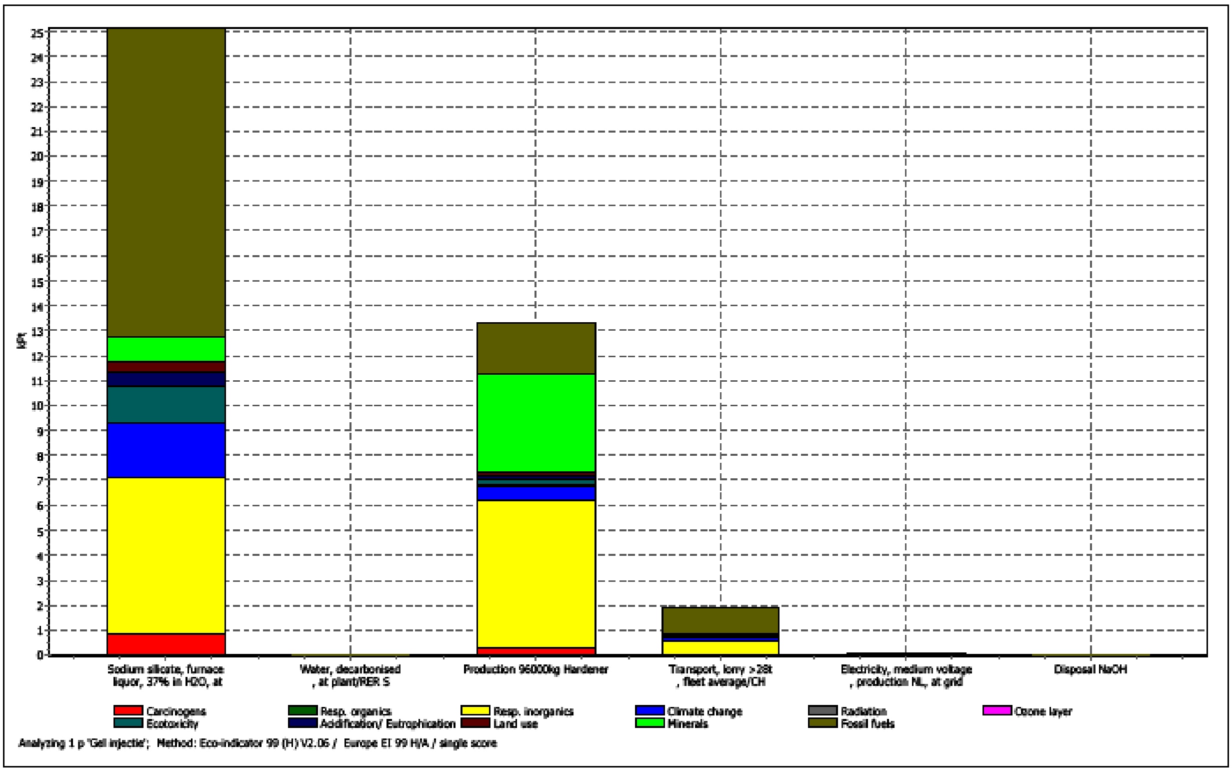

Figure 8.8   Single score for the gel injection process (Eco-indicator 99 H/A).

Figure 8.8 shows that the production of sodium silicate has the highest environmental impact, mainly caused by use of fossil fuels.

8.2 Comparison

One of the goals of this LCA is comparing the different methods with each other. In the following figures, the four different methods are compared with each other. The values are *absolute* impact values.

Figure 8.9 shows a comparison for the four methods after normalization and Figure 8.10 shows a comparison of the single scores.

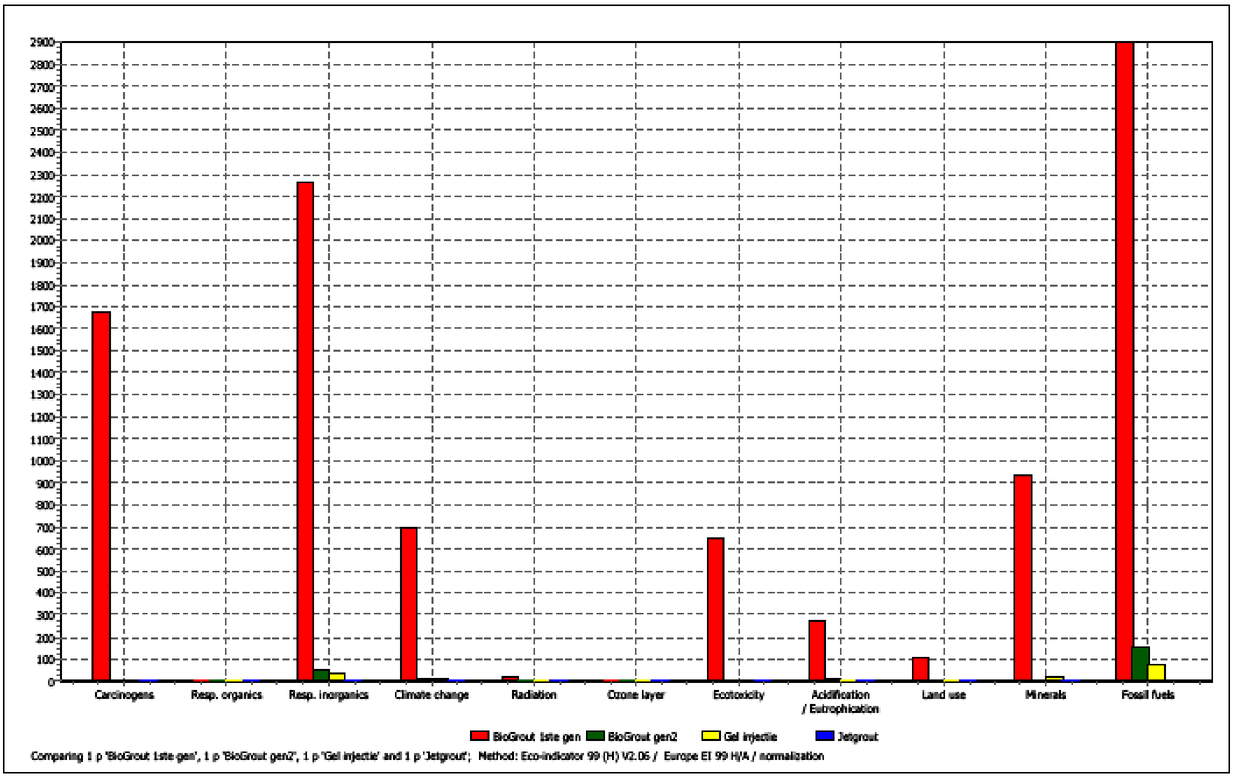

Figure 8.9 A comparison of BioGrout 1st and 2nd gen., gel injection and jet grout after normalization (Eco-indicator 99 H/A).

Figure 8.9 shows the absolute impacts for each impact category caused by the four different methods. In almost all categories, the BioGrout first generation process causes the highest environmental impact. The main caused impacts are the use of fossil fuels, production of respiratory inorganics and the production of carcinogens. No radiation, respiratory organics are produced and no damage of the ozone layer is caused by these four methods.

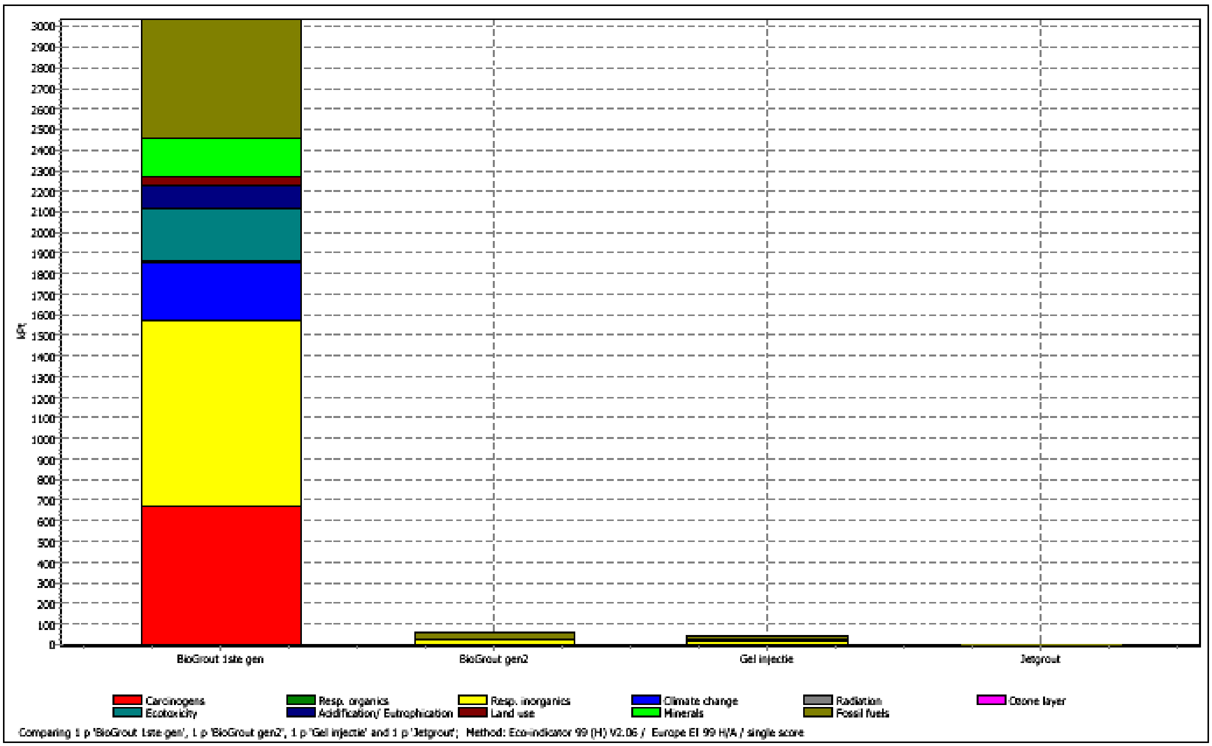

Figure 8.10 Comparison of single scores of BioGrout 1st and 2nd gen., gel injection and jet grout with (Eco-indicator 99 H/A).

Figure 8.10 shows the absolute amount of environmental impact caused by each ground improvement method. It shows that BioGrout first generation causes the highest environmental impact, followed by BioGrout 2nd generation and gel injection. Jetgrout hardly causes an environmental impact, when compared to BioGrout first generation.

8.3 Interpretation

8.3.1 Consistency check

Because a comparison is made, it is important to check for differences between data sources, data accuracy, technical level, temporal aspects, geographical representativeness and functions.

All used data is from the eco-invent database, however this does not mean that the data accuracy is also the same. Most processes include the consumption of raw materials, energy and infrastructure. There is some difference in the technical level because jet grout and gel injection are already used methods and the results of both BioGrout processes are primarily based on experiments. Almost all data is based on European processes and obtained between 1994 and 2000. Bauxite is based on worldwide processes. The functions of the products are the same, namely strengthening 1000 m3 with 1MPa soil. It should be noticed that there is one large difference between the traditional techniques and the BioGrout methods. BioGrout is inserted *in situ*, meaning that it hardly disturbs the soil, in contrast with jet grout and gel injection. This is not taken into account in the LCA, because this is (not yet) a standard procedure in the LCA process.

8.3.2 Completeness check

The goal of this LCA is not to be as complete as possible, but to give a first overview of the impacts on the environment of BioGrout first and second generation compared with each other and with jet grout and gel injection. Therefore, a detailed completeness check is not necessary in this report. In the following years the LCA's, mainly for both BioGrout processes, will be adjusted to the state of the process.

However, to be sure that no wrong assumptions or conclusions are made with these LCA's, experts from Pre-Consults have reviewed this report. Therefore, it is assumed that no important things are forgotten and that this limited completeness check is good enough for this study.

8.3.3 Contribution analysis

Table 8.1 shows information about the contribution of the specific processes to the total environmental score. It is interesting to look in more detail to the main contributors of the environmental impacts, so to urea, acetic acid, cement and sodium silicate (Table 8.2). These percentages are relative for each process, thus cannot be compared with each other.

Method	**Process**	**Percentage of score after normalization and weighting**
BioGrout 1st generation	Urea production	0.5
	Calcium chloride production	0.32
	Production Bacteria	0.1
	Transport	0.1
	Water	0
	Electricity	0
	Waste treatment	**99**
BioGrout 2nd generation	Ca-nitrate	19
	Acetic acid	**47**
	Water	0
	Nutrients	0.3
	Sodium phosphate	11
	Electricity	0
	Transport	0.3
	NO_x emission	23
	CO_2 emission	0.4
	N_2 emission	0
Jet grout	**Cement production**	**61**
	Transport	22
	Electricity	14
	Bentonite production	3
	Water	0
Gel injection	**Sodium silicate production**	**62**
	Production Hardener	33
	Transport	5
	Electricity	0
	Water	0

Table 8.1 The contributions of the different processes to the total amount of environmental impacts for the four soil strengthen methods.

Method	Main contributor	Impact category	Percentage all impact categories
BioGrout 1st generation	Waste treatment Ammonium chloride	Respiratory inorganics Fossil Fuels Carcinogens	30 18 22
BioGrout 2nd generation	Acetic acid	Fossil Fuels Resp. inorganics Carcinogens	78 10 2
Jet grout	Cement	Fossil fuels Respiratory inorganics Climate change	40 29 23
Gel injection	Sodium Silicate	Fossil fuels Respiratory inorganics Climate change	49 25 9

Table 8.2 Specification of the largest three impact categories of the main contributors to the environmental impact for the four methods.

Table 8.3 shows percentage of the main contributor compared with all four methods. The waste treatment of ammonium chloride is the largest contributor to the environment. 97% of the total impact for all four methods is caused by the treatment of ammonium chloride.

Method	Contributor	Absolute amount	Relative amount (%)
BioGrout 1st gen.	Waste treatment	3.01 E6	97
BioGrout 2nd gen.	Acetic acid NO_x	2.90E4 1.37E4	0.94 0.44
Jet grout	Cement	7.34E2	0.02
Gel injection	Sodium silicate Production hardener	2.51E4 1.33E4	0.81 0.43

Table 8.3 The relative impact for each main contributor for the four different methods.

9 Future perspectives

The two BioGrout processes are still in development; therefore using the results of the LCA's it is possible to focus research on the different steps of the process, to improve the environmental impact of the methods.
In this chapter, LCA's are altered by changing the impact of the main contributors.

9.1 BioGrout first generation

The main contributor to the environmental impact is the waste treatment of ammonium chloride. There are possibilities that ammonium chloride can be recycled as nutrient for algae growth, fertilizer, or to converted to urea. A PhD student at the Murdoch University is investigating at the moment the possibilities to convert ammonium chloride back to urea.
Two extra LCA's are made, with different assumption:

1. 100% recycling of the ammonium chloride, where recycling has no impact on the environment.
2. 5% waste water treatment and 95% recycling.

The results of these LCA's are shown in the following figures.

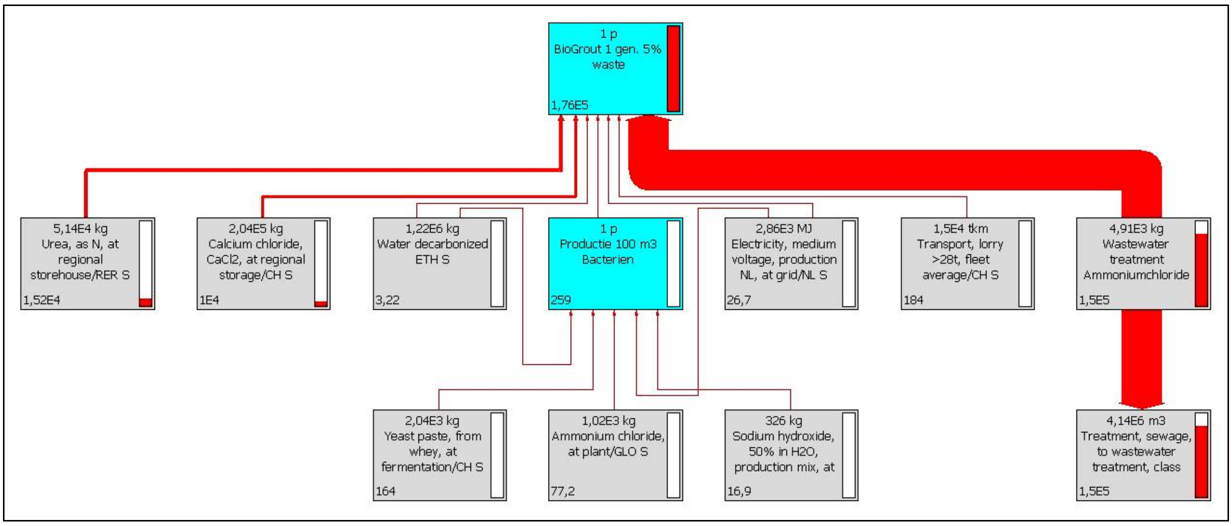

Figure 9.1 Network for BioGrout first generation, with 5% waste treatment.

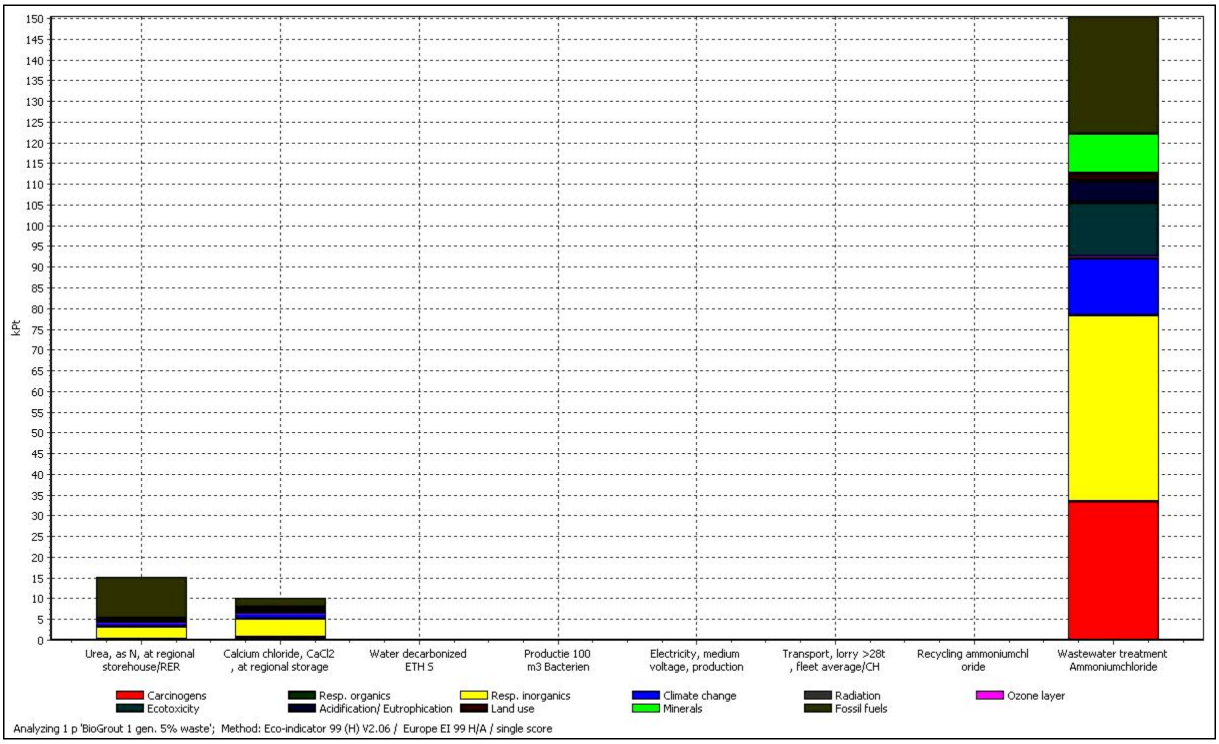

Figure 9.2 Single score of the LCA for BioGrout first generation with 5% waste treatment

Figures 9.1 and 9.2 show that at 95% recycling of the ammonium chloride, the waste water treatment still causes the highest impact

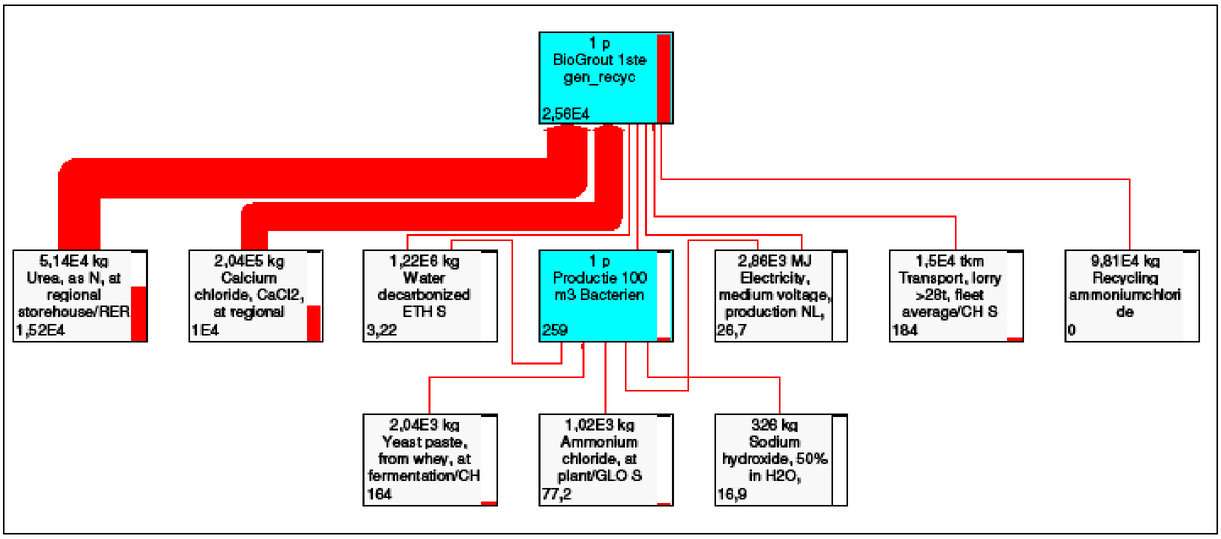

Figure 9.3 Network for BioGrout first generation, with 100% recycling

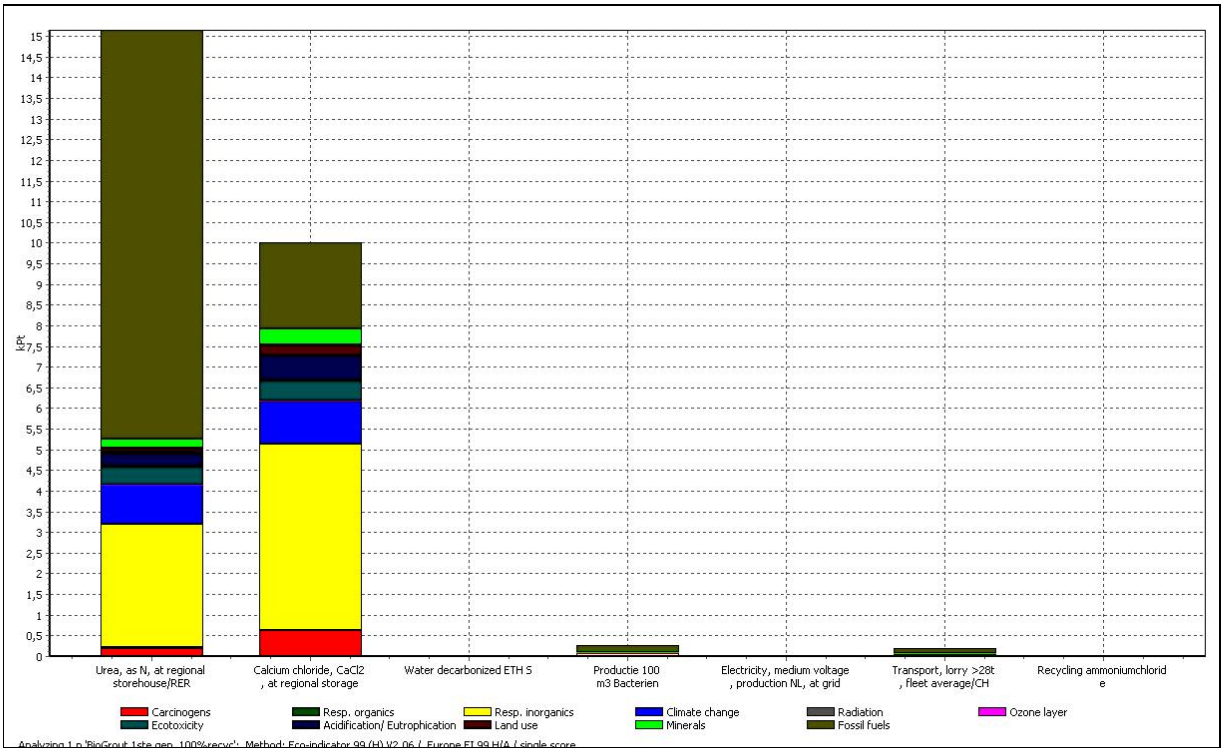

Figure 9.4 Single score for BioGrout first generation, with 100% recycling.

The LCA with 100% recycling is compared with the other three methods shown in Figure 9.5 and Figure 9.6.
When 100% of the ammonium chloride is recycled, other ground improvement methods become less favourable, looking at the environmental impact. For several impact categories Biogrout 2[nd] generation has the highest impact. Also gel injection becomes on some categories less favourable.

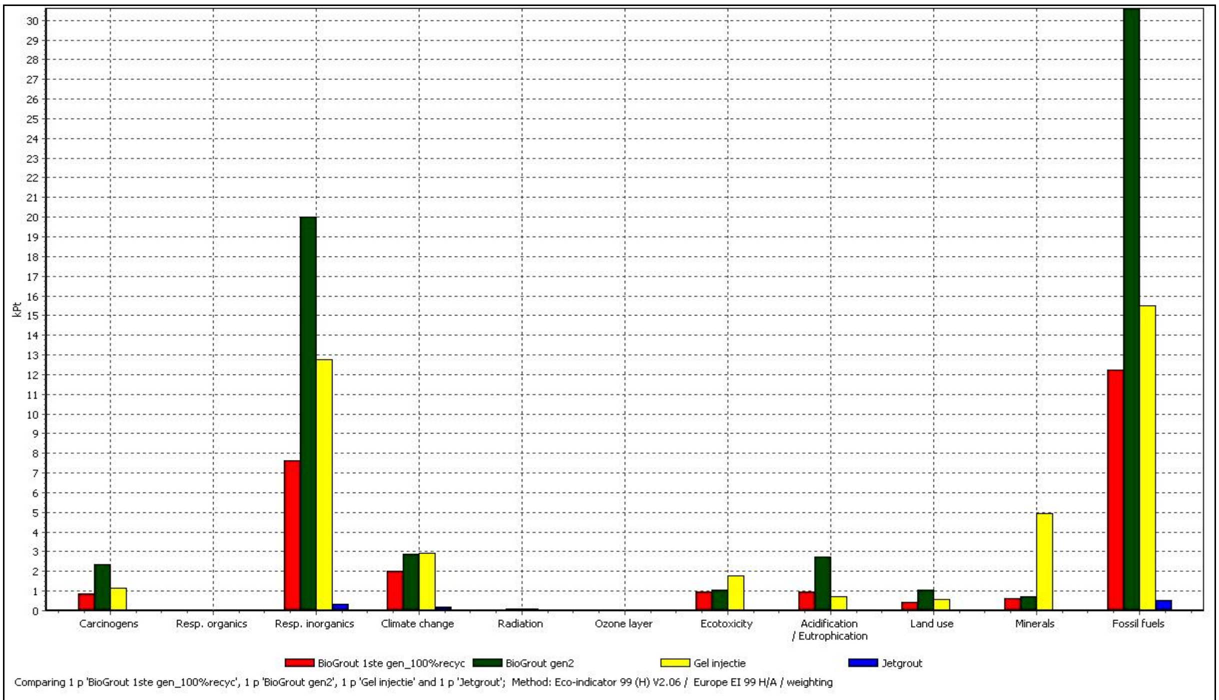

Figure 9.5 A comparison of BioGrout 1[st] gen. with 100% recycling, BioGrout 2[nd] gen., gel injection and jet grout after normalization (Eco-indicator 99 H/A).

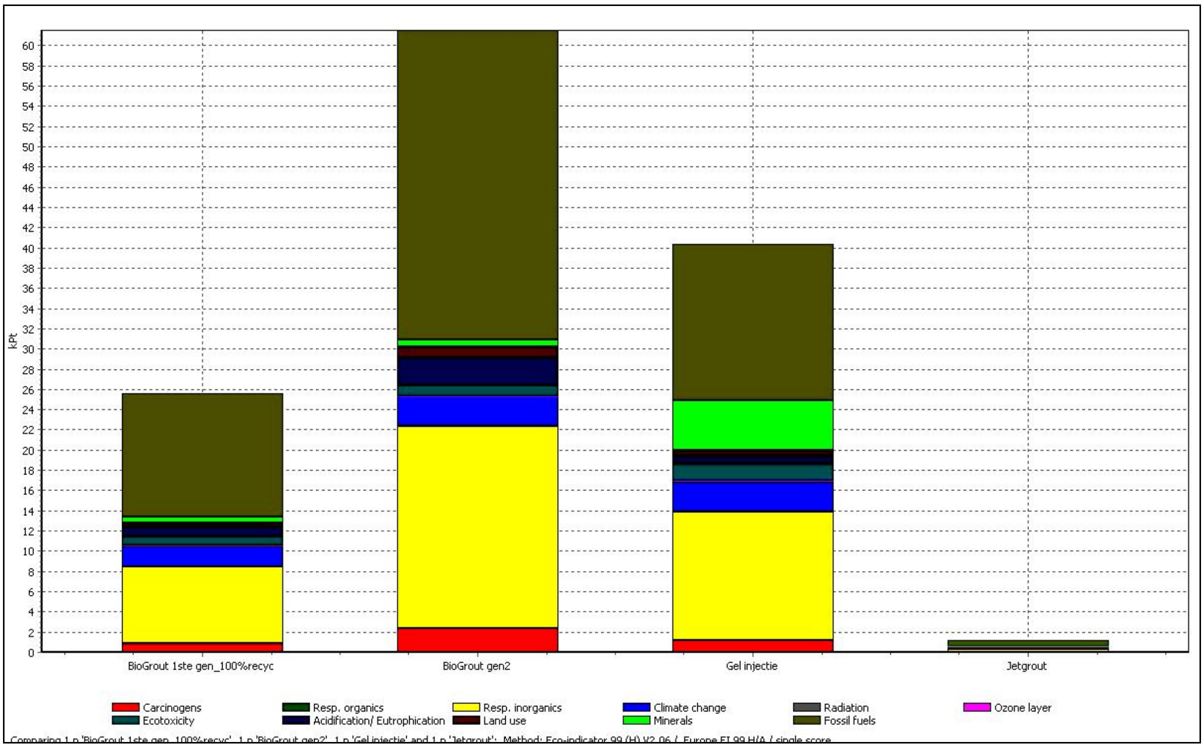

Figure 9.6 A comparison of single score BioGrout 1st gen. with 100% recycling, BioGrout 2nd gen., gel injection and jet grout after normalization (Eco-indicator 99 H/A).

9.2 BioGrout second generation

The largest environmental impact for BioGrout 2nd generation is caused by acetic acid and calcium nitrate. In the future, it is expected that wastewater is used from biological nitrification and biological acidification reactors. Thus, a nitrogen (N)-rich waste stream and a organic-waste stream is used in stead of pure products. For this situation no LCA is made, because there were no alternatives in the database that were sufficient for these two waste streams.

The efficiency of BioGrout 2nd generation is assumed 100%. Thus, the entire product that is inserted into the soil, will be converted into calcite. However, it the first lab results indicate that there is no 100% efficiency. A LCA is made with 10% efficiency, to determine what the effects are for a "worse" case scenario.
The results are compared with the other methods are shown in the following figures.

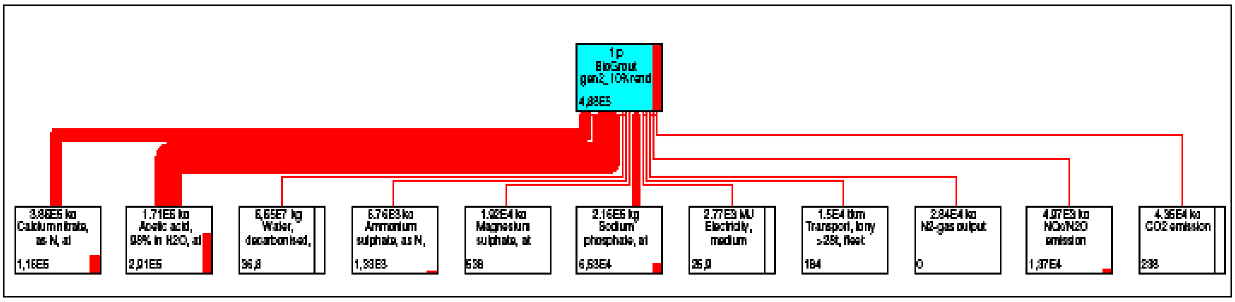

Figure 9.7 Network for BioGrout 2nd gen. with 10% efficiency

The network for Biogrout 2nd generation with 10% efficiency shows that the main contributors are the production of calcium nitrate and acetic acid. This is similar as with 100% efficiency.

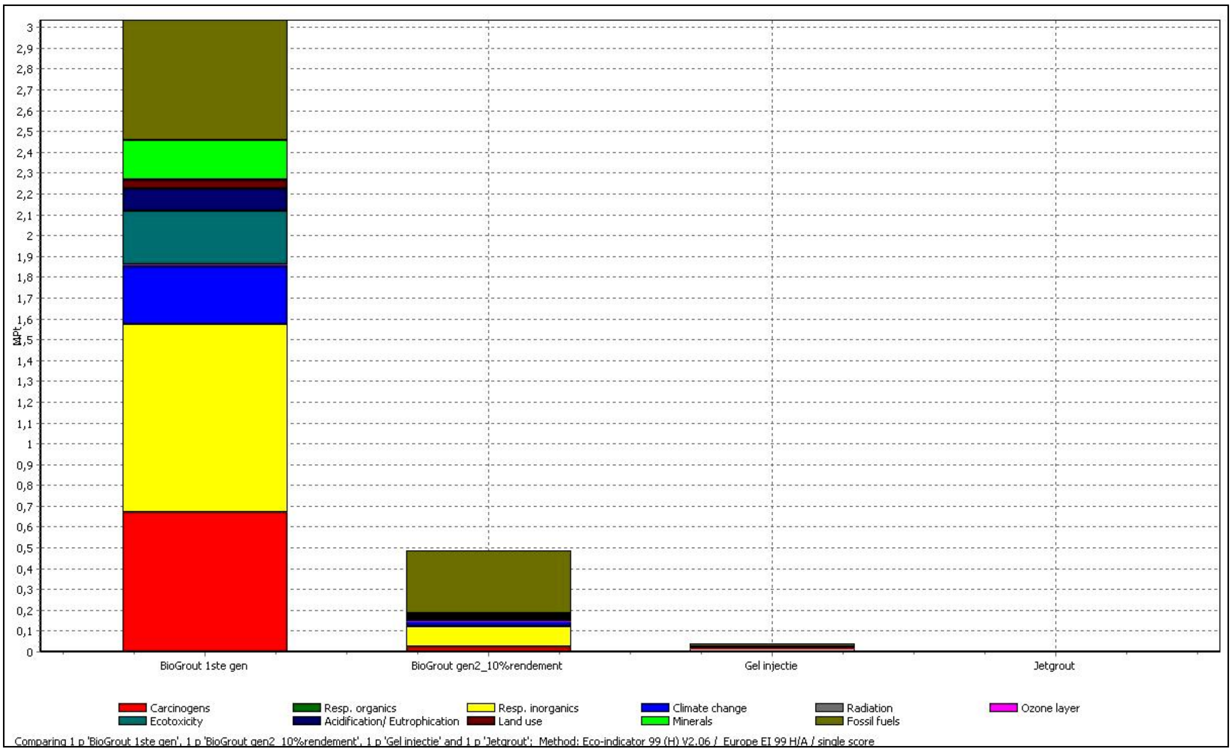

Figure 9.8 Single score for comparison for the 4 different methods, where BioGrout 2nd gen. has 10% efficiency.

With 10% efficiency for BioGrout 2nd generation, BioGrout 1st generation still causes the highest environmental impact. No large changes are shown with 10% efficiency in stead of 100% efficiency.

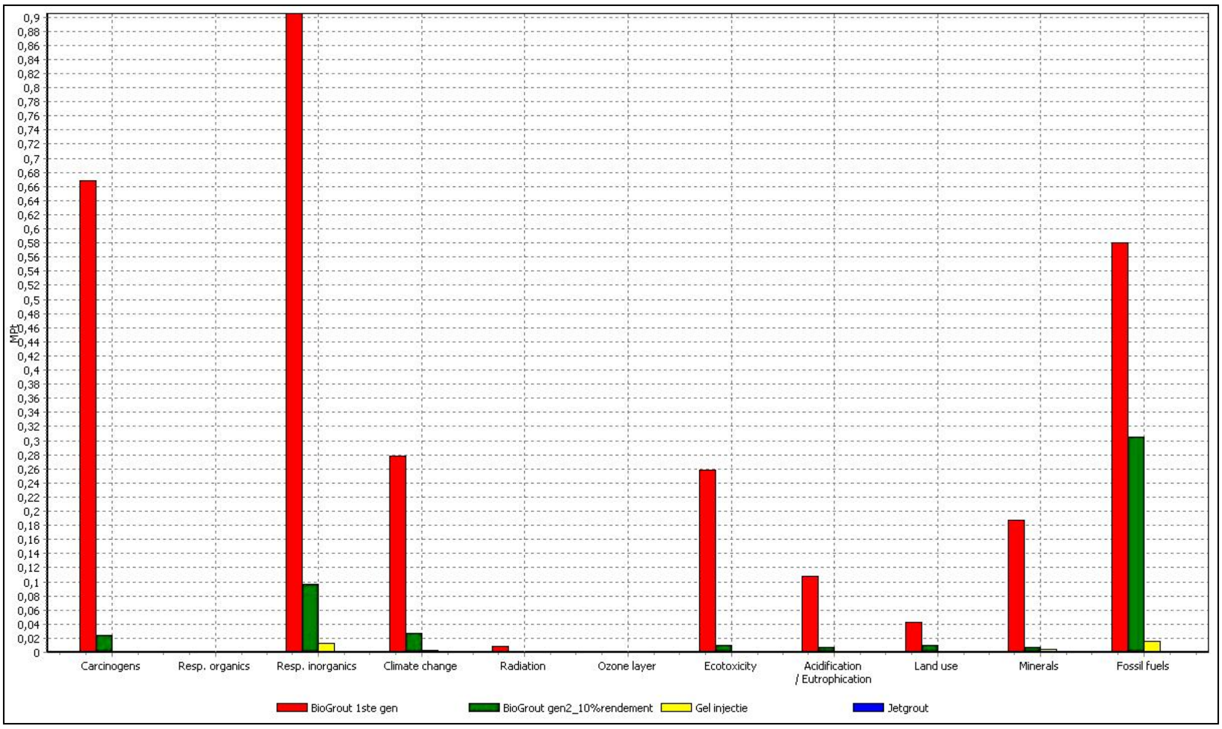

Figure 9.9 Comparison with weighting of the 4 different methods, with BioGrout 2nd gen. 10% efficiency.

10 Discussion

BioGrout 1st generation has the largest environmental impact, due to the treatment of ammonium chloride. There are possibilities that the ammonium chloride can be recycled. However, the recycling LCA for BioGrout 1st generation has shown that at 95% recycling, the ammonium chloride still causes the largest environmental impact. The impact of urea and calcium chloride start to increase, but do not exceed the impact of ammonium chloride. When 100% of the ammonium chloride is recycled, the urea and calcium chloride cause the highest impact. At 100% recycling BioGrout 1st generation, the BioGrout 2nd generation and gel injection have a larger environmental impact.
This indicates that it is necessary to investigate the possibilities of recycling ammonium chloride, and when it can be converted into urea, that would also decrease the impact of the production of urea.

BioGrout 2nd generation and gel injection also have an impact on the environment, but this is much lower than the impact of BioGrout 1st generation. When the efficiency is not 100%, as assumed in the results, but 10% (as shown in chapter 9.2) the impact of BioGrout 2nd generation increases, but does not increase the environmental impact of BioGrout 1st generation. Jet grouting has no environmental impact when compared with the other three methods.

Transport, water and electricity are negligible for both BioGrout processes and gel injection. Only for jet grouting, they play a role on the impact assessment. That is probably, because jet grouting has no other steps in its process that play a large role in the impact. For both BioGrout processes, the largest impact steps are steps where alternatives are possible. This means, that it is possible to improve both processes significantly. Future research should focus on the steps that contain the largest impact. Thus, recycling of ammonium chloride and using wastewater for the BioGrout 2nd generation.

Furthermore, it can be seen that the fossil fuels, respiratory inorganics and climate change are in all four cases the categories that cause the high values in the environmental impact.

The conclusion of these results is that the two traditional methods have a lower environmental impact, compared with the BioGrout methods. However, this ranking should not be the only criteria to choose between the methods. It should be noticed that the LCA does not include certain impact categories, like loss of life support and life diversity because these categories are hard to quantify. This could be issues where BioGrout will score better in comparison with jet grout. It is possible to take some of these aspects in consideration by defining a waste flow of cement for the jet grout process. The cement column will not “vanish” after sometime. Thus, after sometime, this has to be removed and treated. The method of inserting the strengthening fluids could have impact on the environment. With jet grouting, the soil is stirred and treated, affecting the ecosystem of the soil. This is not taken into account. In addition, inserting chemical substances in the soil without removal could have a negative impact on the environment.

Furthermore, it is not always possible to perform jet grouting, because jet grout requires large equipment. By contrast, BioGrout needs little space and thus can be a good alternative for jet grouting. Especially for the case, which is discussed in this chapter, jet grout would not be very useful because this will lead to a lot of economic damage due to the diversion of trains and/or the (temporarily) stop of the railway traffic.
Summarizing, the LCA can be used as one possible way to look at the different methods. However, it is also important to look further. It is for example possible to make a cost-benefit analysis.

11 Conclusions

Four different ground improvement techniques were evaluated by means of an Life Cycle Analysis.

- The two traditional techniques have a low environmental impact. This is especially true for jet grouting, which has no impact compared to the other three techniques.
- However, other aspects should be taken into account. Not all environmental impacts are taken into account with this LCA. With BioGrout the soil is strengthened in situ, without replacing/removing the soil and without influencing the permeability of the soil. In addition, a natural product is precipitated between the sand grains (calcite), where with jet grouting and gel injection chemicals and cement are inserted in to soil. When these aspects are taken into account, other outcomes may result. *It would be highly desirable to develop methods to better take into account the specific requirements of the subsurface.*
- The LCA can be used as one possible way to look at the different methods. However, it is also important to look further. It is for example possible to make a cost-benefit analysis.
- This LCA initially is meant to determine which steps for both BioGrout methods, should be taken to obtain a lower environmental impact. Using the LCA and adjusting the LCA over time, with newly obtained data, should be a one of the several guidelines in the research programme.
- BioGrout first generation has the largest negative environmental impact. As expected this is due to the treatment of ammonium chloride. When all of the ammonium chloride can be recycled, it becomes a more favourable method.
- The largest environmental impact for BioGrout second generation is caused by the use of calcium nitrate, calcium acetate and the emission of NO_x. It is expected that these impacts will change (be reduced) in the near future, when it is demonstrated that wastewater can be used in the proces.

12 Literature

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A Procedure of LCA

Goal and scope definition

The first phase of an LCA is the goal and scope definition. In this phase the initial choices are made which determine the working plan of the entire LCA. The goal of the study is formulated in terms of the exact question, target group and intended application. The scope of the study is defined in terms of temporal, geographical and technological coverage.
After the definition of the goal and scope, the product is described in terms of function, functional unit and reference flows. The functional unit describes the primary function fulfilled by a product system and indicates how much of this function is to be considered in the study. It will be used as a basis for selecting one or more alternative product systems that might provide these functions. The functional unit enables different systems to be treated as functionally equivalent and allows reference flows to be determined for each of them. The reference flow is a measure of the outputs from processes in a given product system which are required to fulfil the function expressed by the functional unit.

Inventory analysis

The inventory analysis is the phase in which the product system(s) is (are) defined. This includes the setting of the system boundaries, designing the flow diagrams with unit processes, collecting data for each of these processes, performing allocation steps for multifunctional processes and completing the final calculations. The main result of this phase is an inventory table that lists the quantified inputs from and outputs to the environment related to the functional unit.

Flow diagram

A flow diagram gives a graphic overview of the processes that are involved in the production of the product. It can be helpful in the understanding of a system and in choosing the system boundaries.

System boundaries

The system boundaries are an important aspect of the LCA. Whenever a system is studied, system boundaries are needed to separate the system from the rest of the world. An LCA Inventory (LCAI) analysis distinguishes three types of boundaries.

The boundary between the product system and the environment system is the first one. When making an LCA, every flow should be followed until its economic inputs and outputs have all been translated into environmental interventions. Economic inputs and outputs are defined as flows of goods, materials, services, energy or waste from one unit process to another. Environmental interventions refer to flows entering the product system which have been drawn from the environment without prior human transformation or flows of materials leaving the product system which are discarded into the environment (Figure A12.1).
The guidelines of the guide of the CML for the making of the economy-environment system boundaries tell to use the definition of the system boundaries that is applied in existing databases and literature sources. It should be noted however, that there might be inconsistencies between the various data sources used.

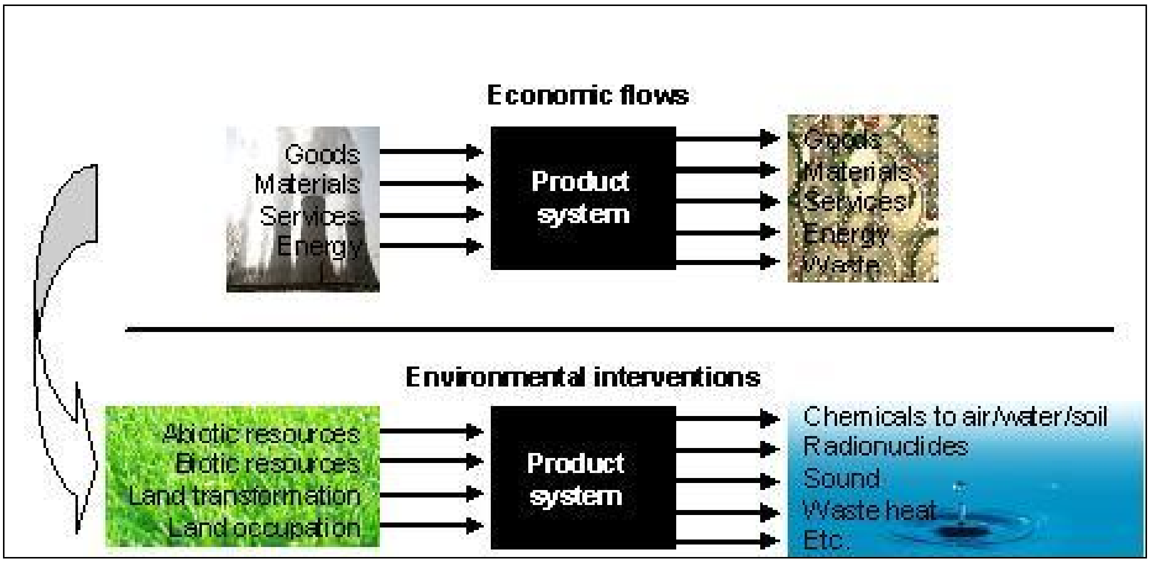

Figure A12.1 All economic flows of a product system translated in environmental interventions.

The boundary between processes that are relevant and irrelevant to the product system is the second system boundary. An LCA should define all processes in the life cycle of a given product system. However, in practice this is impossible. That is why a number of flows must be either roughly estimated or cut off and hence ignored. Cut-off is mainly necessary for reasons of lack of data, in combination with lack of time and money. Most of the time, the problem arises after data collection, when it turns out production processes for some inflows and waste treatment processes for some outflows are unknown or undocumented.

The last system boundary is the boundary between the product system under consideration and other product systems. Most industrial processes are multifunctional. Their output generally comprises more than one single product, and raw materials inputs often include intermediates or discarded products. The problem then becomes that the product system provides more functions than which are investigated in the functional unit of interest. A decision must then be made as to which of the economic flows and environmental interventions associated with the product system under study are to be allocated to the functional unit produced by that system.

In Figure A.2 a visualization of the different system boundaries is shown. The green box shows the first system boundary between the product system and the environment system, the red box shows a possible system boundary between relevant and irrelevant processes and the orange box visualizes the boundary between the product system under consideration and another product system.

12.1.2

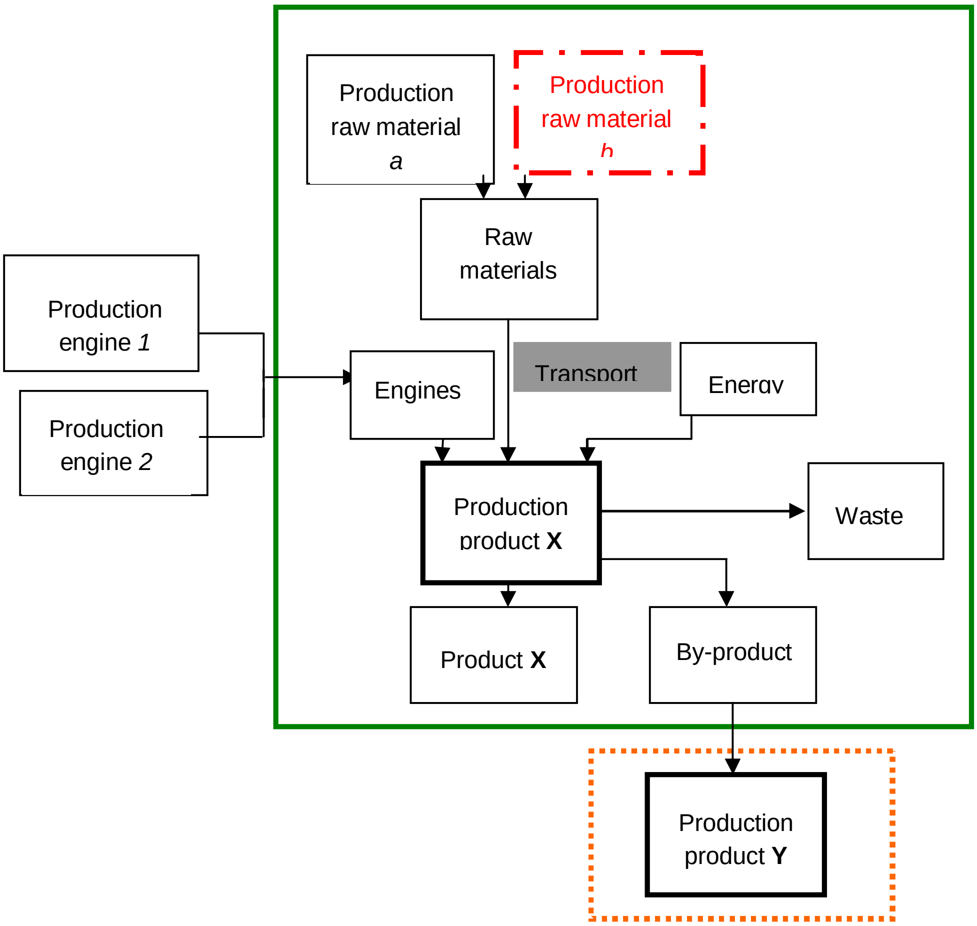

Figure A.2 Visualization of the system boundaries for the production of a product x. The green box ( ) shows the first system boundary, the red ( ) box the second and the orange box the third ( ).

Data collection

The data collection of the Inventory analysis involves the collection of all relevant data of the functional unit and quantifying all flows connected to the unit processes. The process data can be structured in a number of ways. In LCA databases, process data are often organized around unit processes, relating a given economic output to economic inputs and environmental inputs and outputs. Process data provided by companies are often also organized around unit processes, but given in terms of inputs and outputs per unit of time.

The used data for an LCA has a major influence on the results. That is why proper evaluation of data quality is an important step. However, even if the quality of individual datasets is high, such data can still yield errors in the conclusions when the data is used in the wrong way. The data used in a given case study should for instance be representative of that particular study.

Impact assessment

Life Cycle Impact Assessment (LCIA) is the phase in which the results of the Inventory analysis are further processed and interpreted in terms of environmental impacts. The guide of the CML describes different impact categories and models which describe the relation between the environmental intervention and category indicators for these impact categories. The actual modelling results are calculated in the characterization step and the results of this step can be normalized. Finally, the results can be weighted. An overview of the steps which need to be taken in the impact assessment is given in Figure A.3.

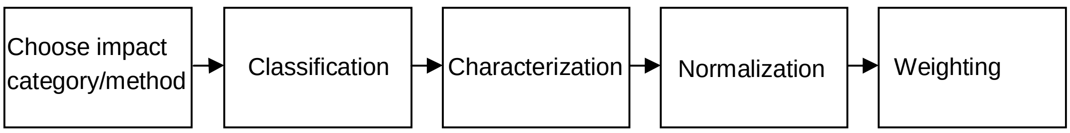

Figure A.3 An overview of the steps of the impact assessment.

Impact categories

In the first step of the LCIA phase is the determination of the relevant impact categories. The CML uses the list of best available impact categories, drawn up by the SETAC Working Group on Impact Assessment as a basic list. The final list distinguishes between 'baseline' impact categories, 'study-specific' impact categories and 'other' impact categories. The baseline impact categories comprise those categories for which a baseline characterization method (see 3.4.2) is selected in part 2b of "*Life cycle assessment: An operational guide to the ISO standards*". The second group contains categories that may be important to include. This depends on the goal and scope the LCA study, whether data is available and the availability of a baseline and/or alternative characterization method. The third group comprises several categories for which no baseline characterization method is proposed in the guide, although alternative characterization methods may be available. An overview of the different impact categories is shown in Table A.1.
The CML method is one of several impact assessment methods. Other impact methods may use other impact categories.

Group	Impact category

Baseline	• Depletion of abiotic resources
	• Impacts of land use
	    o Land competition
	• Climate change
	• Stratospheric ozone depletion
	• Human toxicity
	• Ecotoxicity
	    o Freshwater aquatic ecotoxicity
	    o Marine aquatic ecotoxicity
	    o Terrestrial ecotoxicity
	• Photo-oxidant formation
	• Acidification
	• Eutrophication

Study-specific	• Impacts of land use
	    o Loss of life support function
	    o Loss of biodiversity
	• Ecotoxicity
	    o Freshwater sediment ecotoxicity
	    o Marine sediment ecotoxicity
	• Impacts of ionizing radiation
	• Odour
	    o Malodourous air
	• Noise
	• Waste heat
	• Casualties

Other	• Depletion of biotic resources • Desiccation • Odour o Malodourous water

Table A.1 An overview of impact categories as defined by the CML.

Classification

The qualified and quantified environmental interventions in the Inventory analysis are assigned on a qualitative basis to the selected impact categories in the classification step. This may become confusing when one intervention can be assigned to more than one impact category.
There can be made a distinction between different types of this problem.
Serial impacts are impacts that may have successive impacts. For example, heavy metals may first have influence on the ecotoxicological impacts and subsequently have impacts on human health via food chains. Emissions with combined impacts emissions of substances having a mutual influence on each other's impacts. For example, synergistic or antagonistic impacts of mixtures of toxic substances. These two types are fully assigned to all relevant impact categories.
Emissions with parallel impacts are substances that may in theory contribute to more than one impact category but in practice contribute to only one. This, however, is not a real

problem in practice because the characterization models will calculate the values for the different impact categories and will come to appropriate values.

Characterization

After the environmental interventions have been assigned to the impact categories, they are quantified in the characterization step. This is done in common unit for that category, so the sum of the interventions of one category will lead to a single score: the indicator result. A characterization method consists out of a category indicator, a characterization model and characterization factors.
For example, the characterization model for climate change according to Houghton et al. (Houghton, 1996) is:

$$\text{Climate change} = \sum_i GWP_{a,i} \cdot m_i$$

$GWP_{a,I}$ is the Global Warming Potential for substance *i* integrated over *a* years and m_i is the quantity of substance *i* emitted. The category indicator is kg of the reference substance CO_2 and the characterization factors are the values of GWP.
The baseline characterization methods are the methods that are recommended by the guide as the current best available practice for the impact category in question. Alternative methods may be used instead of the baseline methods only when this choice is justified and well documented. They can also be used next to the baseline method as a sensitivity analysis.

Normalization

In the normalization step, it is possible to calculate the indicator results relative to reference information. The reference information may relate to a given community, like Delft, The Netherlands or the world. It can also refer to a person, like a British citizen, or over a given period of time. The goal of normalization is to better understand the relative impact of the results of the product system. The values after normalization have no unit.

Weighting

In this step, the (normalized) indicator results for each impact category are assigned numerical factors according to their relative importance. There are different ways to assign these factors. It is for example possible to divide the impact categories into different environmental themes or damage categories. For example, you can have the environmental theme ‘spread’, which includes human toxicity, ecotoxicity and photo-oxidant formation. Then all these themes can have the same factor. Another possibility is to weight conform the goals of the government (“distance-to-target” (DtT)).

Interpretation

The interpretation phase is the phase that discusses the results of the analyses and all choices and assumptions that are made. The main elements of the interpretation phase are an evaluation of the results in terms of consistency and completeness, an analysis of results and an overview of the conclusions and recommendations of the study.

Consistency check

The objective of the consistency check is to determine whether assumptions, methods, models and data are consistent with the goal and scope of the study. In the case of a comparison it is important to check for differences between data sources, data accuracy, technical level, temporal aspects, geographical representativeness and functions.

Completeness check

The completeness check needs to be performed to be ensured that all relevant information and data needed for the Interpretation phase are available and complete. Having an expert look at the results of the LCA and how they were generated can uncover errors and incomplete data. An LCA expert could check the methodology used in the different phases of the project and the results and conclusions of the analysis in relation to the goal and scope.

Contribution analysis

The contribution analysis answers questions about the contribution of specific environmental flows, processes or impacts to a given environmental score. The contributions are usually expressed as percentages of the total. It is possible to conduct different contribution analyses. For example:

- Individual processes within the overall process (e.g. pasteurizing as a phase within the production of milk)
- A group of processes within the overall process (e.g. various conservation measures as a phase within the production of milk).
- A life-cycle stage within the overall process (e.g. the agricultural production of milk)
- An environmental flow within the overall process (e.g. SO_2 flow in the production of milk)

Perturbation analysis

Perturbation analysis involves the study of the effects of small changes within the system on the results of an LCA. The effects of these small changes are calculated simultaneously for all flows within the system. The analysis can be conducted at the level of inventory, indicator results, normalized indicator results or weighting results. The guidelines of the CML guide tell that perturbation analysis requires dedicated software routines and therefore it may be skipped in many cases.

Sensitivity and uncertainty analysis

The sensitivity analysis provides information about the robustness of the results. This part of the Interpretation phase assesses the influence on the results of variations in process data, model choices and other variables. The uncertainty analysis uses empirical data on the uncertainty ranges of specific data to calculate the total error range of the results.

B Offer Visser & Smith BioGrout

VISSER EN SMIT BOUW B.V.		**afd. Grond- en Funderingstechniek**			
BIOGROUTING		calc.nr.:		datum:	07/11/07
	CONCEPT	project:	Spoorlichaam	revisie:	0
		plaats:		km:	100
ALGEMENE GEGEVENS					
Omschrijving	lengte	breedte	oppervlak		
Te behandelen opp. (l x b)	150	15	2250		
Hoogte grondverbetering	1,5	Inhoud	3375		
Poriëngehalte	40%				
Afstand injectielansen [m]	1				
Afstand vacuümlansen [m]	3				
Totaal aantal injectielansen	150				
Totaal aantal vacuümlansen	150	Aantal deeltrajecten	15		
Ureum-injectie					
Aantal injectiepompen	1		Injectietempo	30	l/min.
			Werkuren / dag	8	uren
			Effectiviteit	90	%
			Injectietijd/deeltraject	50	uur
Injecteren punten	15	dagen	Mob/demob	1	dagen
			Ureuminjectie per deeltrajectdrain	90	m3
			Ureuminjectie totaal	1350	m3
Ureum brine	40	%	Ureum	102	ton
Hoeveelheid ureum/m3 grond	30	kg	Hoeveelheid ureum brine	255	ton
Water benodigd per uur	12	m3	Totaal te injecteren Ureum	1350	m3
Calciumchloride-injectie					
Aantal injectiepompen	1		Injectietempo	30	l/min.
Aantal injectiefasen	2		Werkuren / dag	8	uren
			Effectiviteit	90	%
			Injectietijd/deeltraject	50	uur
Injecteren punten	45	dagen	Mob/demob	15	dagen
			Calciumchloride per deeltraject	90	m3
			Calciumchloride totaal	1350	m3
Hoeveelheid calciumchloride/m3	55,5	kg	Hoeveelheid calciumchloride	188	ton
Water benodigd per uur	8	m3	Totaal te injecteren calciumchloride	2700	m3
Spoelen reststoffen					
Aantal injectiepompen	8		Injectietempo	30	l/min.
Aantal spoelingen	2		Werkuren / dag	8	uren
			Effectiviteit	90	%
			Spoeltijd per deeltraject	100	uur
Spoelen punten	45	dagen	Mob/demob	1	dagen
			Spoeling per deeltraject	180	m3

			Spoeling totaal		1350	m3
Water benodigd per uur	8	m3	Totaal spoelwater		2700	m3
AKTIVITEIT	AANTAL	Hoeveelheid	UREN	TARIEF	FACTOR	TOTAAL
		Dagen				

C Impact Methods SimaPro 7.1

The impact methods which are available in SimaPro 7.1 are listed in Table C.1. The method EDP 2007 is not included because only a draft version of the method is available. TRACI is not included because no normalization data and official documentation are available.

Method	Impact categories	Remarks
CML 1992	Acidification Ecotoxicity Eutrophication Greenhouse Human toxicity Ozone layer depletion Smog Solids	Results may not be completely reliable because emissions are often specified under a collective name (e.g. aromatic hydrocarbons), although there might be considerable variation in the environmental impact of the emissions. No weighting.
CML 2 baseline 2000	Acidification Climate change Depletion of abiotic resources Ecotoxicity: Fresh-water aquatic Ecotoxicity: Marine Ecotoxicity: Terrestrial Eutrophication Human toxicity Ozone depletion Photo-oxidant formation	Categories divided in three groups. Only baseline categories are available in SimaPro. No grouping and weighting.
Cumulative Energy demand	Non renewable, fossil Non renewable, nuclear Renewable, biomass Renewable, wind, solar, geothermal Renewable, water	No normalization. Weighting all factor 1.
Eco-indicator 95	Acidification Carcinogens Energy resources Eutrophication Greenhouse Heavy metals Ozone layer Pesticides Solid waste Summer /Winter smog	Weighting factors based on distance-to-target principle.
Eco-indicator 99	Acidification Carcinogens Climate change Ecotoxiciy Eutrophication	Damage categories: Human Health, Damage to Ecosystem Quality and Damage to resources Three versions of method using

	Fossil fuels Land use Minerals Ozone layer Respiratory organics Respiratory inorganics Radiation	archetypes specified in Cultural Theory: Egalitarian-, hierarchist- and individualist perspective. Weighting is performed at damage category level. Different weighting values for three perspectives.
Ecopoints 97 (CH)		No classification, assesses impacts individually.
EDIP 1997	Acification Bulk waste Ecotoxicity soil chronic Ecotoxicity water chronic Ecotoxicity water acute Eutrophication Global warming Hazardous waste Human toxicity air Human toxicity water Human toxicity soil Ozone depletion Photochemical smog Radioactive waste Resources Slags/ashes	Weighting based on politically set target emissions per person. Weighting for resources is based on proven reserves per person. Due to the different weighing method, resources may never be included in a single score.
EDIP/UMIP 1997 (resources only)	Resources	Resources are given in individual impact categories
EPS 2000	Crop production capacity Depletion of resources Life expectancy Fish and meat production capacity Morbidity Nuisance Production capacity of (irrigation) water Production capacity of (drinking) water Severe morbidity and suffering Severe nuisance Species extinction Wood production capacity	Damage categories: Human Health, Ecosystem production capacity, Abiotic stock resouces, Biodiversity, Cultural and recreational values No normalization applied. Weighting factors represent the willingness to pay (WTP) to avoid changes.
IMPACT 2002+	Aquatic acidification Aquatic ecotoxicity Carcinogens Ecotoxicity: terrestrial Global warming Ionizing radiation Land occupation Mineral extraction	Damage categories: Human Health, Ecosystem quality, Climate change and Resources. Suggested to look at damage categories separately. However, when aggregation is needed, the default weighting factor is 1, but it

	Non-carcinogens Non-renewable energy Ozone layer depletion Respiratory inorganics Respiratory organics Terrestrial Acidification/nutrification	is also possible to use self-determined weight factors.
IPCC 2001 GWP	Global warming	This method lists the climate change factors of IPCC with a timeframe of 20, 100 and 500 years. No normalization and weighting.

Table C.1 Impact methods and their impact categories in SimaPro 7.1.