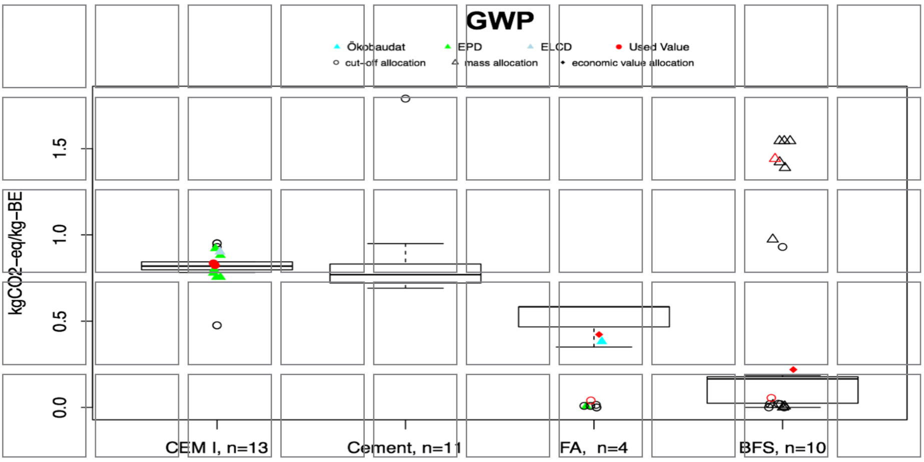
Working Group Sustainability Assessment of the
Institute of Technology and Testing of Construction Material
Graz University of Technology



Environmental Comparison of Base Materials for Sprayed Concrete

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Graz, 26th of May 2017

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Abstract

Purpose The ASSpC project at TU Graz aims at developing new sprayed concrete mix designs with respect to durability and sustainability. This thesis addresses the environmental aspects of sprayed concrete and its constituents. Its objectives are (1) providing the state-of-the-art of Life Cycle Assessment (LCA), which is a capable method to quantify environmental impacts of materials and processes, (2) providing a database of environmental impacts of different materials used in different sprayed concrete mixes and (3) comparing new developed mix designs to traditional ones on basis of environmental friendliness.

Methods A Systematic Literature Review (SLR) is used to exploit publications dealing with LCA and sprayed concrete or at least one of its base materials. A meta-analysis of final samples of journal papers is conducted in Excel. The LCA of sprayed concrete (six wet and five dry mixes), performed in SimaPro with link to the environmental database EcoInvent v2.2, is accomplished on a cradle-to-gate basis to gain insights in the environmental impacts of sprayed concrete and its base materials. Six environmental impact indicators are calculated, using EPD (2013) v1.03 as Life Cycle Impact Assessment method. This is done for the constituents on a one-kilogram-basis, while materials with binding capacity are then compared with respect to their binding equivalent[1]. For the comparison of different mix designs, 1 m^3 sprayed concrete is used as the functional unit. Economic Value Allocation is used as base case scenario with cut-off approach and mass allocation serving as sensitivity check. Furthermore, the robustness of the results is checked by means of Monte Carlo Simulation, and using EcoInvent v3.3[2] for environmental background data.

Results and discussion In addition to the results of the meta-analysis providing the state-of-the-art of LCA, which also showed that literature lacks LCAs on sprayed concrete, a detailed look at three wet mixes is conducted: NRef1 as traditional mix design, NRef4, where some amount of cement is replaced with fly ash (FA) and blast furnace slag (BFS), and N1, where the substitution is accomplished with a mix of reactive and inert fillers. Within the economic value allocation methodology, the substitution is environmentally beneficial with regard to five

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[1] The binding equivalent quantifies the binding properties of a material relative to the binding property of 1 kg CEM I.

[2] Within EcoInvent version 3.3 the system model "Allocation, recycled content" is used.

of the six examined impact indicators. Interestingly, this one exception occurs not at the same indicator for NRef4 and N1. Sensitivity Analysis shows that a change of the background data source (EcoInvent v3.3) changes the one indicator where the substitution of cement is not environmentally beneficial if NRef4 is compared to NRef1.

Conclusion Results show that the substitution of cement with supplementary cementitious materials (SCM) such as FA and BFS, or fillers is environmentally beneficial if economic value allocation or the cut-off approach is used. Mass allocation totally reverses this statement, making FA the material causing the biggest environmental burden by far, followed by BFS. With regard to the examined impact indicators, inert Micro- and Meso-Fillers are - from an environmental point of view - the most promising materials to lower the burden of sprayed concrete, because they are environmentally beneficial regardless of allocation method or data source used. But due to their inert nature, only a very small amount of cement can be replaced by them. Furthermore, admixtures - often excluded in LCAs of normal concrete - play an important role in quantifying the environmental impacts of sprayed concrete.

Kurzfassung

An der TU Graz werden derzeit im Rahmen des ASSpC-Projektes neue Spritzbetonrezepturen entwickelt, die dauerhafter und nachhaltiger als bisherige Rezepturen sein sollen. Die vorliegende Arbeit bezieht sich auf die Umweltaspekte von Spritzbeton und dessen Bestandteile. Es sollen (1) der aktuelle Stand der Forschung bezüglich Ökobilanzierung (Life Cycle Assessment, LCA) ermittelt, (2) Datengrundlagen zu Umwelteinflüssen der verschiedenen Spritzbetonbestandteile erarbeitet, und (3) die Umwelteinwirkungen der verschiedenen Spritzbetonrezepturen verglichen werden.

Um Publikationen zum Thema LCA und Spritzbeton oder seiner Bestandteile zu finden, wird eine systematische Literaturrecherche (SLR) durchgeführt. Eine Metaanalyse der relevanten Publikationen wird in Excel realisiert. Für die Ausgangsmaterialien und Spritzbetone selbst (sechs Nass- und fünf Trockenrezepturen) wird eine LCA in SimaPro, unter Rückgriff auf die Umweltdatenbank EcoInvent v2.2, auf cradle-to-gate-Basis durchgeführt. Dabei wird EPD (2013) v1.03 als LCIA Methode verwendet. Für die einzelnen Materialien geschieht dies auf Basis von 1 kg; die Rezepturen werden anhand der Umweltauswirkungen von 1 m^3 verglichen. Die Allokation erfolgt anhand des monetären Wertes, wobei allerdings zwei weitere Allokationsverfahren als Sensitivitäts-Check angewandt werden. Weiters wird die Robustheit der Resultate mithilfe einer Monte Carlo Simulation und EcoInvent v3.3[3] überprüft.

Hauptaugenmerk während des Vergleichs verschiedener Spritzbetonrezepturen liegt auf den Nassrezepturen NRef1, einer traditionellen Rezeptur, NRef4, wobei ein Teil des Zements durch Flugasche (FA) und Hüttensand (BFS) ersetzt wird, und N1, wobei die Substitution von Teilen des Zements mittels einer Mixtur aus reaktiven und inerten Füllern passiert. Mit der gewählten Allokationsmethode (monetärer Wert) ist eine Substitution in fünf der sechs untersuchten Umweltkategorien vorteilhaft. Diese Kategorie ist aber nicht dieselbe für NRef4 und N1. Auch eine Änderung der Umweltdatenbank (EcoInvent v3.3) ändert den einen Umweltindikator, bei dem NRef4 schlechter als NRef1 abschneidet.

Ergebnisse zeigen, dass eine partielle Substitution des Zements Vorteile in Hinblick auf die Umweltauswirkungen hat. Wird allerdings Allokation nach Masse angewandt, verschwindet

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[3] EcoInvent v3.3 wird unter der Verwendung des Systemmodells "Allocation, recycled content" benutzt.

der Vorteil sofort, da nun FA (gefolgt von BFS) die größte potentielle Umwelteinwirkung besitzt. Nur die inerten Mikro- und Meso-Füller behalten ihren Umweltvorteil, was sie zu den vielversprechendsten Materialien dieser Studie macht. Allerdings ist der Anteil des Zements, der durch sie ersetzt werden kann, aufgrund ihrer inerten Eigenschaft sehr gering. Weiters konnte festgestellt werden, dass Zusatzmittel wie Verflüssiger oder Erstarrungsbeschleuniger, die oft bei LCAs von herkömmlichem Beton vernachlässigt werden, eine große Rolle in der Ökobilanzierung von Spritzbeton darstellen.

Contents

1. Introduction

Building construction and operation account for about 50% of worldwide CO_2 emissions [Achal2015]. Concrete is the second most used material, with a production of about one tonne to one cubic meter per person and year, which fells only short to the usage of water [Achal2015; Flower2007; Habert2013]. Within the construction industry, concrete is the most used material due to its outstanding technical properties like strength or durability [Aitcin2000; Habert2013; Komastka2003]. Unfortunately, conrete is also among the building materials which cause the most CO_2 emissions [Achal2015].

At least since the publication of the IPCC Fifth Assessment Report in 2014 [IPCC2014], which enforced the increasing awareness of global warming and environmental stress produced by human kind even more, society and research push in the same direction: The development of sustainable and environmentally friendly alternatives to traditional products. Due to the large quantities produced and its large amounts of CO_2 emitted, concrete is a perfect candidate to investigate with regard to the quantification of these emissions and opportunities to reduce them. This was done by e.g. [Feiz2015; Won2015; Yang2015].

However, the environmental burden caused by a material is not fully accounted for by only monitoring its CO_2 emissions. There are other substances, which are harmful for nature or even human kind, which are emitted over the life cycle of a product. The expansion of the discussion about CO_2 to also incorporate other environmental impacts of concrete was done by e.g. [LopezGayarre2016; Muller2014; Muller2014a; Serres2016].

For sprayed concrete, a specific type of concrete, such research is almost not existent. A research project at TU Graz tries to fill this hole: The research project ASSpC (Advanced and Sustainable Sprayed Concrete) tries to find new sprayed concrete formulas and technologies, especially to improve sprayed concrete with respect to durability and sustainability.

This thesis addresses the environmental performance of sprayed concrete and its base materials. At first, a systematic literature review was conducted. Main findings from it are presented in chapter 3. Then, base materials of sprayed concrete are characterized and compared by their environmental performance.

The main issue of this thesis, a Life Cycle Assessment (LCA) of sprayed concrete, is presented in chapter 5. The LCA is done in SimaPro and Excel, uses a Cradle-to-Gate approach and 1 m3 of sprayed concrete as functional unit. The main data source is the EcoInvent database in version 2.2.

Six wet and five dry mixes are compared, before turning to three wet mixes and analysing their contributors: The first one (NRef1) is the most traditional one as it consists of cement, water, gravel and admixtures. The other two looked at in particular try to reduce the amount of cement used by replacing it with fly ash, blast furnace slag and limestone (NRef4), respectively Meso- and Micro-Fillers (N1).

Sensitivity analysis is conducted based on allocation methods used. Also Monte Carlo Simulation (MCS) is used to gain information of the uncertainty of the modelling. Furthermore, a sensitivity check regarding the data source is provided, as results of EcoInvent v2.2 are compared with results derived under version 3.3[1].

1.1. Background

Sprayed concrete is concrete which is applied on a surface through a spray nozzle and compacted through its impact energy. Its mix designs are similar to designs of normal concrete with the exception that more admixtures like set accelerators are used to provide sufficient early strength. Also the water to binder ratio is fitted more to this requirement than it is in normal concrete. The early strength is one of the most important (if not THE most important) properties of sprayed concrete, because it doesn't use a framework and therefore has to support itself since the time of its application. Sprayed concrete is either used by itself, or it is reinforced with steel bars, steel mats or fibers.

There are two techniques: The dry mix technique and the wet mix technique. Within the first method, cement, aggregates and other solid constituents if required are mixed together and the addition of water and admixtures takes place at the nozzle, shortly before the mix is sprayed on a surface. Among its advantages are the flexibility (because the amount of water used can be adjusted by the nozzleman, and work stoppage is easily possible) and lower maintenance costs.

Within the wet mix technique all constituents are mixed together before they are procured to the nozzle. Thereby it is possible to maintain the same quality and homogeneity of the mix. Furthermore, its advantages involve less rebound and less formation of dust than the work with dry mixes.

Sprayed concrete is used for securing excavations or slopes, in tunnel construction and partially

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[1] Within EcoInvent version 3.3 the system model "Allocation, recycled content" is used. Information on different system models can be derived from `https://www.pre-sustainability.com/ecoinvent-different-system-models`, 26.05.2016

to repair concrete components. It is used especially as part of the *New Austrian Tunneling Method* (NATM), where the rock is supported by layers of sprayed concrete.
Among the problems of sprayed concrete is its vulnerability to thaumasite sulfate attack and leaching of calcium, which leads to a shorter longevity and high maintenance demand. This doesn't only cause additional costs, it also - because like every building material also sprayed concrete has got an environmental footprint - increases its environmental burden.
The research project ASSpC (Advanced and Sustainable Sprayed Concrete) at TU Graz tackles both issues by inventing more durable and sustainable sprayed concrete mix designs: On the one hand, the new mixes shall be less vulnerable to thaumasite and leaching. Indeed, the initial application costs for these designs may rise, but due to the expected longer durability and therefore less maintenance demand and cost, overall costs should decrease. On the other hand, also the environmental burden of these mix designs shall be lower than traditional designs.

1.2. Scope/Aim of this Thesis

This thesis addresses parts of the second issue within the ASSpC project: Its main objective is to verify whether the new mix designs are environmentally beneficial compared to traditional mixes. Other objectives of the ASSpC project are discarded, i.e this thesis does not go into the technical properties of sprayed concrete. Due to insufficient information regarding long term behaviour of the new mix designs at present, also durability is not addressed.
Beside its main objective, also some other questions concerning the topic environmental footprint of sprayed concrete shall be answered with this thesis. These research questions are:

- What research has already been done on assessing the environmental performance of sprayed concrete and/or its base materials?
- What base materials are the main drivers of global warming, ozone depletion etc.?
- Do the new developed mix designs cause a lower environmental burden than traditional ones?
- Is a substitution of cement with other materials environmentally friendly?
- Are results data source dependent?

1.3. Hypotheses

On basis of the research questions and general research interest, five hypotheses are set up, which are to be - not exclusively - answered with this thesis. The hypotheses are:

1. In literature, LCAs on sprayed concrete are scarce.
2. Among the base materials of sprayed concrete, cement is responsible for the largest environmental burden.
3. Admixtures play an important role in quantifying the environmental burden of sprayed concrete.
4. The environmental advantage of substituting cement with materials like fly ash and/or blast furnace slag depends on the allocation rule used.[2]
5. The use of other data sources doesn't change the results much.

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[2] The environmental performance of these materials with regard to allocation rules was already investigated by other authors, e.g. [Chen2010; Habert2013]. This thesis goes one step further as it verifies this hypothesis not only on basis of base materials, but also with regard to final sprayed concrete mix designs.

2. Methods

To achieve the termed objectives, answer the formulated research questions and validate the hypotheses, this thesis uses a **Systematic Literature Review** and **Life Cycle Assessment (LCA)** as main methods.

Life Cycle Assessment is an accepted and capable tool to quantify environmental impacts caused by a product during its life[Kloepffer2014]. It is standardized by [ISO14040] and [ISO14044]. The life cycle of a product can be divided into 4 major **Life Cycle Phases**, with the first three (A, B and C) serving as the products life according to [EN15804] and stage D as "additional information". Each stage[1] can be separated into substages (A1-A5, B1-B7 and C1-C4). The stages are Product Stage (A1-A3), Construction Process Stage (A4-A5), Use Stage (B) and End-of-Life Stage (C).[EN15804]

The product or process under study fulfills one determined function. Every LCA result refers to this **Functional Unit**. A functional unit (fU) can be for example "the production of 1 kg concrete" or "one square meter floor covering over a period of 30 years".[Kloepffer2014]

Within a determined system boundary, the examined product system is diversified into so-called unit processes, which represent the smallest part of this system. To rephrase this, connected unit processes build the product system under study. Material flows are determined and inputs/outputs are assigned to these Unit processes (Life Cycle Inventory analysis (LCI)). If outputs of so-called multifunctional processes[2] are involved, one has to consider how material flows caused or consumed by this process should be divided between the generated products[Ekvall2001]. This is called **Impact Distribution** or **Allocation**.

Then, on basis of LCI data these are assigned to different impact categories in the stage called classification. Finally, the corresponding impact indicators[3] are calculated by using characterisation factors[4]. LCA software has access to different **Life Cycle Impact Assessment (LCIA) -**

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[1] with the exception of stage D

[2] Multifunctional processes are processes with more than one outcome.

[3] An example for an environmental impact indicator is *Global Warming Potential*, which is quantified in kg-CO2-equivalents.

[4] Characterisation factors are used to convert impacts of substances so that they can be expressed in one unit, i.e. they answer the question how many kg of, for example, methane do have the same Global Warming Potential as one kg of CO2.

Methods, where characterisation factors to calculate certain impact indicators are implemented. As result, values of different impact indicators quantify the environmental impact of a product.[Kloepffer2014]
For this reason, LCA is used to - not exclusively - verify the hypotheses 2-5. Because there are - as addressed later - many methodological choices (e.g. addressed Life Cycle Phases, used Allocation and LCIA method) within a Life Cycle Assessment, and to verify hypothesis 1, a Systematic Literature Review (SLR) is conducted first. This is a method to gain an overview of publications regarding a specific topic. Scientific databases are searched for topic related or research question related keywords and the found sample of papers is minimized by exclusion criteria on basis of title, abstract and fulltext until only relevant literature remains [Higgins2008]. It can be imagined as a funnel, where all literature which touches the topic of interest are put in, but only the relevant publications seep out. So on the one hand, every paper in the field of interest is touched, but on the other hand the final sample includes only literature which is relevant for the research question. A more detailed description of the used methods can be in the sections below.

2.1. Systematic Literature Review

The SLR[5] uses databases for scientific research, namely ScienceDirect[6] and Springer[7]. These two databases are used because they contain the journals which are relevant for the SLR, for example "The Journal of Cleaner Production" (ScienceDirect) or "The International Journal of Life Cycle Assessment" (Springer). Keyword strings, derived from a material list of sprayed concrete, are typed in and found papers are transferred to the reference management software Mendeley[8]. On basis of exclusion criteria, e.g. foreign research field, papers are excluded by title, abstract and full text. The following information are extracted of the remaining papers and summarized in an excel sheet: author(s), title, country, year of publication, journal title, covered life cycle phases, functional Unit, data source(s), allocation method(s) and impact assessment method(s). Also, the environmental impacts regarding the material searched for are included in the excel sheet, if some are available and referring to midpoint indicators[9]. The following key word strings were used:

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[5] For more information on the process of an SLR see [Higgins2008].

[6] `http://www.sciencedirect.com`, 03.11.2016

[7] `http://link.springer.com`, 03.11.2016

[8] available on `https://www.mendeley.com`, 03.11.2016

[9] Midpoint indicators refer to impact categories which are along the environmental mechanism of a process, like climate change. The final impact can be measured with endpoint indicators like human health or ecosystem quality.[Desideri2014]
This thesis focuses on midpoint indicators.A short discussion is provided in section 3.4

- Sprayed concrete AND LCA
- CEM AND LCA
- Admixtures AND concrete AND LCA
- Limestone AND concrete AND LCA
- Gravel AND concrete AND LCA
- Sand AND concrete AND LCA
- Fly ash AND concrete AND LCA
- Blast furnace slag AND concrete AND LCA

Furthermore, in another excel sheet the environmental impacts corresponding to midpoint indicators of all materials, which are of interest for the production of sprayed concrete, are pooled together. So in addition to the materials searched for, environmental information on other constituents could be obtained as well.

2.1.1. Relation to LCA

The SLR is done for two purposes: On the one hand, it provides the state-of-the-art of LCA. Since there are a lot of methodological choices (e.g. used functional unit, allocation method) in LCA, the SLR helps making the right decisions, which then also will be accepted by the scientific community. For example, if everyone is using method A, it is clear that using method B won't help reaching the goal of providing scientific and comparable LCA results.
On the other hand, some materials are not included in environmental databases and one has to draw on other sources for this information. Popular sources are published studies or Environmental Product Declarations (EPDs)[10], where the material in question has already been examined. Derived environmental information through the SLR can then be used as input in the LCA, or the validity of data used within SimaPro can be checked with data from literature. Graph 2.1 shows the described connection between SLR and LCA.

2.2. Life Cycle Assessment

The LCA of sprayed concrete is performed as described in the standards [ISO14040] and [ISO14044]. The phases of the LCA are as follows and explained in with reference to [ISO14040]:

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[10] Examples are the EPDs of admixtures owned by the European Federation of Concrete Admixtures Associations (EFCA), which are later used in this thesis.

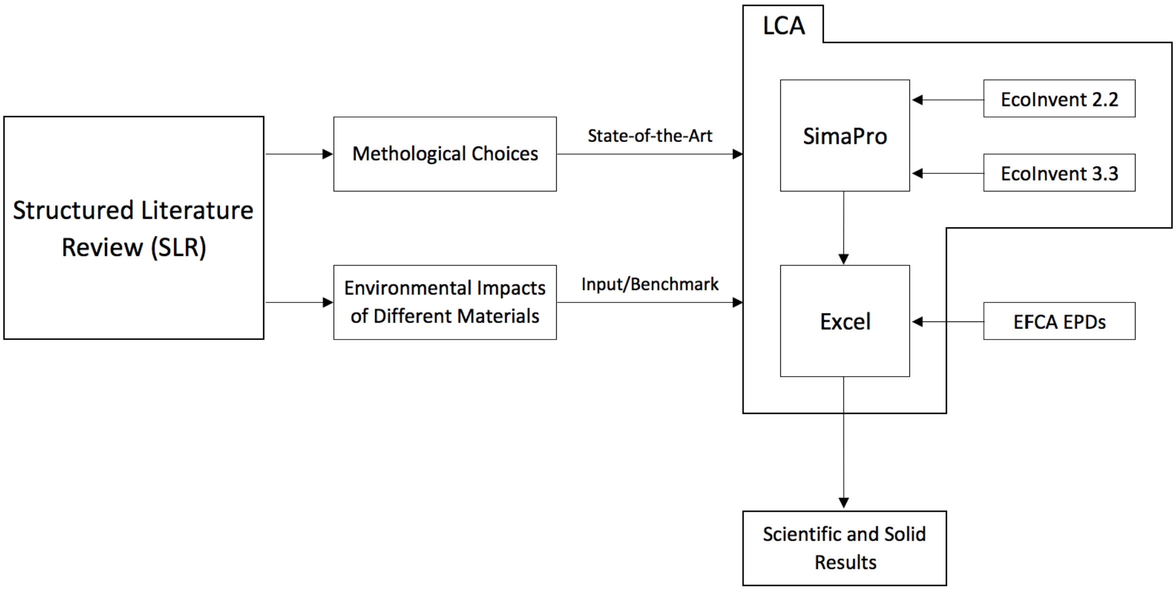

Figure 2.1.: *Connection of SLR and LCA*

- Goal and Scope definition: Goals and system boundaries of the LCA are defined.
- Life Cycle Inventory analysis (LCI): Inputs and Outputs referring to the product under study are identified and quantified.
- Life Cycle Impact Assessment (LCIA): Dimensions of environmental impacts of the examined product are assessed.
- Interpretation: Results from LCI and/or LCIA are judged with regard to Goal and Scope definition. The objective of this phase is to derive conclusions and advices.

In this section, the first phase and methods used for accomplishing the next two are addressed. More information regarding some methods and the used materials is found in section 5.1.1. Results and interpretation are presented in section 5.3. Figure 2.2 shows the stages of an LCA.

2.2.1. Goal and Scope

This LCA uses a Cradle-to-Gate approach, which is equivalent to addressing the phases A1-A3. Phase A1 addresses the extraction of raw materials, A2 refers to their transport to the manufacturing place, and A3 covers the manufacturing process itself [EN15804]. The choice to perform a Cradle-to-Gate-study is mainly made due to the current state of knowledge, which doesn't allow a solid and scientific Cradle-to-Grave study because long-term behaviour of the new mix

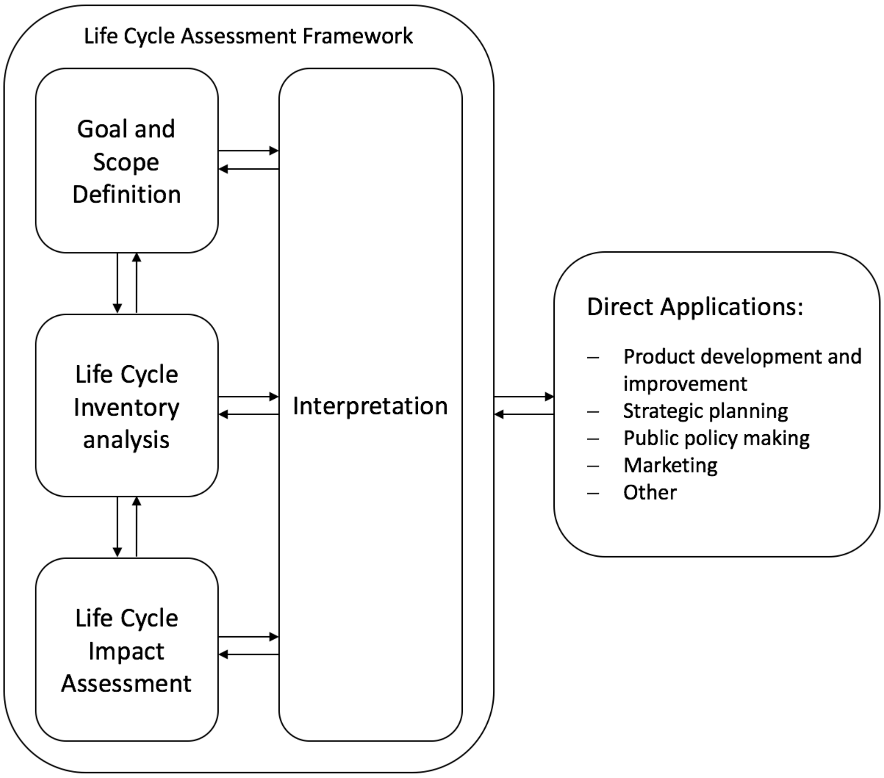

Figure 2.2.: *LCA Stages*
Source: Own illustration based on [ISO14040]

designs are not known yet. Tests are currently planned or in progress to gain information and a Cradle-to-Grave study may follow within the next three years.

The LCA is performed for two reasons in particular: On the one hand, a first collection of environmental impacts of different base materials on a Cradle-to-Gate basis should be established in SimaPro and/or Excel. On the other hand, the currently available mix suggestions should be compared. It should be determined in which way and to what extent a substitution of cement alters the environmental impacts. Also, the impacts of used admixtures should be assessed to underline the importance of their inclusion in every LCA dealing with sprayed concrete.

This study ends with the packed materials in storages. So there is no transport to a specific site or further downstream activities included. Also excluded is the mixing of the materials to a sprayable mass. Furthermore, rebound or other losses are not accounted for.[11]

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[11] For the comparison of different mix designs, these exclusions don't affect the environmental preferability of mixes if it is assumed that all mixes need the same mixing energy and have the same amount of losses and rebound.

2.2.2. Methodological Choices

LCA requires methodological choices throughout its four stages. Choices within the first stage, Goal and Scope definition, where system boundaries and addressed life cycle phases are determined, were already described above.

Within the next stage, Life Cycle Inventory analysis (LCI), where unit processes making up the product system with corresponding inputs and outputs are identified, one has to answer questions regarding allocation method and data source used.

In third stage, Life Cycle Impact Assessment (LCIA), impact indicators are calculated based on LCI data and characterisation factors. Here the methodological choices refer to which impact categories and indicators should be examined and further which LCIA-method should be used to calculate their values.

For a proper execution of the last LCA-stage, Interpretation, results are checked by performing sensitivity and uncertainty analyses. Varying applied methods or data sources provides insight in the robustness and validity of derived results.

Functional Unit

This LCA uses 1 m3 of sprayed concrete as the functional unit. As already pointed out, rebound and other losses are not included in this study. Therefore it is assumed that application of the amounts of materials which theoretically add up to 1 m3 of sprayed concrete - under the assumption of 0% losses and 0% rebound - really result in 1 m3 of sprayed concrete.

Data Source

The main data source for background data is EcoInvent v2.2. Because not every used material is available in EcoInvent, journal papers or EPDs are utilized in addition. For comparison reasons, also the environmental databases Ökobaudat[12] and ELCD[13] are used. A detailed look at different materials and their corresponding background data source is provided in subsection 5.1.1.

Foreground data, i.e sprayed concrete mix designs, come from Dr. Joachim Juhart from TU Graz, who is also part of the ASSpC-project.

Allocation

This LCA-study uses allocation based on economic value as base case scenario, i.e inputs and outputs of processes generating more than one product are divided between these products

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[12] `http://www.oekobaudat.de`, 15.02.2017

[13] Version 3.2, accessed via SimaPro.

on basis of their market value. Allocation based on mass, and the cut-off approach, where all inputs and outputs of the multifunctional process are attributed to the main product and other by-products are assigned with zero environmental burden, are used as kind of sensitivity check. More on allocation can be found especially in sections 3.5, 4.5, 4.6 and subsection 5.1.2.

LCIA method

This LCA uses EPD v1.03 as LCIA method. Reason for this is the fact that environmental impact indicator values of admixtures were calculated using this method in their corresponding EPDs and a method mix should be avoided. The included impact indicators are Acidification, Eutrophication, Global Warming, Ozone Depletion, Photochemical Ozone Creation and Abiotic Depletion Potential.

2.2.3. Sensitivity Analyses

Beside the sensitivity check through application of three different allocation methods, additional analyses regarding sensitivity of the results and/or uncertainty in the underlying parameters are performed. At first, the modelling of two materials[14] is verified by varying the LCIA method and two crucial inputs. Furthermore, a sensitivity analysis of the sprayed concrete mix designs with regard to the used LCIA-method is performed. Then, to address uncertainty in the background data on basis of sprayed concrete mixes, a Monte Carlo Simulation is ran. Finally, results of using EcoInvent v2.2 are compared with results derived under version 3.3[15]. More information on these methods and its results are presented in chapter 6.

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[14] The modelling of these materials is explained in subsection 5.1.1.

[15] Within EcoInvent version 3.3 the system model "Allocation, recycled content" is used.

3. Systematic Literature Review - Results

To support the LCA of sprayed concrete, a Systematic Literature Review (SLR) is conducted. Main findings and a meta-analysis of found paper samples are presented.

As mentioned in section 2.1, the following key word strings were used. Additionally, in brackets one can see the number of the initial sample[1] and the number of final papers in the corresponding sample. By looking at both numbers one can see that samples shrink much during the exclusion process.

- Sprayed concrete AND LCA (251/4)
- CEM AND LCA (248/35)
- Admixtures AND concrete AND LCA (111/26)
- Limestone AND concrete AND LCA (360/82)
- Gravel AND concrete AND LCA (388/121)
- Sand AND concrete AND LCA (704/122)
- Fly ash AND concrete AND LCA (349/83)
- Blast furnace slag AND concrete AND LCA (233/61)

In this chapter, main findings of the SLR and meta-analyses of different LCA choices are presented. Environmental impacts of different base materials of sprayed concrete, which were found in literature are shown in chapter 4.

3.1. Papers on Sprayed Concrete

During the Systematic Literature Review a huge research gap with regard to LCAs on sprayed concrete was identified. Just four LCA papers in both databases combined included sprayed concrete, with one of them being not reviewed in more detail due to its bad quality.

Huang et al (2015) conducted an LCA of a Norwegian Road tunnel. Unfortunately, the whole

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[1] combination of Springer and ScienceDierect

tunnelling process is assessed at once as the functional unit is 1 meter of tunnel. The results are indeed divided in different materials, but sprayed concrete seems to be included as a whole in concrete, which is of course also part of other processes. A more detailed look at the constituents sprayed concrete is not provided.[Huang2015]

Stripple et al (2016) compare Rockdrain, a new drainage system in tunnels, to a traditional drainage system with the functional unit of 1 square meter drainage area over a lifetime of 60 years. The results are just divided in life cycle phases (construction, maintenance, operation, and additional tunnel driving) and not on basis of its base materials. Also PVC layers and other materials for the drainage system are included in the LCA, which makes it nearly impossible to compare the study with an LCA of normal sprayed concrete[2].[Stripple2016]

Pretot et al (2014) performed an LCA of a wall consisting of a timber frame and sprayed hemp concrete. Here the lime-based binder is identified as the main contributor to several environmental impacts. This binder consists of 75% hydrated lime (98% CaO), 15% hydraulic binder (corresponding to CEM I) and 10% pozzolanic binder (not clarified in more detail). Here the environmental hot spots are identified, but the system examined is clearly not related to usually applied sprayed concrete. Also the composition differs a lot since hydrated lime is the main component of the binder and hemp is also used.[Pretot2014]

One more paper on sprayed concrete was found using the snowball approach[3]: Miliutenko et al (2012) examined a swedish road tunnel by the means of LCA, but only GWP and Cumulative Energy Demand (CED) are addressed. It is stated that concrete is the main contributor, especially the cement production and the process of calcination, but a closer look at constituents is not provided.[Miliutenko2011]

Another paper included the term shotcrete, but just stated that it is part of the refurbishment of a building without going in more detail or addressing it more precisely in the results section [Ferreira2015]. With this in mind, it becomes clear that there is a research gap, since no study on sprayed concrete deals with sprayed concrete on its own or even examines usual sprayed concrete. Furthermore, no paper concentrates on all constituents in relation to the end product or declares to take admixtures like superplasticizers or accelerators into account. Also the use of SCMs (supplementary cementicious materials) like fly ash or blast furnace slag to lower the environmental burden is not included the LCAs. This also emphasizes the innovative content of the present study.

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[2] Given the same functional Unit (m2) and life cycle phases assessed.

[3] For more information on the snowball approach see [Wohlin2014].

3.2. Number of Publications

The SLR revealed an increase of publications in the last couple of years. The first - even if small - spark was in 2010. The second and big one was in 2014. Graph 3.1 shows the combination of all examined papers with the two years highlighted, but also every sample based on the material searched for exposes the same.
Especially the second spark is formed very well. At the beginning of 2014, the IPCC Fifth Assessment Report was finished, providing an update on climate change. Also in that year, the World-SB[4] took place in Barcelona, recognizing LCA as an „*...adequate instrument in assessing sustainability...*“[5]. These two issues with focus on climate change and sustainability within the construction sector highlighted the need for "greener" alternatives to conventional building materials, paving the way for LCA practitioners springing at this topic.

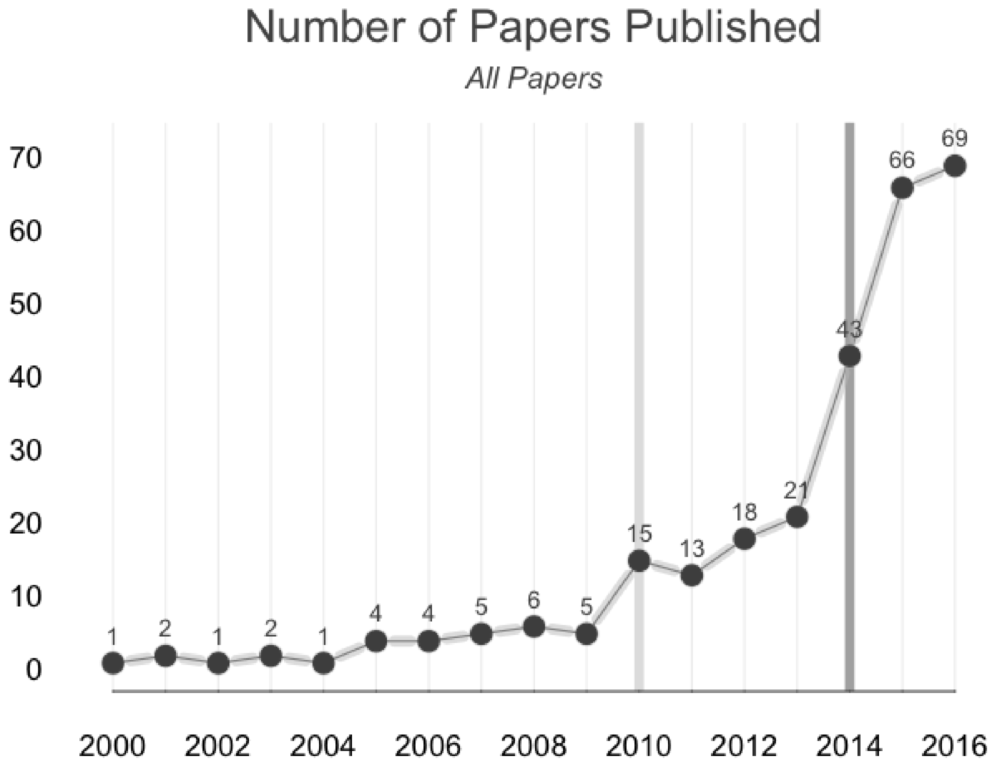
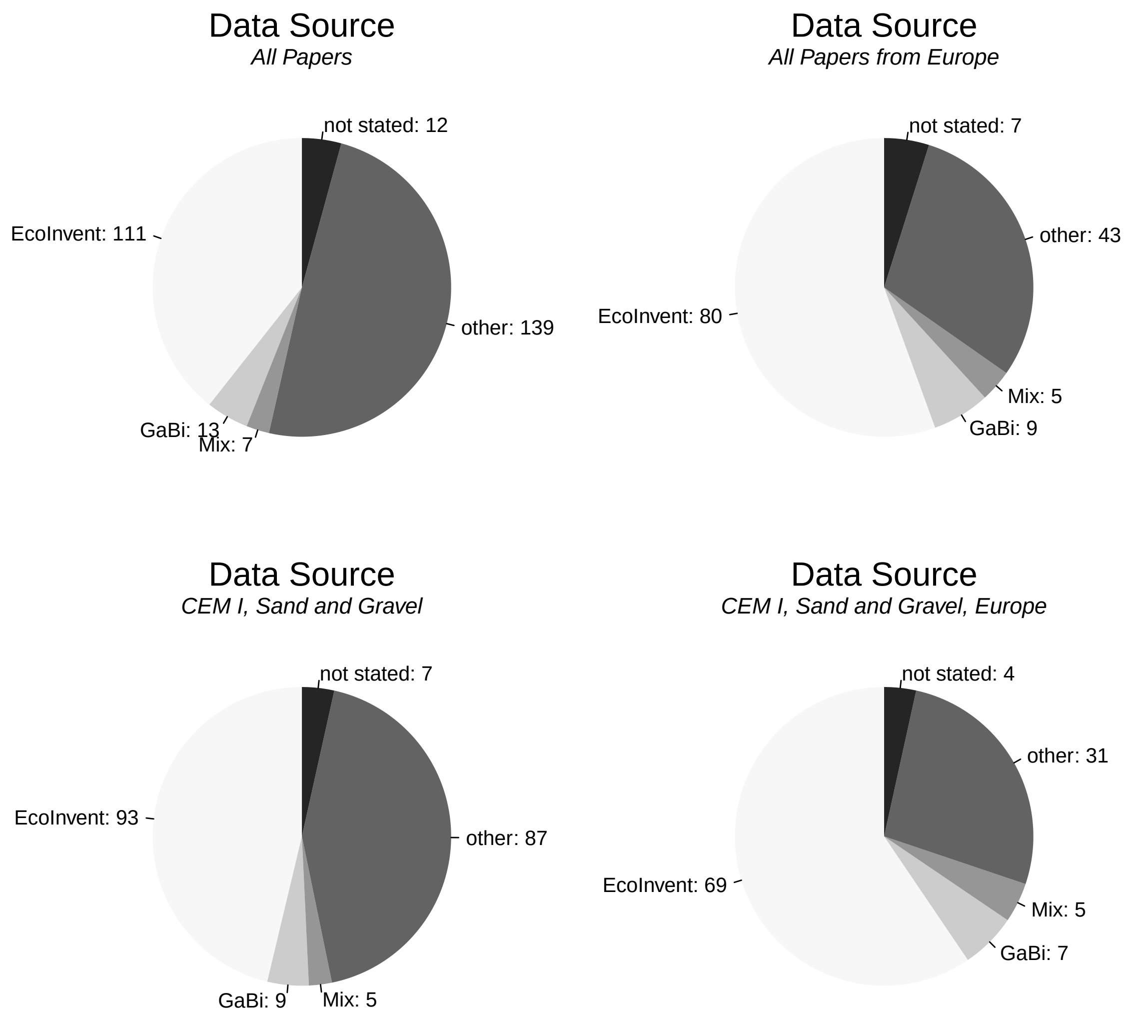


Figure 3.1.: *Temporal Distribution of Examined Papers*



Data Source
All Papers

Data Source
All Papers from Europe

Data Source
CEM I, Sand and Gravel

Data Source
CEM I, Sand and Gravel, Europe

Figure 3.2.: *Data Sources*

3.3. Data Source

A look at the data sources of published studies is very essential, because it directly answers one methodical question of which data source should be used in the LCA of sprayed concrete. Looking at data sources provides the state-of-the-art of ongoing research and prevent one from referring to outdated databases or sources not accepted by the scientific community. It also leads to more comparable results, if background data of different studies come from the same source.

It was watched out for two databases in particular: EcoInvent and GaBi. These two were

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[4] The World Sustainable Building 2014 Conference, `http://wsb14barcelona.org`, 16.01.2017

[5] The World Sustainable Building 2014 Conference, `http://www.gbce.es/archivos/ckfinderfiles/WSB14/WSB14_conclusions.pdf`, 16.01.2017

expected to be the most used sources on environmental data among published LCAs. The SLR confirmed just one of them: Among all papers reviewed and found of enough quality (282), 39% used EcoInvent, but just 5% used GaBi. Another 2% used both. It is clear, that therefore GaBi is discarded as possible database and EcoInvent becomes the one to concentrate on.

But figure 3.2 also show a different thing: The mix of all *other data sources* is dominating. Among them are data from other authors or studies, industrial partners, on-site measurements and foreign databases like the South Korean LCI database. Especially studies on admixtures don't use EcoInvent, because there are no data for these available, so authors have to draw on EPDs. Furthermore, EcoInvent is also lacking data on fly ash and blast furnace slag. As expected, the share of studies using EcoInvent increases if papers on these materials are excluded. The combined sample of sand, gravel and CEM I (201 papers) lead to the figure of 46%, which are using EcoInvent.

An even bigger increase is witnessed if just European papers are considered. An exclusive look at Europe seems legitimate because this study addresses sprayed concrete used in the heart of it. Furthermore, it is more or less useless for the purpose of this LCA to know which databases are used on the other side of the planet. Taking all European papers into account (144 papers), 56% of the studies are using EcoInvent . Again, if the same exclusion like above is done and just samples of sand, gravel and CEM I are considered (116 papers), the share becomes even bigger with 59%.

To be sure that no important database was missed, a deeper look at papers which refer to "other" data sources was committed. However, in European context, no often used data source (except EcoInvent) was identified. Among the other databases used are GEMIS or ICE, but the majority of those papers revealed literature or industrial partners as their main data source.

The increase of the usage of EcoInvent (or other environmental databases) in Europe compared to the world aligns with expectation. It is known that most LCA computer programs and databases just contain data from Europe or North America [Gursel2016]. There are in fact some databases specific for some small parts of Asia, like the Korea LCI database or LCA programs developed by the Architectural Institute of Japan, or the Japanese Society of Civil Engineering. But for other parts of the world, for example the whole continent of South America [Oyarzo2014], there is no specific life cycle inventory. Practitioners there have to rely on literature, and company specific or measured data, to perform proper LCAs in their own country's context.

The next set of graphs 3.3 covers the distribution of different versions among papers which used EcoInvent. All of them show that generation 2 is most used by far. Furthermore, 2.2 is the most used version, outscoring all 3.x, 1.x and other 2.x versions. Joining the scientific majority in order to fulfill the state-of-the-art requirement and the comparability requirement, version 2.2 is the chosen version within this thesis.

Besides that, it is also clear that not many studies with the newest version 3.3 have been published, because this version was released in August 2016[6]. So, in order to be up-to-date, EcoInvent v3.3 with the system model "Allocation, recycled content" is also used. It serves as a validity check for the results derived with v2.2. Furthermore, differences between these two version can be identified.

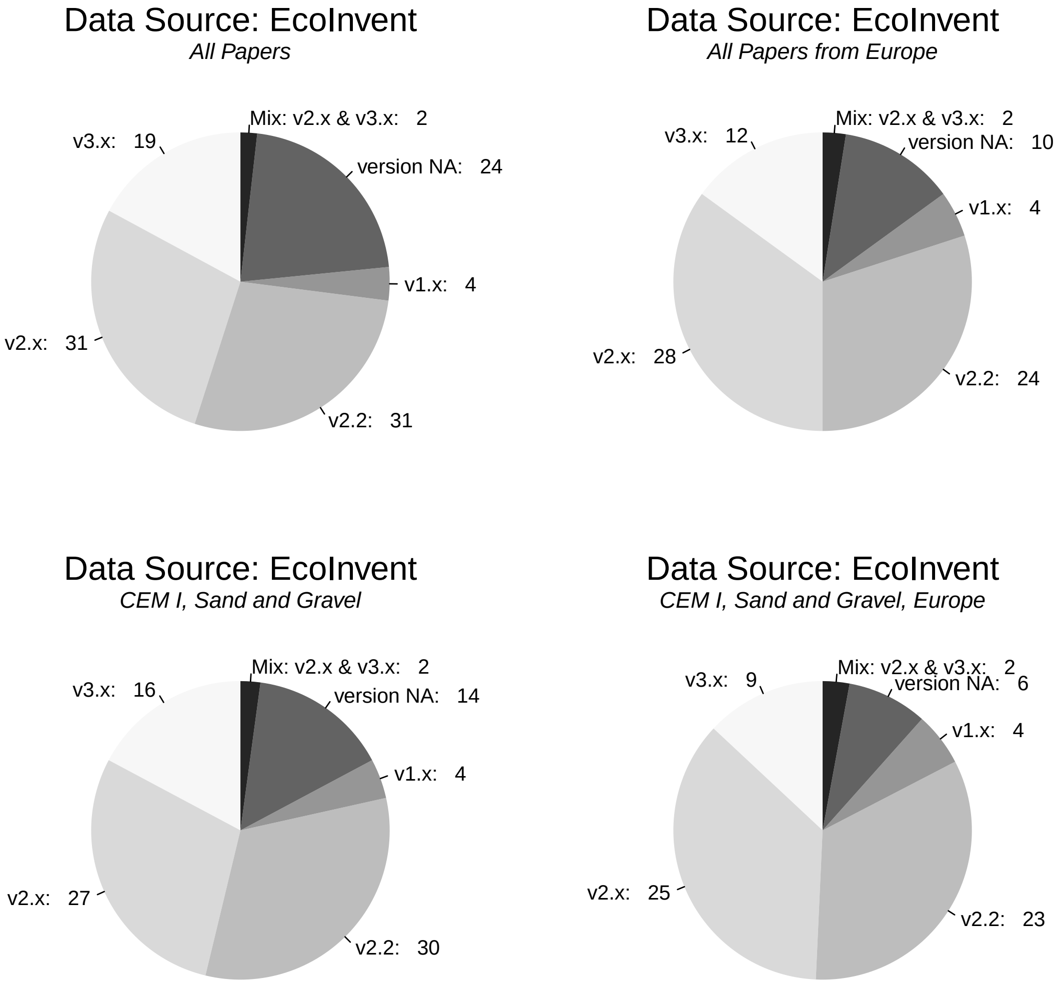

Figure 3.3.: *Data Sources - Version of EcoInvent*

3.4. LCIA Methods

Of the examined papers, 87 (31%) don't lose a word on which LCIA method(s) was used. This is a very high figure bearing in mind that these studies all offend against ISO requirements. As graph 3.4 shows, there is not a clear domination of one method like the dominance of EcoInvent

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[6] `http://ecoinvent.org`, 9.2.2017

regarding data sources. The most used method is CML with 22%, followed by Eco-Indicator, IPCC and ReCiPe with 10% to 13%. This is in line with findings from other reviews, stating CML is the most used midpoint method while Eco-Indicator is the most used endpoint one [Desideri2014; Ferrandez-Garcia2016]. Furthermore, 13% of the papers used other methods, like USeTox, or they were not clear which exact method they used. Interestingly, just one paper stated that characterization factors according to EN 15804 were used.

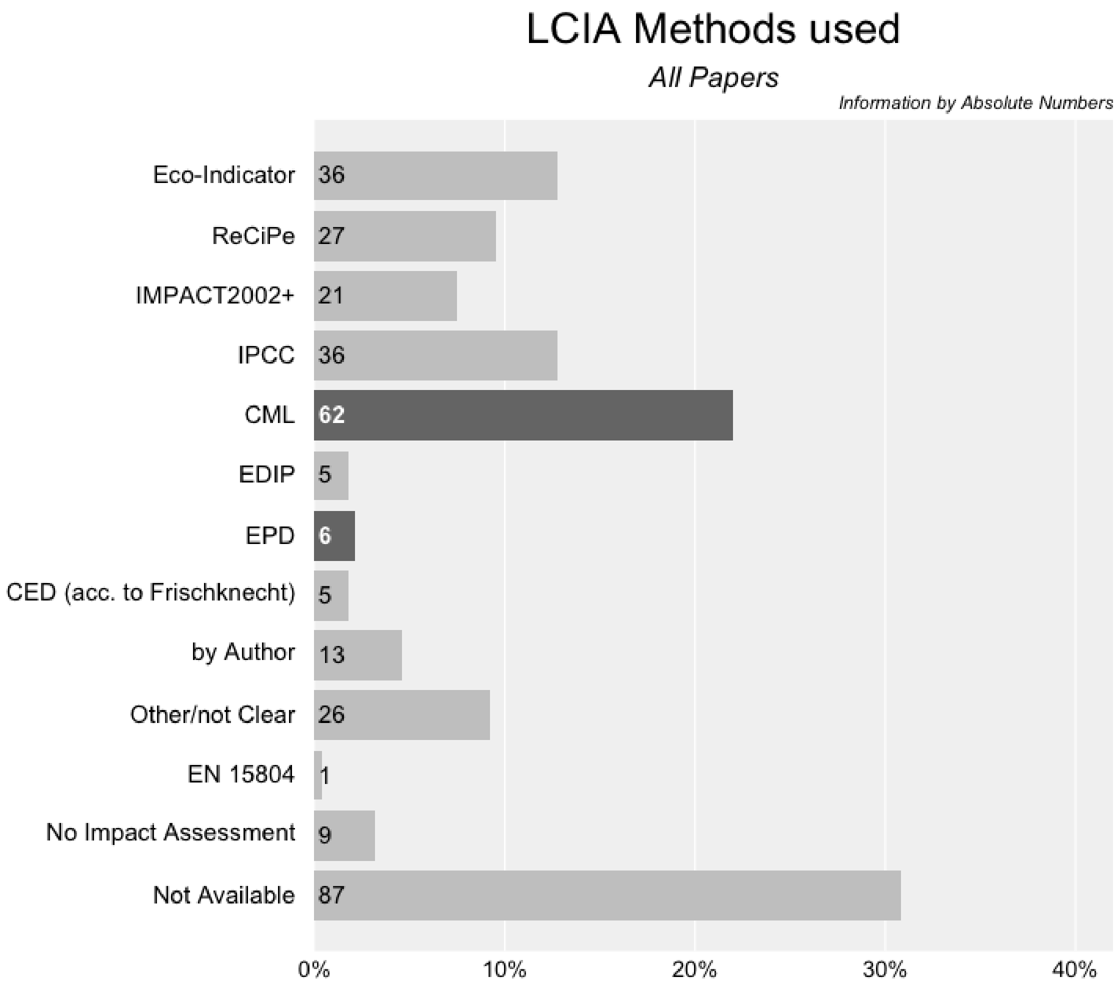

Figure 3.4.: *LCIA Methods used*

For the purpose of this study, it would be great to use the most used method CML 2002 baseline in its version 3.04. It is a midpoint - or pressure-oriented - method, which is often argued to contain less uncertainty than endpoint methods [Jolliet2003; LopezGayarre2016]. Beside the "traditional" midpoint indicators (AP, EP, GWP, ODP, POCP, ADP) CML also includes indicators related to toxicity (human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity and terrestrial ecotoxicity). Especially the admixtures are suspected to have a high impact on toxicity,

and since they are used in more amount in sprayed concrete than in normal concrete, it would be preferable to also cover these categories.
Unfortunately, there is no information on toxicity for admixtures which are used in the ASSpC project. The data for admixtures were calculated with the EPD method. It is supposed that admixtures have a not neglectable impact within sprayed concrete and can't be excluded like in some studies on ordinary concrete [Flower2007; Seto2016]. Because there is a lack of information on toxicity indicators regarding the used admixtures it wouldn't make sense to calculate these indicators for sprayed concrete. Therefore, and also to avoid mixing LCIA methods, the CML method is discarded and this study aligns itself with the method used for the admixtures: The EPD method.

3.5. Allocation

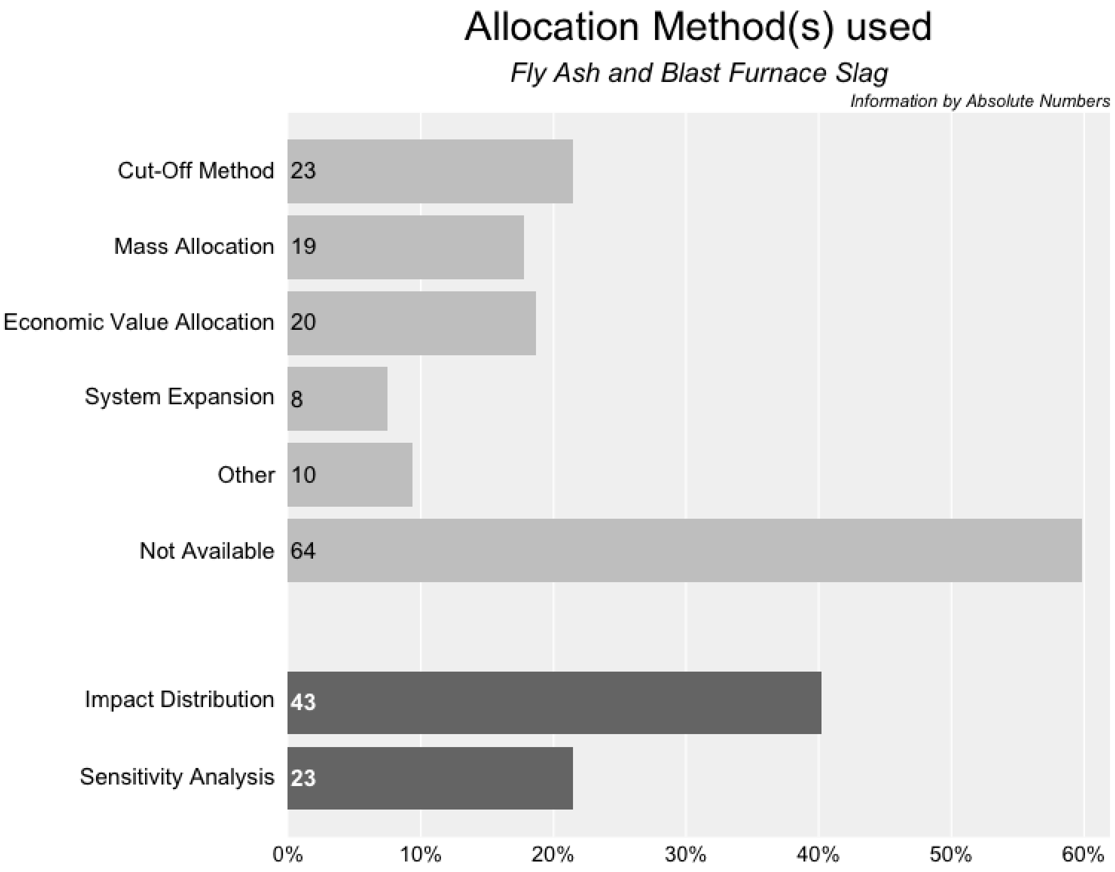

Figure 3.5.: *Allocation Rules Among Papers on Fly Ash and/or Blast Furnace Slag*

Impact distribution – or allocation – is the most controversial methodological choice which has to be made if so called by-products are involved in the functional unit [Frischknecht2000;

Ekvall2001]. By-products come from multifunctional processes. These are processes which have more than one product as outcome. Among the key word strings searched for during the SLR, fly ash and blast furnace slag are definitely by-products, since they are produced during the production of the main products electricity and pig iron. If such by-products are involved, one has to answer the question how the greenhouse gases emitted, electricity consumed etc. by the process should be divided between the different products.

The issue of allocation is of huge importance because the rule applied influences the results a lot. ISO states that one should avoid allocation by doing a system expansion [EN15804; ISO14044]. Therefore the examined system is expanded and all by-products of included multi-functional processes are included. On the one hand, allocation is evaded which obviates the question of a "fair" allocation method. On the other hand, new problems arise, like a revision of the functional Unit or the necessity of assessing all other by-products, which leads an increased effort at data collection [Kloepffer2014]. Also the consistency and hence the comparability of different LCAs can't be guaranteed [Chen2010]. Furthermore the replicability can get lost if system expansion leads to very large product systems.

Altering the functional unit is not reasonable for this study. ISO states, that if a system expansion is not possible, an allocation rule according to physical flow should be applied, but the results derived under the used rule should be verified by also applying other allocation rules [EN15804; ISO14044].

In literature, this requirement is fulfilled by most LCA practitioners using the cut-off rule and doing a sensitivity analysis with mass allocation and economic value allocation. The cut-off rule treats the by-product as waste, the other allocation rules divide the environmental burden on basis of mass or economic value. Both mass and economic value allocation have advantages and disadvantages: Advocates of the mass allocation highlight its accordance with the "physical relationship"-target demanded by ISO and criticize economic value allocation because of its exposure to market value fluctuations. Supporters of the economic value allocation claim that their rule best represent the reason for the production of a product: its economic value.

In general, none of these allocation rules is always the most appropriate [Kloepffer2014]. Nevertheless, for SCMs like addressed in this thesis, Chen et al (2010) clearly recommend economic value allocation over mass allocation, because economic value is linked to binding properties of the SCMs and the use of mass allocation (where usually more environmental burden is assigned to the SCMs) could lead to the cement industry turning away from SCMs and they could become wastes again, harming nature even more.[Chen2010]

Unfortunately, as shown in graph 3.5, not every LCA seems to be aware of allocation methods: Looking at the combined sample of fly ash and blast furnace slag (107 papers) – both materials are by-products and LCAs addressing them should use some kind of allocation criteria – just 43 papers (40%) performed impact distribution and only 23 papers (21%) ran a sensitivity analysis.

This is a very low number because it means that nearly 80% of the studies are not in line with ISO requirements. This LCA will meet the ISO rules and use cut-off, mass and economic value allocation.

3.6. Life Cycle Phases

As expected, most LCAs are done using Cradle-to-Gate (A1-A3) or Cradle-to-Grave (A1-C5) methodologies, which are highlighted in graph 3.6. Also sometimes Cradle-to-Gate is supplemented with transport to the site, which leads to a Cradle-to-Site LCA (A1-A4), or benefits from reuse or recycling are added to a Cradle-to-Grave study to cover all phases of a product from A to D[7]. These four types make up 64% of all examined LCA studies.

Adding not just the transport to the site, but also adding the site work itself to a Cradle-to-Gate study covers the whole stage A and is also quite common with 11%. 12% of all papers head one step further as they also include stage B. This combination of A+B is very popular in LCAs of houses or dwellings, because there it's the use stage, especially with its heating demand, that contributes much to the environmental impacts.

LCAs which do not start with the cradle of the product are not published very often, because they are not in line with EN 15804. The standard clearly points out that the phases A1-A3 have to be included [EN15804]. As the graph shows, studies covering just one of the stages B, C or D, or a combination of C and D are very rare. They add up to only 5% of all papers reviewed.

Less common are only LCAs that skip phases. For instance, a Cradle-to-Site LCA is complemented with the end-of-life stage C, skipping site work (A5) and the whole use stage B. Another example is a Cradle-to-Gate LCA where material extraction (A1) is cut off, leaving behind an LCA which covers just A2 and A3. One can doubt that with these studies comparable or useful results are derived.

But the biggest surprise is that almost 5% of the reviewed papers fail to disclose the covered life cycle phases. While one can be – up to a certain extend – able to relate to studies not stating anything about allocation or LCIA methods, withholding information on the phases assessed is, besides being also not on line with ISO regulations, simply inexplicable. Results of such studies are useless if the authors are not contacted for information on the covered phases.

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[7] Within the meaning of the standards regarding LCA, phase D is not part of the life cycle as it represents additional information.

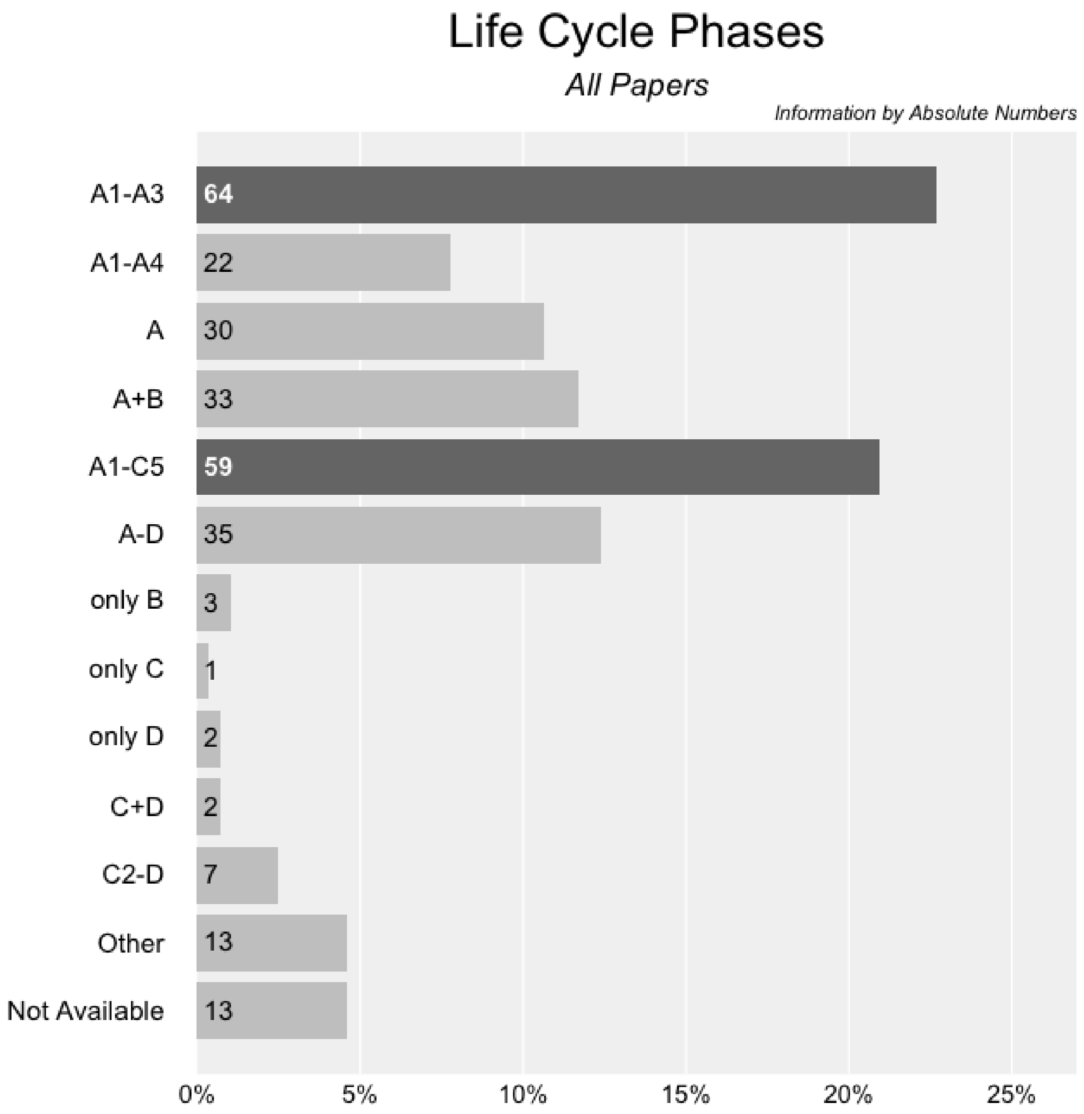

Figure 3.6.: *Covered Life Cycle Phases*

3.7. Functional Unit

Because construction materials or constituents of them were examined, it was expected that most papers use weight (kg/t) or volume (m3) as the functional Unit (fU). As the graph shows, there are also a lot of studies which use a piece, an area (m2/km2) or length (m/km). A "piece" as the fU can be a concrete slab or column with specific dimensions, a whole house, a bridge or a defined high way section. LCAs with an area as fU mostly come from the housing sector, where m2 net floor area is the most common unit to refer to. Studies with meter or kilometer as fU are mainly LCAs of streets or pavements.

A look at papers which cover only A1-A3 (Cradle-to-Gate) confirms what was said: Because now most LCAs of houses and dwelling are not included (they mostly use also phase B), also the share of LCAs which use square meter as fU decrease. The same is true for LCAs of streets and pavements. They use meter or kilometer as fU and usually cover at least the whole construction stage (A).
Therefore, in graph 3.7 the share of LCAs using an area or length decrease if just Cradle-to-Gate studies are considered while the share of studies with weight or volume as fU increase. This leaves behind the choice between kg or m3 of sprayed concrete for this study. Since the mix designs for sprayed concrete are available referring to one cubic meter, the choice is not hard to also use it as the functional Unit.

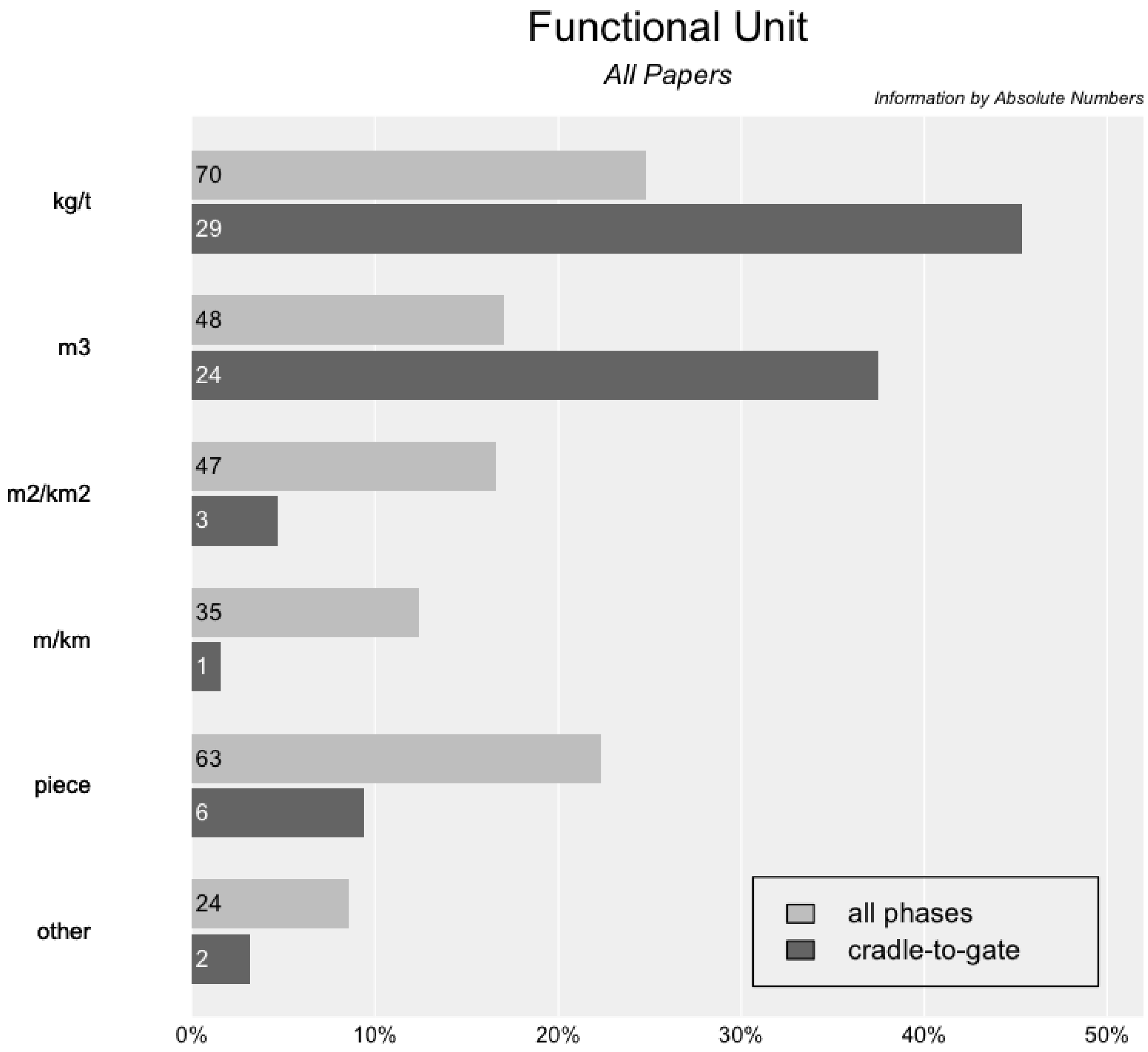

Figure 3.7.: *Functional Unit with Emphasis on Cradle-to-Gate Studies*

3.8. Further Findings

Another interesting but expectable result of the SLR is the realisation that too many LCA experts are only interested in GWP, or even just CO2. For cement alone this was already observed by Kajaste and Hurme (2016) [Kajaste2016]. This does not mean that focusing just on one impact indicator has no advantages, but it can lead to losing the whole picture resulting in wrong decisions.

Another gap found is the lack of information on impacts of very very fine milled material. It is known that more and more energy has to be spent the finer the targeted grain size gets, but detailed notes were not found during the SLR.

4. Environmental Performance of Sprayed Concrete Constituents

In this chapter the main constituents of sprayed concrete are examined and compared by their environmental impacts. A short description of the material is provided at the beginning of each section. Then, the midpoint indicators Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP), Ozone Layer Depletion Potential (ODP), Photochemical Ozone Creation Potential (POCP) and Abiotic Depletion Potential (ADP) of 1 kg of material are shown on basis of data provided by literature (found with the SLR), EPDs or retrieved from the databases Ökobaudat[1] and ELCD[2], if data was available. Also the impacts of the actually used materials[3] will be compared to results from the SLR. The presented impacts always cover the phases A1 - A3, i.e. they represent the environmental burden on a Cradle-to-Gate basis.

Because the SLR did not lead to a large number of results for every material, not for every material a graph is plotted. Results of the SLR for these materials are shown in the appendix or in the supplementary electronic material.

4.1. Cement

The cement production uses the main raw materials limestone, sand, clay, and iron ore. The materials are crushed, milled and burned in rotary kilns. Then, after cooling, the product is milled and gypsum is added to delay the setting time.[4] [Huntzinger2009; Scholz2011; Hegger2005]

Due to its outstanding qualities regarding strength and - for sprayed concrete even more interesting - early strength development etc., cement is one of the most used materials in the construction industry. Unfortunately, as shown in previous LCAs, cement is the main driver

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[1] `http://www.oekobaudat.de`, 15.02.2017

[2] Version 3.2, accessed via SimaPro. Indicators were calculated using the EPD v1.03 method.

[3] Used materials are listed in subsection 5.1.1

[4] Information on the cement production process with regard to the modelling in EcoInvent can be found in [Kellenberger2007].

of CO2 emissions of normal concrete [Collins2010; Flower2007]. The impact of cement goes to the extent that its production is liable for 4-7% of all CO2 emissions worldwide [Achal2015; Flower2007; Shin2016; Yang2015].

But also the high impact on other indicators of cement is well known. Serres et al, for example, reports in their Cradle-to-Gate LCA of concrete that cement is responsible for at least 70% of all environmental impacts also assessed under the EPD methodology[5]. For GWP it is with at least 90% even more.[Serres2016] Bearing that in mind, it is not surprising that there is a strong endeavour to reduce the cement content in concrete to make the concrete more environmentally friendly. Whether the same is true for sprayed concrete will be shown in chapter 5.

4.1.1. CEM I

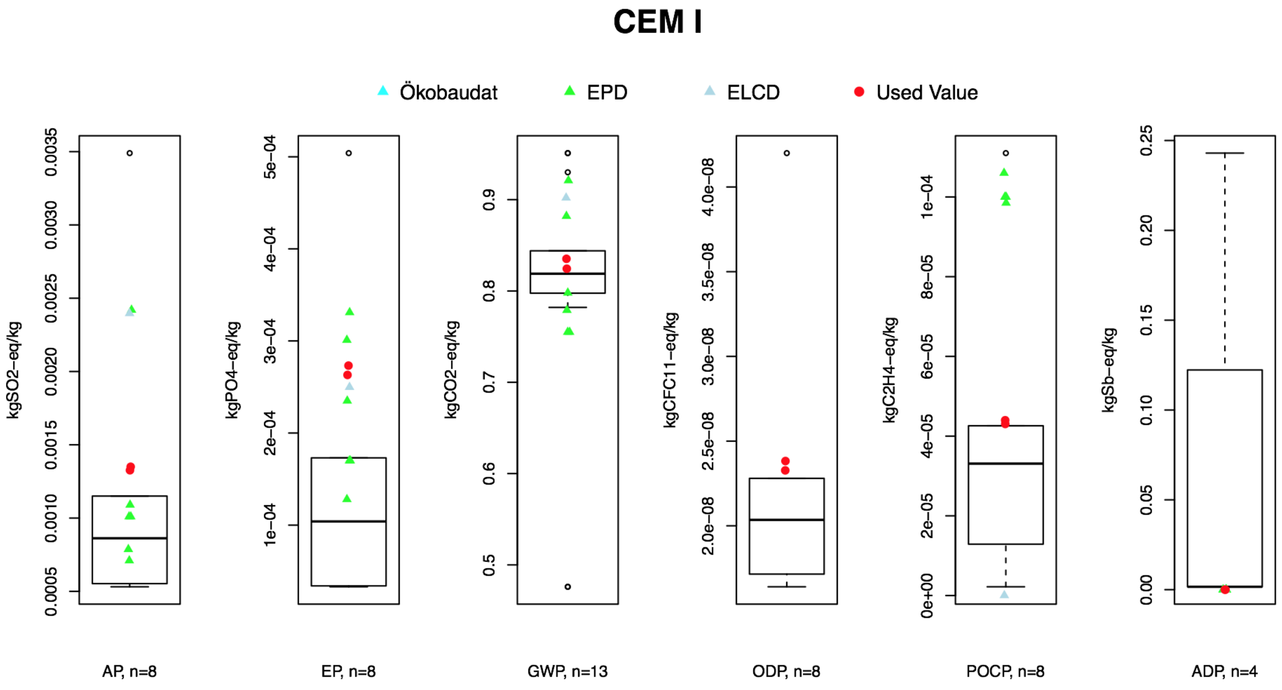

Figure 4.1.: *Impacts of 1 kg CEM I*

CEM I is the cement type with the highest amount of cement clinker with at least 95% [Scholz2011]. Therefore, the high environmental impacts of the clinker also determine the impacts of CEM I. As graph 4.1 shows, the used impacts on Acidification and Eutrophication are very slightly above findings from literature, but are in line with found EPDs and the ELCD database. For GWP there is even a better fit.

When it comes to ODP, the graph doesn't even show data from the other sources because they differ very much: Findings from ELCD (2e-4) assign much more ODP to CEM I than the literature

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[5] AP, EP, GWP, ODP, POCP and ADP.

(2e-8). In contrast, the EPDs state lower figures for ODP (4e-13 to 7e-9). At POCP quite the opposite is true, as EPDs assign more impacts to CEM I than is used in literature while ELCD is vaguely in line with impacts derived from the SLR. However, for both indicators, the used data fit well to observations from literature, even though they affiliate at the upper end of the spectrum. For Abiotic Depletion Potential, the boxplot is not representative because there were only four observations. It can be stated that here the used data, data from EPDs and ELCD are somewhat in line with each other.

Of course impacts differ within the CEM I sample, because there are different types of CEM I regarding strength and setting time. In this LCA there are also two different CEM I used: One with 42,5 MPa and one with 52,5 MPa. Of course, the higher the strength, the higher the environmental impacts of the cement.

4.1.2. Ordinary Cement

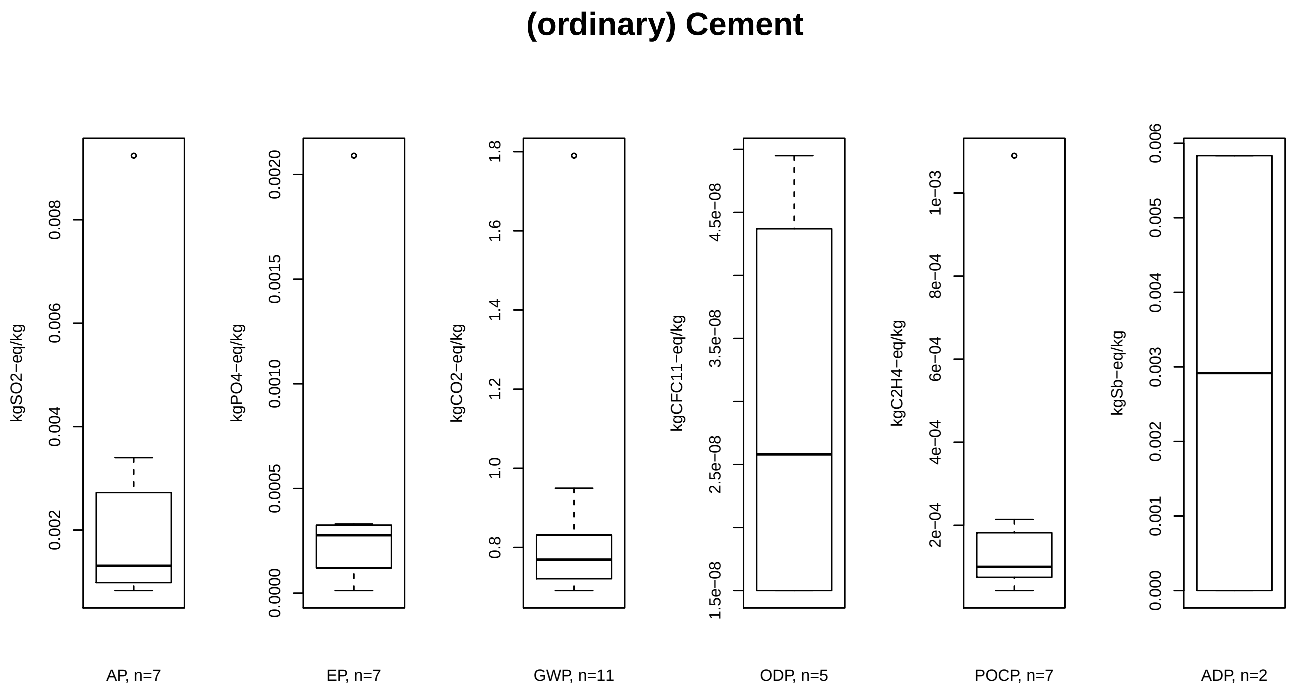

Figure 4.2.: *Impacts of 1 kg Cement*

As illustration 4.2 indicates, the term "cement" is accompanied by a bigger uncertainty regarding all examined environmental impacts than CEM I. In contrast to CEM I, where the amount of additives is limited to 5 percent, other cement types can have much higher shares of additives, altering the environmental impacts of the product. For example, Ökobaudat[6] lists some types of CEM II, CEM III and CEM IV, with CEM III having just half the Global Warming Potential as CEM

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[6] `http://www.oekobaudat.de`, 15.02.2017

II.
The allowance of more additives reduces the amount of clinker in an "average cement", which should reduce the environmental impacts of the product. Interestingly, the EP and POCP used within literature are slightly higher for cement than for CEM I. Reasons for this could be the use of slags as additives, and depending on the allocation method used impacts stemming from the pig iron production are assigned to these additives, resulting in higher EP and POCP.

Since the used mix designs for sprayed concrete use only CEM I, the other cement types are of less importance and not examined in more detail here. This is also the reason why no numbers from other databases or EPDs for these cements are plotted. However, the shown results of the SLR refer to the term "cement" or "average cement", where the authors failed to declare the exact cement type. Unfortunately, these results are unsuitable as inputs or benchmarks for the LCA of sprayed concrete.

4.2. Aggregates

After extraction in quarries or surface mines, aggregates are washed, crushed, dried and sorted.[7] They represent the biggest share of sprayed concrete mix designs, but, nevertheless, have a very little environmental impact since the necessary processes are by far not as intensive as processes in the cement production.

In the SLR, "Sand" and "Gravel" were searched separately. The difference between them is the grain size. Results for the samples can be found in the appendix. But to give a full view over aggregates, findings for gravel, sand, and other aggregates[8] were combined. Also results from databases or EPDs are plotted in graph 4.3.

For AP, EP and GWP literature, used data, ELCD and EPDs agree with each other. The two different values for used data arise because two different types of gravel are used: round and crushed.

At the graph presenting ODP, the other data sources again, like for CEM I, do not agree with literature because impacts assigned from ELCD (5e-7 to 1e-6) are much higher than the SLR suggests (1e-9). Ökobaudat does the contrary as it allots much less burden (1e-12) to it. For POCP on the one hand at least Ökobaudat (1e-6 to 4e-6) fits to literature On the other hand, ELCD does the opposite as it does for ODP as it assigns less POCP (3e-10) to aggregates than literature. Compared to the already good accordance of used values and values derived from

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[7] Information on aggregates' production process with regard to the modelling in EcoInvent can be found in [Kellenberger2007].

[8] Other aggregates refer to "Sand and Gravel", "Aggregates" and all other aggregates which couldn't clearly be assigned to "Sand " or "Gravel".

the SLR, at aggregates there is an even better fit.
As the graph indicates, there is a broad distribution at ADP in literature. The used data (7e-9 to 2e.8) and data from Ökobaudat (3e-9) are located at the lower tail of this distribution. ELCD reduces the assigned depletion potential even further to a minimum of 7e-11 kgSb-eq/kg.

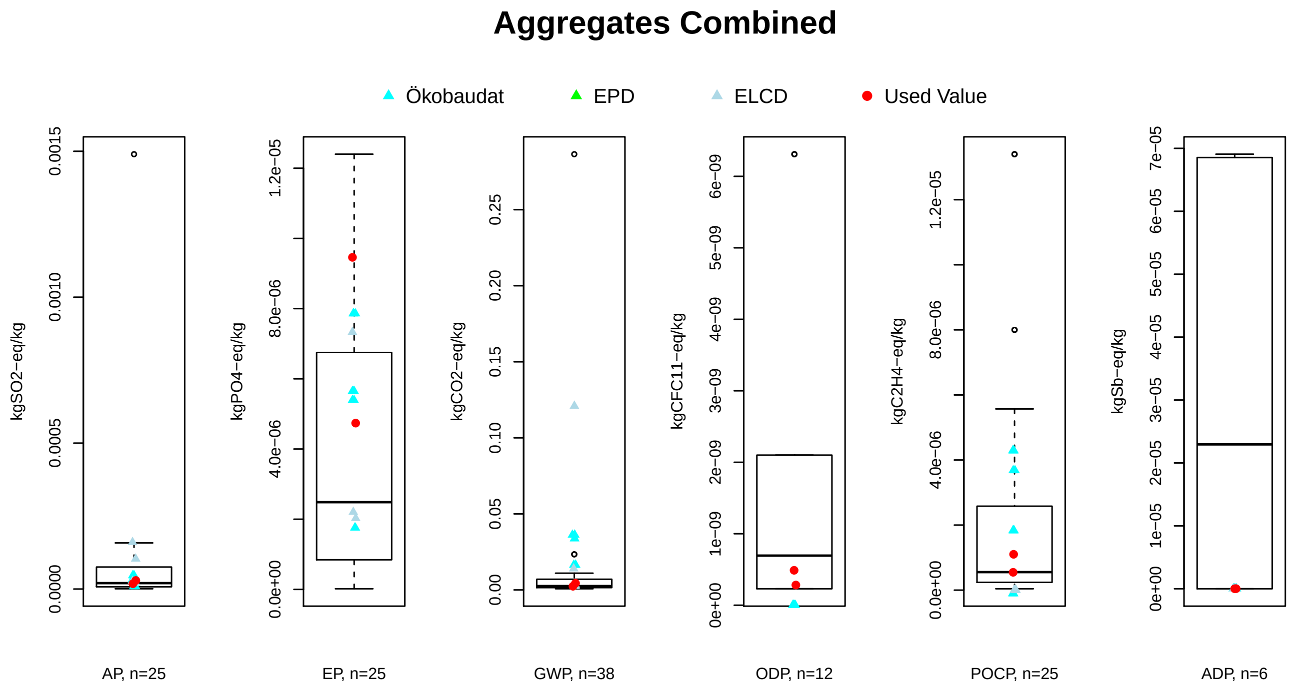

Figure 4.3.: *Impacts of 1 kg Aggregates*

This is in line with the fact, that ADP is the most controversial impact indicator among the six examined, due to the impossibility to establish "correct" characterisation factors. Among the reasons for this are problems at setting up just one abiotic depletion definition and different paths to the quantification of it - all with different results. Depending on the respective understanding of the abiotic depletion, different LCIA methods use wide apart characterisation factors, which inevitably lead to huge gaps in the results.[VanOers2016]
As already stated, the environmental impacts are very low compared to CEM I and average cement. Differences within the group "Aggregates" can be traced back to the base material, differences in quality, whether they are recycled or quarried and whether they are imported or not. While it is clear, that the higher the quality of the aggregates are, the higher are the environmental impacts [Faleschini2016] and importing the aggregates worsens the environmental impacts because transport is added [Gan2016], findings diverge on the issue of recycling. Some authors state that recycled aggregates have lower environmental impacts than natural ones [Faleschini2016; Gan2016], others claim the opposite [Marinkovic2010; LopezGayarre2016].

4.3. Admixtures

Admixtures[9] are essential constituents of sprayed concrete. Since there aren't any environmental data about it on databases like EcoInvent or ELCD, most authors refer to the EPDs from the European Federation of Concrete Admixture Associations Ltd. (EFCA) if they lack company specific data. In some LCA studies on concrete, admixtures are omitted from the assessment, because of their low total impact [Flower2007; Seto2016].

Beside the fact that this should be called into question for concrete, for sprayed concrete discarding impacts from admixtures would be a fatal mistake. While [Flower2007] states that 2 litres admixtures per cubic meter of concrete can be ignored, the examined sprayed concrete mixes use approximately 30 litres per cubic meter. On a per kilogram basis, Superplasticizers have a more than two times bigger impact regarding AP, EP and GWP than CEM I, while surpassing CEM I by a factor of 7 and 8 at POCP and ADP.

4.4. Limestone

In the building and construction industry limestone occurs mainly in three different chemical compositions. Unfortunately all three of them are sometimes referred to as limestone, although they differ a lot in their properties and environmental impacts. For comparisons one has to look deeply in found literature to make sure which kind of lime is meant. The three types are [Scholz2011; Hegger2005]

- limestone $CaCO_3$,
- quicklime CaO and
- hydrated lime $Ca(OH)_2$.

The rock is quarried, crushed and sieved.[10] Then the inert limestone it is either packed, stored and sold, or it is transferred to the kiln, where the calcination takes place and quicklime emerges. Quicklime can be used for example as fertilizer, but within the "lime circulation" it is milled and hydrated by water to obtain hydrated lime. Hydrated lime, due to its hydraulic properties, is then used in the production of mortar or renderings.[SagastumeGutierrez2012; Scholz2011; Hegger2005]

There is a huge difference between limestone, quicklime and hydrated lime regarding the

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[9] For more information on different types on admixtures see [Scholz2011].

[10] Information on the lime production process with regard to the modelling in EcoInvent can be found in [Kellenberger2007].

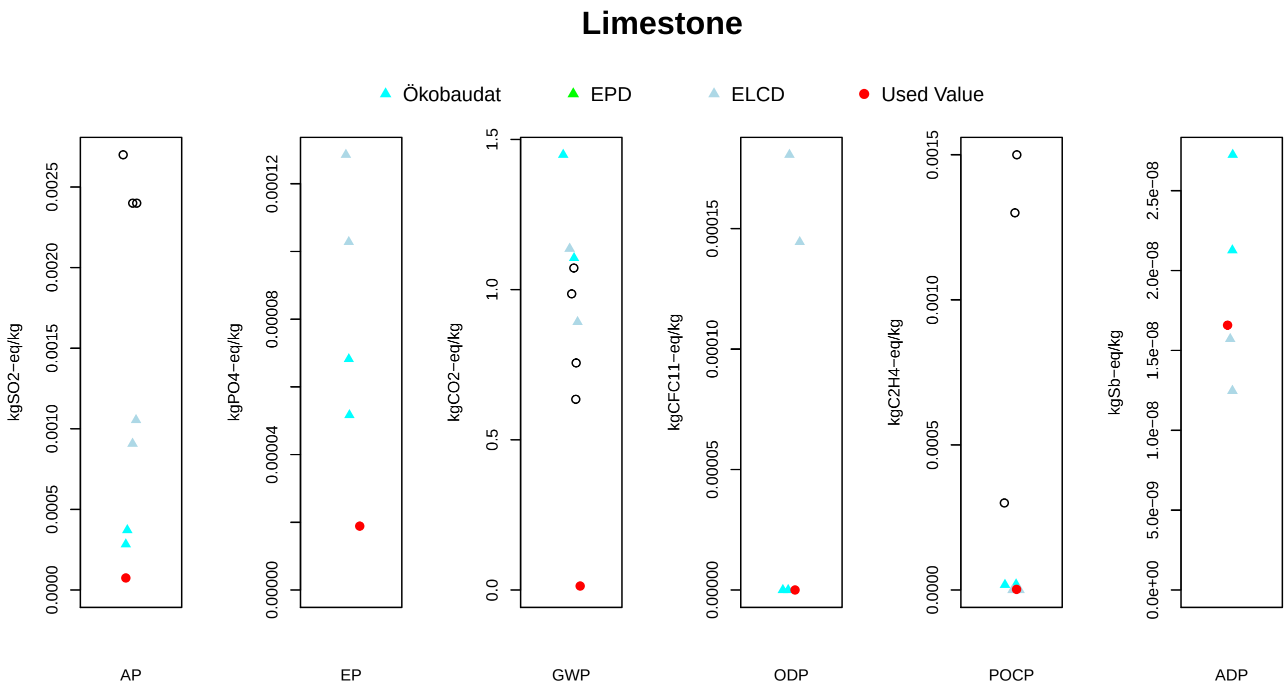

Figure 4.4.: *Impacts of 1 kg Limestone*

environmental impacts, because the calcination of the limestone is responsible for the highest share of the environmental burden. For the sprayed concrete mix designs, the term limestone refers to a inert limestone powder with d50=30µm which is used as a macro-filler for optimisation of the packing density. Because there is no calcination necessary, very little impacts are associated with it, like graph 4.4 indicates. The observation from literature all show impacts for hydrated lime, while Ökobaudat and ELCD both possess data on quicklime and hydrated lime. It can be seen in the picture, that literature is lacking environmental information on limestone. Of the 82 papers on LCA and limestone examined, only five of them revealed any environmental impacts of the material. Just two of them refer to Cradle-to-Gate assessments. Sagastume shows impacts for limestone of three different plants in Cuba, addressing only AP, GWP and POCP of the indicators which are used in this thesis[SagastumeGutierrez2012]. Grist only includes GWP [Grist2015] which leads to a graph having no information from the SLR regarding EP, ODP and ADP.

Interestingly, data from literature and additional information from Ökobaudat and ELCD match to some extent only at one impact indicator, GWP. While ELCD and Ökobaudat agree on all other five examined indicators, there is a huge difference at ODP. Nevertheless, the data used in this study differs a lot (except for ADP) from the other data shown, because, as already mentioned, the milled limestone itself without calcination and/or hydration is used for sprayed concrete. As a result, the substitution of cement with this macro-filler has the ability to lower the environmental burden of sprayed concrete.

4.5. Fly Ash

The best way to reduce the environmental burden of concrete is to replace a big amount of cement with so called SCMs (supplementary cementitious materials) like fly ash (FA) or blast furnace slag (BFS) [Habert2013; Josa2004; Mandley2015]. Van den Heede/de Belie report a 18-27% lower GWP if high volumes of fly ash are used as a replacement for cement [VandenHeede2014]. Teixeira et al even show a GWP decrease of 47% if 60% of the cement is replaced by fly ash. The other impact indicators within the EPD methodology also decrease by 13-44%.[Teixeira2016]

The problem with statements like these is that the allocation rule used behind such results has to be considered, because now the by-products FA and BFS are involved. As already explained in subsection 3.5, results can change a lot if another allocation rule is applied.

Fly ash originates when coal is burned in coal power plants for electricity generation [Chen2010]. This means, it is produced in a multifunctional process, i.e. a process which generates more than one product. Since 2008, a European directive states that fly ash and blast furnace slag are not wastes anymore and have to be treated as by-products [EuropeanCommission2008]. This means that an allocation rule has to be introduced to assign the appropriate share of the electricity generation process to fly ash. Among the three examined methods cut-off, mass and economic value allocation, mass allocation is the most unsuitable one [Chen2010], as also pointed out in subsection 3.5.

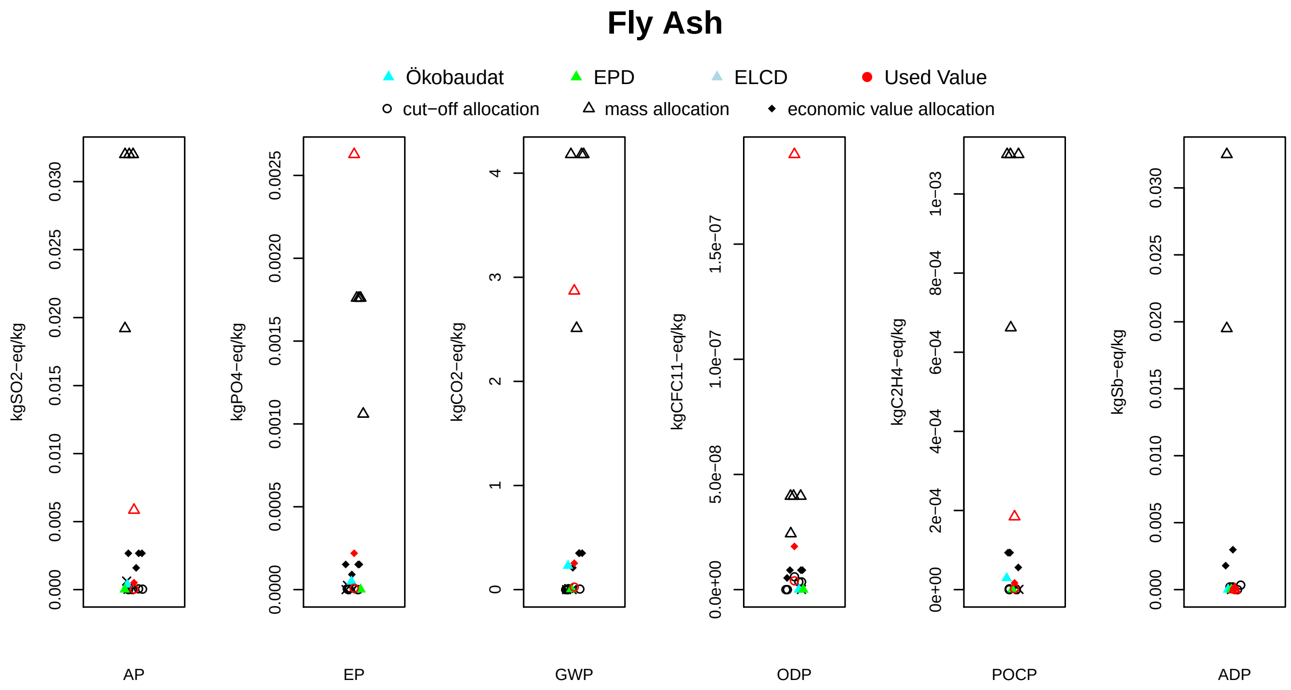

Figure 4.5.: *Impacts of 1 kg Fly Ash*

Because of the small number of data sources within the literature for 1 kg of fly ash and to show the several allocation methods used, a different manner of representation is chosen here. As graph 4.5 clearly shows, there is a huge gap between the three main allocation methods. Mass allocation assigns by far the most impacts to the product, increasing the declared environmental burden by a factor of 12 compared to economic value allocation for five of the six assessed impact categories.

Within the cut-off-approach (or no-environmental-impact-approach) only the impacts from the secondary process, i.e. drying and transportation to intermediate storage, should be assigned to fly ash [Chen2010]. But some Authors [Muller2014; Muller2014a] even discard these processes, assigning zero environmental burden to the product within the cut-off approach.

The graph also shows that most of the examined papers reveal exactly the same environmental impacts for the different allocation approaches. This is due to the fact that most authors refer to Chen et al (2010) when it comes to including fly ash or blast furnace slag in their LCAs. Chen et al (2010) show a detailed description on these two products with regard to LCA, also providing the results for eleven impact indicators (CML 01) for the three allocation approaches. Furthermore, inputs and outputs are presented for the corresponding processes to make it possible to model fly ash and blast furnace slag in a LCA computer program.

Also Ökobaudat provides indicator results for fly ash, unfortunately failing to state clearly which allocation method was used for the primary process. The description admittedly states that *some* demand for electricity and heat are allocated to fly ash but not to which extent. However, the secondary processes according to Chen - transport to storage and storage itself - are included. Looking at the results, the fly ash from Ökobaudat is located between economic value allocation and the cut-off approach, underlining the inappropriateness of mass allocation. Also an EPD from the Danish Technological Institute for Fly Ash, clearly admitting the use of economic value allocation, confirms this issue.

As shown in more detail in chapter 5, in this LCA fly ash and blast furnace slag are modelled in SimaPro on basis of inputs and outputs presented in [Chen2010]. The graph shows that there is a discrepancy between the impacts derived in this LCA study and the original ones from Chen et al (2010)[11]. Interestingly, the deviations occur in different directions and magnitudes among the different impact indicators. Thus, this thesis assigns more EP and ODP, but less AP, GWP, POCP and ADP to fly ash than Chen et al (2010).

The discrepancy in three of the six impact indicators is not disastrous. But, considering AP and POCP, the differences are very big because the derived impacts are only about one fifth of the original ones. The deviation is even more severe for ADP, where the assigned impact is not even close to the per mill range.

Although the divergences are big for three indicators, these calculated values are used. A look

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[11] This discrepancy is discussed in subsection 5.1.1.

at the graph still shows a good fit of the used data to data from the Danish EPD or Ökobaudat if mass allocation is discarded.

4.6. Blast Furnace Slag

Blast furnace slag (BFS), the second SCM addressed in detail is also a by-product, because it is generated during the pig iron production in blast furnaces [Chen2010]. Among literature, the CO2 reduction potential of blast furnace slag is known [Bieda2012]. Studies of normal concrete report GWP reductions of 37-54% if high volumes of the binder (60-65%) are substituted with BFS [Collins2010; Won2015].

While the use of BFS in normal concrete can have also technological advantages like an increase in long term strength and durability, using too much BFS in sprayed concrete can have disastrous consequences because it lowers the early strength [Won2015]. This is also the reason why CEM III, which has a very high slag content is useless for sprayed concrete.

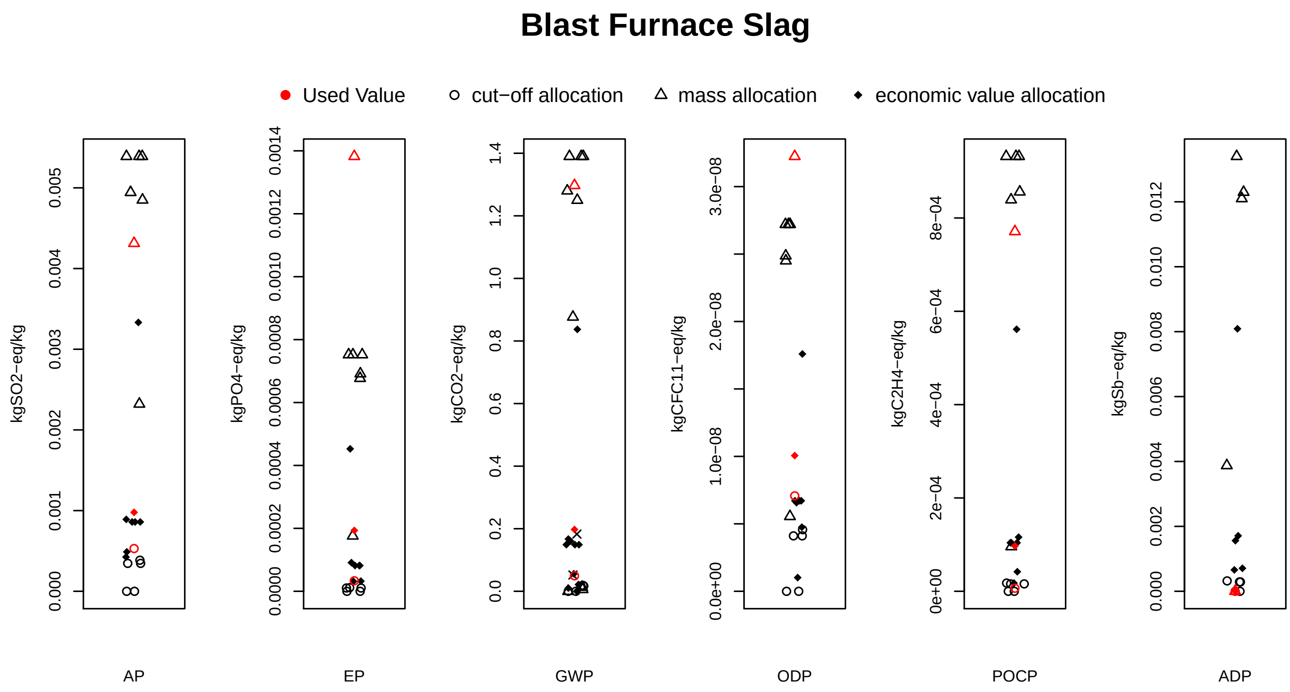

Figure 4.6.: *Impacts of 1 kg Blast Furnace Slag*

What was said for fly ash is also true for blast furnace slag (BFS): The gap between mass allocation and economic value allocation is indeed not that big, but an increase by the factor of 9 can be found in half of the assessed impact categories. But also within the economic value allocation methodology, one outlier upwards is detected. This is the highest possible impact according to Habert 2013, as he uses an allocation range of 0,6 to 12,6% depending on different prices for the slag and the iron or steel [Habert2013]. So he calculates an area where the impacts will fall into, ranging from 0,056 to 0,837 kgCO2-eq/kg GWP for example. As comparison, Chen et al use 2,3%. As the other observations among literature show, this high impacts seem not very suitable.

Another outlier is Saade et al, who show little environmental burden using the mass allocation method compared to other authors. Interestingly, the share of the blast furnace process allocated to BFS is with 19,68% perfectly in line with the 19,4% used in Chen et al (2010).[Chen2010; Saade2015]

As for fly ash, the most cited paper is the one from Chen et al (2010). Within the cut-off methodology, they allocate the burden of the secondary processes (granulation, dewatering, drying, grinding and stock) to the product and most of other authors follow. Just Müller et al. (2014,2014a) again discard the secondary processes completely, arriving at a product with no associated environmental burden [Muller2014; Muller2014a].

While on the one hand, as graph 4.6 shows, there are more data sources within literature available than for fly ash, on the other hand, neither Ökobaudat, ELCD nor EcoInvent lists some kind of blast furnace slag. Furthermore, no EPD was found.

Graph 4.6 shows that deviations of the used values lie in the same direction as they did in section 4.5 Fly Ash. However, the used impacts for BFS are very close to the one displayed in the original paper by Chen et al (2010). Only the abiotic depletion potential - again - is not of the same magnitude. Moreover, the EP used is more than two times the value calculated by Chen et al (2010). Nonetheless, a look at the picture with focus on economic value allocation shows that it is within the range calculated by [Habert2013].

4.7. Fillers

Fillers are used for optimisation of the packing density of sprayed concrete, which leads to a higher tightness and durability. For this the grains have to be small enough to fit in between the cement particles. A grain size ratio of 1 to 10 compared to cement would be preferable, but the production of fillers that fine is nearly impossible at reasonable expenses.

For a better distinction of fillers on basis of their grain size Fischer/Juhart (2014) introduced Makro-, Meso- and Micro-Fillers and arbitrarily set their limits to d50=30µm and d50=5µm [Fischer2014]. To reach very fine grain sizes, the material is milled in hammer mills or ball mills, material of the targeted size is separated and the rest is milled again. This steps are repeated until the whole material is of the targeted grain size. Unfortunately, the energy demand increases exponentially, the finer the filler should be. Two issues contribute to that in particular: On the

one hand, internal stress, which helps bursting the material is relieved with every milling step. This means that more and more energy is necessary the more often the material goes back to the mill. On the other hand, the amount of material which is separated because of the finished grain size becomes less in every milling step.[Fischer2014; Reinisch2014]
During the SLR, it was found that the scientific community recognizes that environmental burdens increase the smaller the grain size gets. Unfortunately, beside data from ELCD for fine milled silica sand with d50=20µm, almost no other suitable results were found. Fortunately, a bachelor thesis at TU Graz [Reinisch2014] examined milling energy demands at different grain sizes for fillers, making it possible to model these in SimaPro.
The fillers could be of an inert nature, i.e. they do not have hydraulic or pozzolanic properties, not contributing to binding properties of the binder, or they could have hydraulic or pozzolanic reactivity, like Metakaolin, Silica Fume or very fine milled blast furnace slag with the latter almost not available. The different types of fillers are introduced below, while the modelling of them within the LCA is discussed in subsection 5.1.1.

Inert Fillers

Inert fillers have almost no effect on the binding properties within concrete (or sprayed concrete), because they only should lead to a tighter packing density, although even a slightly increased early strength was observed in normal concrete if the grain size gets very small. Dolomite, limestone or quartz is used here. While dolomite and limestone demand nearly the same amount of grinding energy, quartz needs more because of its higher hardness after Mohs.[Reschke2005]
It is clear that inert fillers have - at the same grain size - a lower environmental burden then the pozzolanic ones, as they do not need energy for burning/heating the material.

Metakaolin

Metakaolin is produced by heating kaolinite, a clay mineral, which leads to dehydroxylation and recrystallization of the material leading to the required reactivity. Due to its small grain size and high reactivity, the usage of Metakaolin can increase concrete's strength, resistance to chemicals, or durability.[Wan2017] Also an increased early strength, due to the fast running pozzolanic reaction, can be observed [Reschke2005]. For these reasons it is used, for example, in high performance concretes. Some environmental impacts from literature, and also for the next material, were found during the SLR.

Silica Fume (Microsilica)

Silica Fume is a very fine mineral material which arises during the production of silicon or alloys of silicon in electric arc furnaces. It's much finer grained than cement, even finer than Metakaolin. It has a high reactivity and also an ability to improve mechanical characteristics and durability of concrete.[Zhang2016; Scholz2011]

4.8. Comparison of Cement, Fly Ash and Blast Furnace Slag

This section shows a comparison of different constituents based on the SLR regarding the six examined impact indicators. The compared materials are CEM I, average cement, fly ash (FA) and blast furnace slag (BFS). Further used materials within the addressed sprayed concrete mix designs, like fillers, are not included in this section, because they were either not among the key word strings searched for during the SLR - and therefore not many results from the SLR exist - or they don't fulfill the same function in terms of binding capacity as the examined ones.

The comparison of these materials is made on basis of the functional Unit "1 kg binding equivalent (BE)", which means that the values of the environmental indicators are compared on basis of the material amount required to attain the same binding capacity as 1 kg of CEM I. While it is obvious that CEM I has got a BE of 1kg, it is assumed that also average cement retains this value. As far as FA and BFS are considered, more amount of material has to be used to arrive at the same binding capacity as 1 kg CEM I. Therfore, the BE[12] of these SCMs have to be higher than 1 kg, in fact they are 1/0,6 kg for FA and 1/0,9 kg for BFS [Chen2010; Habert2013]. So the following values presented in this section refer to 1 kg CEM I, 1 kg average cement, 1,67 kg FA and 1,11 kg BFS.[13]

To begin with the most familiar impact indicator in general, the comparison based on GWP makes the start. The graphs always show cradle-to-gate-impacts based on 1 kg-BE of material. The boxplots for FA and BFS are plotted based on economic value allocation, but also points for observations for mass allocation or the cut-off approach are included.

Because there are partly huge differences - mainly due to used allocation rules regarding SCMs - it instantly becomes clear that some graphs have to be cropped in order to give a better view at differences between the materials. Pictures where some data are not shown in this manner are marked with a * at the end of the picture title. Corresponding graphs containing the whole data are plotted in the appendix.

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[12] An explicit formula of the calculation of BE can be found in [Chen2010].

[13] A less detailed comparison on a general 1-kg-basis, where other used materials are also included, is presented in subsection 5.1.1.

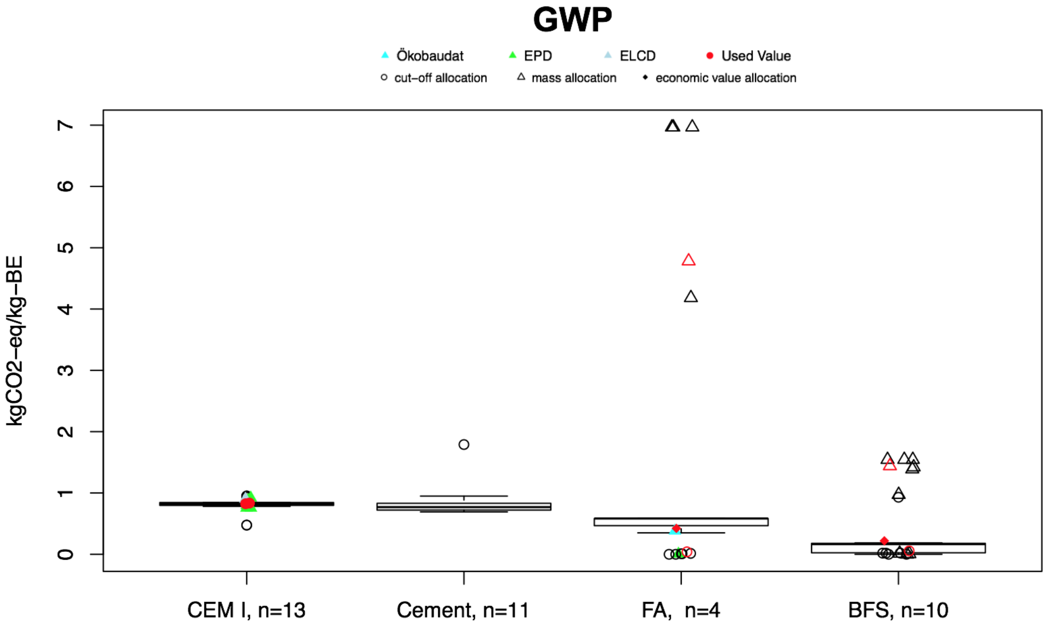

Figure 4.7.: *GWP of Different Materials*

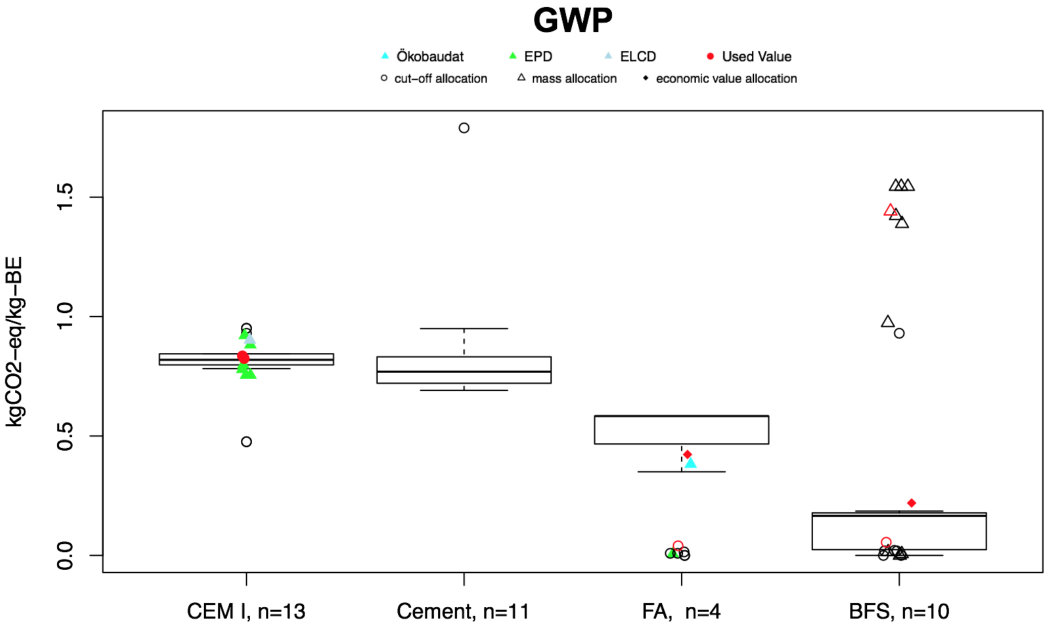

Figure 4.8.: *GWP of Different Materials**

Graph 4.7 shows clearly what was already pointed out by several authors who studied SCMs in detail: The environmental friendliness of fly ash and BFS compared to cement disappears if mass allocation is used.[Chen2010; Habert2011; Habert2013] Not just that the substitution of

CEM I becomes useless, environmentally speaking, the use of fly ash worsens the environmental sustainability, because using mass allocation assigns four to seven times more GWP to fly ash than CEM I. As already pointed out, economic value allocation should be preferred [Chen2010]. Graph 4.8 gives a better view at the different impacts. It can be seen that using economic value allocation actually makes FA and BFS an environmentally "better" material than cement. Also findings from other data sources (Ökobaudat, EPDs and ELCD) and the used data underpin this.
Just relying on the lower GWP of FA and BFS than cement, could be fatal if these SCMs instead impinge more on other impact indicators. Picture 4.9 shows that this could be true for acidification, without being in general agreement. Literature indicates that fly ash is the material with the highest environmental burden regarding this impact category, while results from other sources disagree. Based on the EPDs for fly ash, it has a lower AP than CEM I. Also the used data is in line with the EPD, as in this study fly ash is considered to have the lowest AP of the three materials with binding properties addressed in this graph.

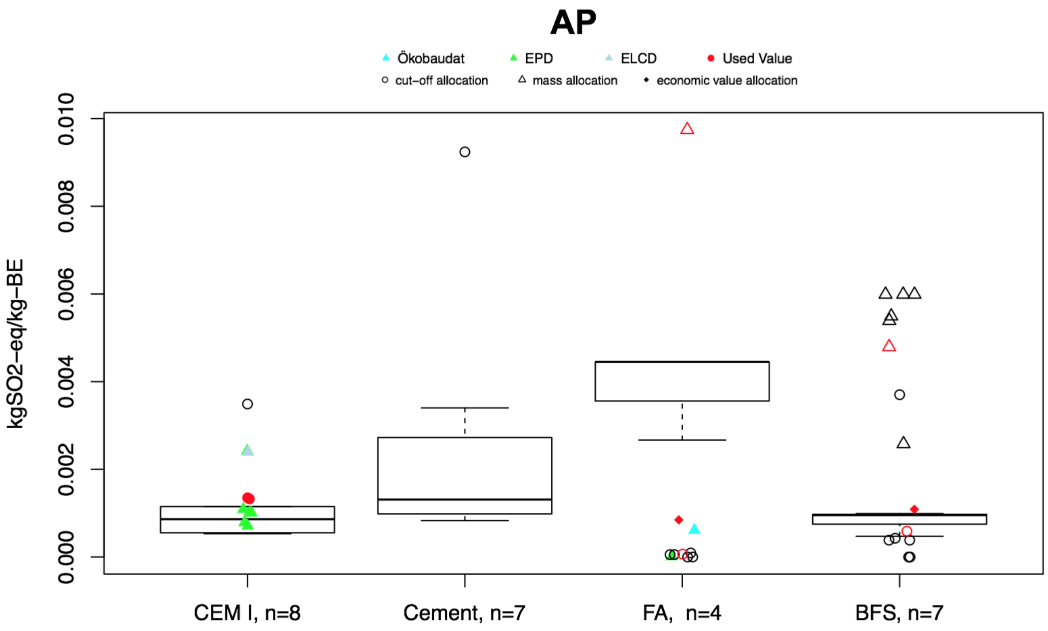

Figure 4.9.: *AP of Different Materials**

Picture 4.10 shows data on eutrophication. While literature is not quite sure whether BFS under the economic value allocation has a lower EP than CEM I, it assigns more EP to FA than to the other shown materials. Other data sources do not confirm this as they assign less EP to FA than they assign to CEM I. For all three materials, the used data allot a little more burden to them than values from the SLR would suggest. Indeed, there is not much difference in EP assigned to these three materials if the used data and economic value allocation are considered. But the picture shows that the substitution of CEM I especially big amounts of fly ash may have the potential to worsen this indicator if the substitution is done on a BE-basis.

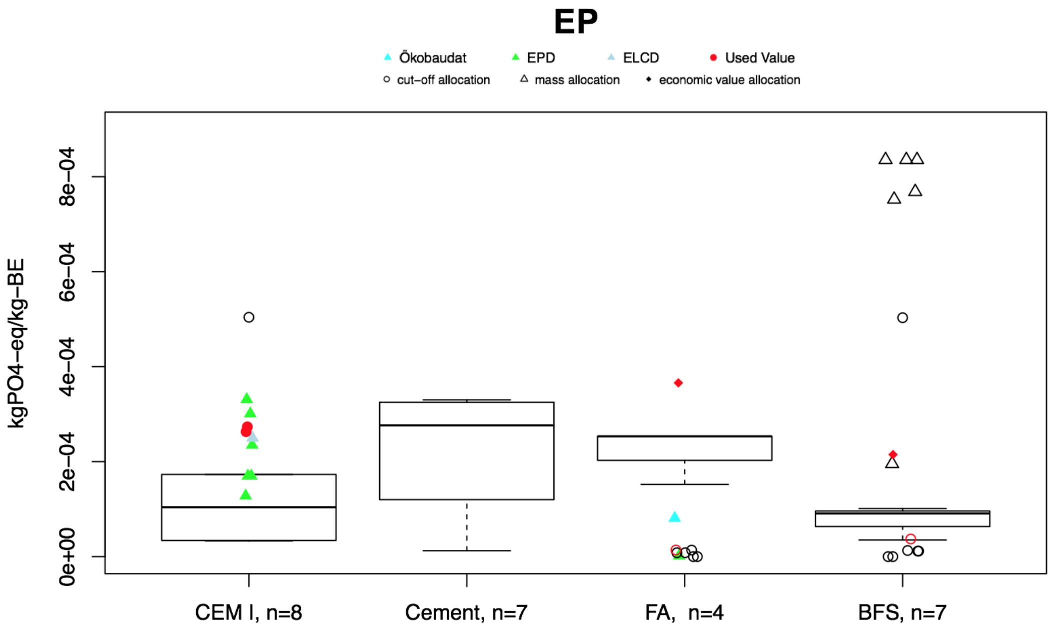

Figure 4.10.: *EP of Different Materials**

Moreover, according to literature, FA and BFS have a lower ozone depletion potential than CEM I. This can be derived looking at picture 4.11. This study assigns more ODP to FA and BFS under the economic value allocation than literature suggests. Like for EP, here also FA has the highest impact on this indicator, while BFS has the lowest.

Graph 4.12 shows similar issues like graph 4.9 on acidification did. Again, literature and used data do not agree with findings from other sources, not fully answering the question whether SCMs are really more environmentally sustainable than cement. However, one difference is that with regard to POCP, BFS becomes also more harmful to nature than cement, depending on the data source.

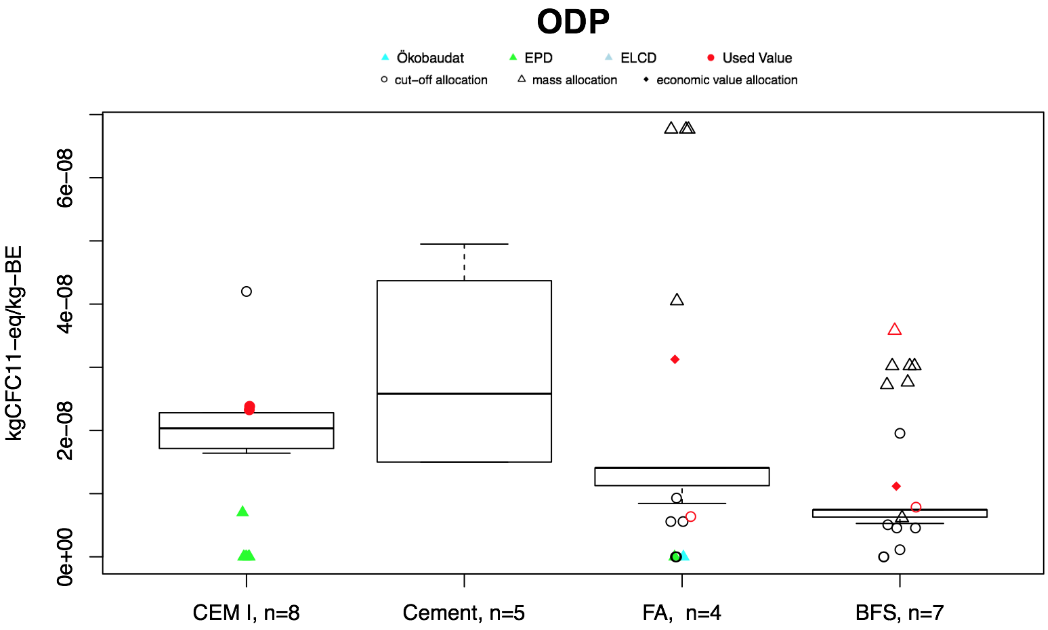

Figure 4.11.: *ODP of Different Materials**

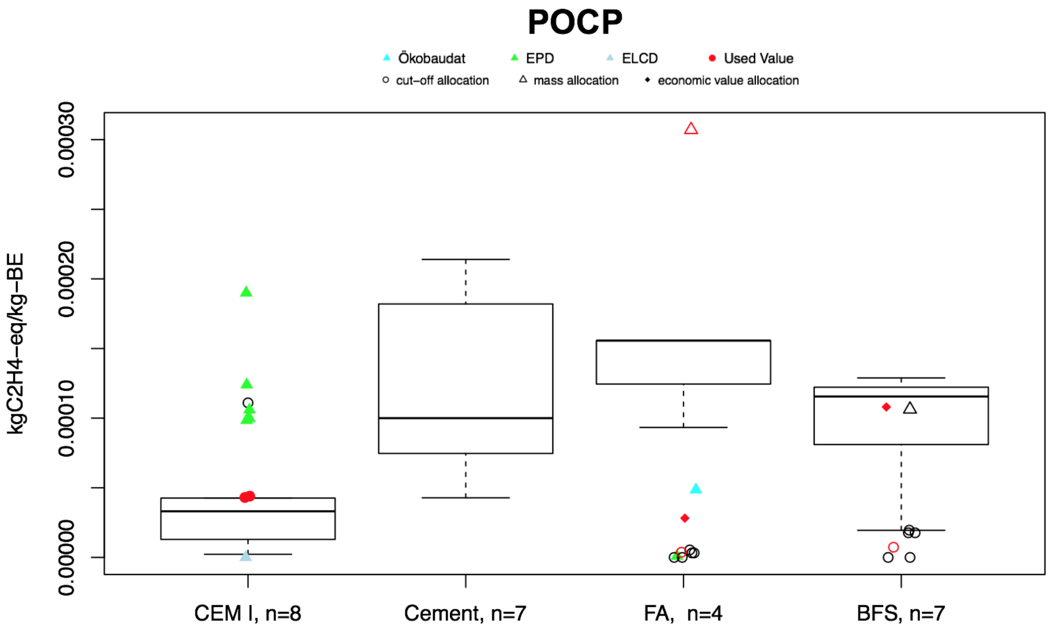

Figure 4.12.: *POCP of Different Materials**

Graph 4.13 and 4.14 show by far the most controversial impact indicator among the six assessed in this thesis. There the impacts observed vary that much that it needs two cropped graphs to show the variability. A look at the axis labels clarifies the magnitude of the deviations: In picture 4.13 impacts are plotted up to a value of 6e-2, while in picture 4.14 the limit is 3e-7. It shows that some observations from the SLR are not even close to data from other data sources or the used values. As already discussed in section 4.2 and fully explained in [VanOers2016], this impact indicator experiences the biggest deviation during the modelling of FA and BFS. However, the modelled impacts for FA are very close to data from the Danish EPD and Ökobaudat.

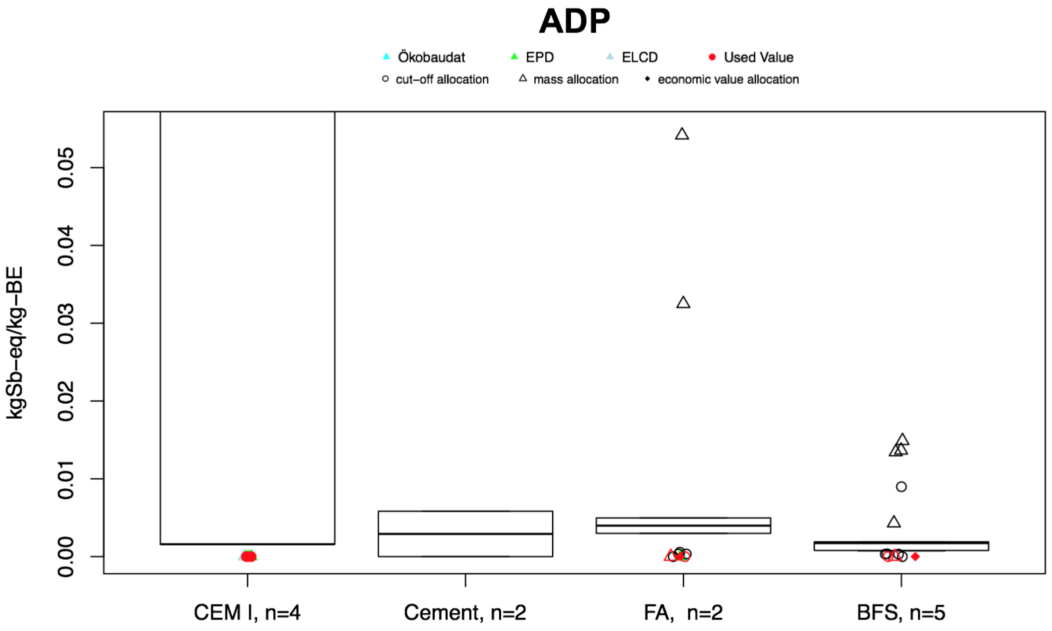

Figure 4.13.: *ADP of Different Materials**

By discarding the mass allocation methodology, it is possible to summarize that literature, other data sources and the used data are only sure that examined SCMs have a lower environmental impact with regard to their binding equivalent at only one impact indicator: GWP. For EP and ODP literature would suggest that this is also the case, but other data sources and used data don't confirm this issue. For these indicators the used value for FA is a little bit higher than the used one for CEM I, while the calue for BFS is a little bit lower.

If AP or POCP is considered, the opposite is true: Data from the SLR suggest an environmental disadvantage of the substitution, especially if fly ash is used, but other sources and used data disagree.

Unfortunately, general environmental statements can not be made in terms of abiotic depletion potential. There the impacts vary that much that using a different datasource could increase one

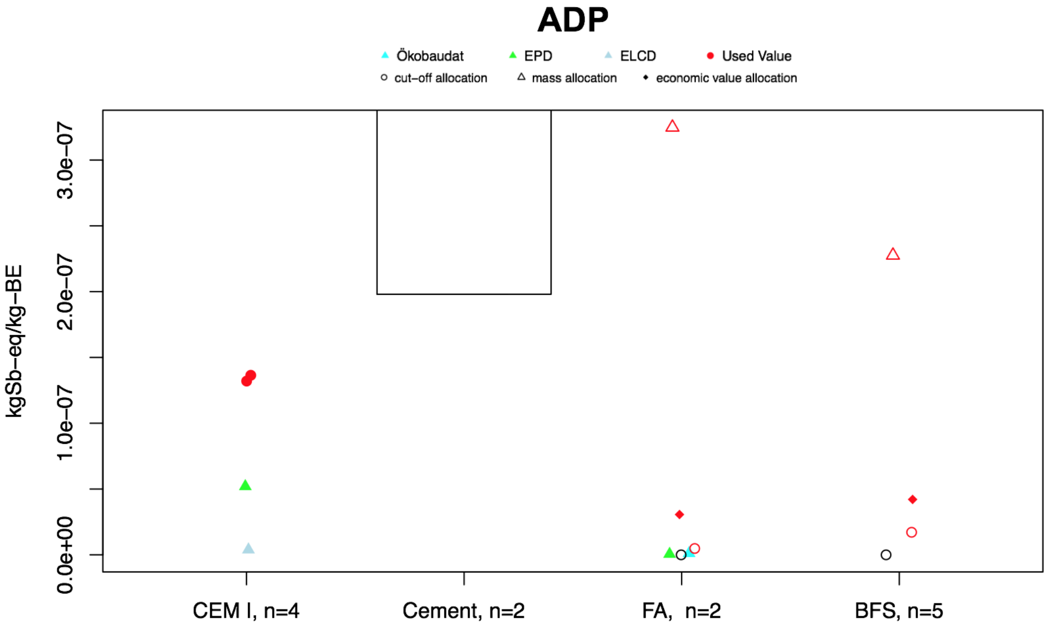

Figure 4.14.: *ADP of Different Materials* - Zoom*

material's ADP by a factor of 10e5. Consequently, one has to be careful before declaring SCMs as superior to CEM I in every impact category. Admittedly, their environmental benefits prevail slightly regarding the examined indicators. A look at other impact indicators could clarify the picture.

Some further findings are, that literature is sure that fly ash performs worse than blast furnace slag in all environmental categories. The used data agree with that only at EP, GWP and ODP. For AP and ADP, there is no big difference in the corresponding indicator value, while used data on POCP clearly point to BFS as the material with the higher burden.

To conclude, the substitution of cement with a mixture of fly ash and blast furnace slag should be - within the economic value allocation methodology - environmentally beneficial, because it should lower the overall GWP of the sprayed concrete mix design, while the other five indicators should stay nearly the same. This should be true regardless of using the simulated values or a kind of average of findings from literature and other data sources. This can be verified by looking at pictures 4.8 to 4.14. Nevertheless, the comparison in this section is made on a BE-basis. Whether the actual substitution within the sprayed concrete mixes will be conducted on this basis and whether the substitution is environmentally beneficial regarding whole mix designs will be shown in the next chapter.

5. Life Cycle Assessment of ASSpC Sprayed Concrete Mix Designs

Life Cycle Assessment is a capable method to become aware of environmental impacts produced by product systems or processes during their whole life cycle ("Cradle-to-Grave") or part of it. It is often used in the construction sector to find ways to reduce its associated environmental impacts or to compare different building materials [Feiz2015]. As already found in the literature review, there are a lot of LCAs which compare cements or concretes, but detailed studies on sprayed concrete are rare if even existent.

In sprayed concrete, cement is suspected to be the biggest contributor to environmental impact indicators among base materials. Therefore - and also for technical reasons like reduction of leaching and improvements in durability - the new suggested mix designs within the ASSpC-Project at TU Graz try to reduce the amount of cement by substituting it with materials like fly ash, blast furnace slag, limestone or Meso- and Micro-Fillers. This chapter shows whether these new mixes really have a lower environmental burden than a traditional mix design.

5.1. Methods

In this section the LCA methods used, which were already introduced in section 2.2, are summarized and partly discussed shortly. Additionally, a close look at used materials and their corresponding background data source is committed.

5.1.1. Materials and Data Sources

The LCA is performed using SimaPro 8.3.0.0 with link to the environmental databases EcoInvent 2.2 and 3.3[1], plus some additional calculations in Excel. The main LCA will be performed using EcoInvent 2.2, while the version 3.3 serves as a form of sensitivity analysis. Results of using version 3.3 are shown in an extra section 6.4 at the end of this chapter. So in the following, the term "EcoInvent" refers to version 2.2 and will be substituted by version 3.3 in section 6.4. Other data sources used stay the same during the check with version 3.3.

It should be pointed out already now, that there is not that one number describing an environmental impact of a material. For example, there are different types of fly ash available. The environmental impacts of fly ash depend on the coal used, the origin of the coal (transporting distances and chemical composition). Furthermore, impacts of Metakaolin differ depending on the burning process used and the quality produced. The same is also true for other materials. Nevertheless, this renders the presented results useless by no means. It just should make the reader aware that presented numbers will vary a little bit from the real numbers. The materials used with the corresponding data sources are as follows:

- CEM I

  There are two types of CEM I used in the LCA, one with strength class 42,5 MPa and one with 52,5 MPa. They are both taken from EcoInvent.
- Gravel

  There are also two types of gravel, one round and one crushed. Also both are taken from EcoInvent.
- Limestone

  Inert limestone is taken from EcoInvent.
- Fly ash

  Fly Ash is modelled in SimaPro with link to EcoInvent according to the inputs and outputs displayed in [Chen2010]. Wherever possible, modifications are made to mirror the situation in Austria. So, for example, the Austrian electricity grid is used.
- Blast furnace slag

  As Fly Ash, also Blast Furnace Slag is modelled according to [Chen2010] with modification to fit better in the Austrian context.
- Metakaolin

  The impacts of Metakaolin are directly taken from [Habert2011].
- Silica fume

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[1] Within EcoInvent version 3.3 the system model "Allocation, recycled content" is used.

Also the impacts of silica fume are taken from [Habert2011].

- Filler

  As stated earlier, there is almost nothing available for fillers with grain sizes in micrometer range. So the fillers were modelled in SimaPro with ground limestone as starting substance and additional grinding energy (electricity) was added according to [Reschke2005].
- Water

  Water comes direct from EcoInvent.
- Superplasticizer

  Superlasticizer's impacts come from the EPD commissioned by the EFCA [EFCA2015]. They are added in Excel.
- Set Accelerator

  Like Superplasticizer, also here the corresponding EPD of the EFCA [EFCA2015a] is used to get the impacts, which then are added in Excel.

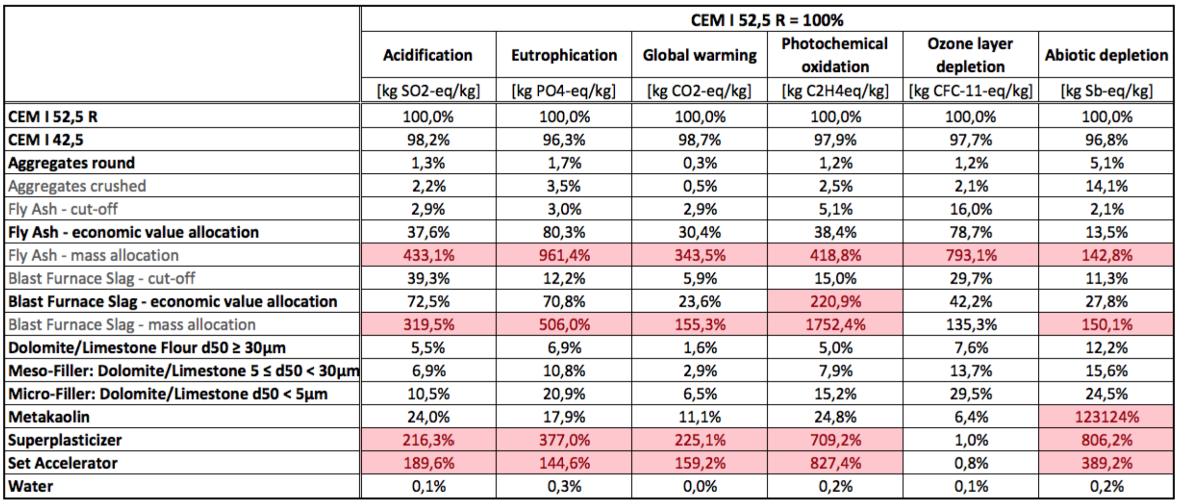
As already found in chapter 4, used impacts of fly ash and blast furnace slag differ from impacts calculated in the paper by Chen et al (2010). Beside little differences originating from adaptation to the Austrian context, the main differences seem to stem from data source and LCIA method: The original paper uses EcoInvent 2.1 and an outdated version of CML, while this thesis refers to EcoInvent 2.2 and EPD in its version 1.03 (2013). A mistake in the modelling was eliminated as it was double-checked by Marcella Ruschi Mendes Saade and Asst.Prof. Alexander Passer from TU Graz. Also Prof. Guillaume Habert from ETH Zürich, co-author and corresponding author of the paper by Chen et al (2010), looked through the model and didn't find differences. He also pointed at the mismatch of data sources and LCIA methods.

With Metakaolin and Silica Fume two materials with a different LCIA method are used, because Habert et al (2011) use the CML method to calculate the environmental impacts. This leads to an LCIA method mix within this study. Unfortunately, this cannot be prevented because no other proper source of environmental data on these materials could be identified.

Furthermore, the data source of admixtures is not in line with other materials assessed because their EPDs reveal GaBi 6 as their background data source. Also here no other reliable data source was found. Moreover, background data on admixtures may introduce an additional error source: For example, there are different generations of plasticizers, which of course differ in their associated environmental impacts. To be sure that the correct types of admixtures are used, it was of the highest importance to use the EPDs of EFCA in this study. Moreover, a comparison with indicator values from literature shows that the used EPDs refer to the highest and most current values for admixtures. Therefore, using these EPDs also fulfill a conservative approach with regard to the final LCA results of sprayed concrete.

Table 5.1 shows the environmental impacts of 1 kg of different materials used in this LCA in

relation to 1 kg of CEM I. Values higher than 140% are highlighted in red. The table underlines that on a mass-allocation-basis fly ash and blast furnace slag have a higher environmental burden than cement. Also the inclusion of admixtures in the study is essential because they have a lot higher impacts (except ODP) than cement and are not used in a small amount.
Furthermore, the use of fillers at different sizes promises a decrease of the environmental burden of sprayed concrete. One exception is the high ADP of Metakaolin.
Also the substitution of cement with fly ash and blast furnace slag looks promising if cut-off allocation or economic value allocation is used. Only the POCP of BFS disagrees. A deeper look at this and also the role of admixtures is presented in section 5.3.



	CEM I 52,5 R = 100%					
	Acidification	Eutrophication	Global warming	Photochemical oxidation	Ozone layer depletion	Abiotic depletion
	[kg SO2-eq/kg]	[kg PO4-eq/kg]	[kg CO2-eq/kg]	[kg C2H4eq/kg]	[kg CFC-11-eq/kg]	[kg Sb-eq/kg]
CEM I 52,5 R	100,0%	100,0%	100,0%	100,0%	100,0%	100,0%
CEM I 42,5	98,2%	96,3%	98,7%	97,9%	97,7%	96,8%
Aggregates round	1,3%	1,7%	0,3%	1,2%	1,2%	5,1%
Aggregates crushed	2,2%	3,5%	0,5%	2,5%	2,1%	14,1%
Fly Ash - cut-off	2,9%	3,0%	2,9%	5,1%	16,0%	2,1%
Fly Ash - economic value allocation	37,6%	80,3%	30,4%	38,4%	78,7%	13,5%
Fly Ash - mass allocation	433,1%	961,4%	343,5%	418,8%	793,1%	142,8%
Blast Furnace Slag - cut-off	39,3%	12,2%	5,9%	15,0%	29,7%	11,3%
Blast Furnace Slag - economic value allocation	72,5%	70,8%	23,6%	220,9%	42,2%	27,8%
Blast Furnace Slag - mass allocation	319,5%	506,0%	155,3%	1752,4%	135,3%	150,1%
Dolomite/Limestone Flour d50 ≥ 30µm	5,5%	6,9%	1,6%	5,0%	7,6%	12,2%
Meso-Filler: Dolomite/Limestone 5 ≤ d50 < 30µm	6,9%	10,8%	2,9%	7,9%	13,7%	15,6%
Micro-Filler: Dolomite/Limestone d50 < 5µm	10,5%	20,9%	6,5%	15,2%	29,5%	24,5%
Metakaolin	24,0%	17,9%	11,1%	24,8%	6,4%	123124%
Superplasticizer	216,3%	377,0%	225,1%	709,2%	1,0%	806,2%
Set Accelerator	189,6%	144,6%	159,2%	827,4%	0,8%	389,2%
Water	0,1%	0,3%	0,0%	0,2%	0,1%	0,2%

Table 5.1.: *Impacts of Constituents Relative to CEM I 52,5 R*

5.1.2. Allocation

For fly ash, blast furnace slag and one type of Meso-Filler (consisting of blast furnace slag) allocation rules have to be used. Cut-Off allocation, allocation by economic value and allocation by mass is applied in this study. Cut-off allocation assigns the least burden to a material, while mass allocation assigns the highest one. As already discussed, mass allocation is inappropriate for these kinds of materials. The cut-off allocation is also not appropriate because it violates the already introduced European directive [EuropeanCommission2008]. Therefore, economic value allocation serves as the basis in this LCA. The other two are used as sensitivity check. But, if not stated otherwise, results etc. are presented under the economic value allocation.

5.1.3. Summary of Methods

As already explained in section 2.2, this LCA uses a Cradle-to-Gate (A1-A3) approach and "1 m3 of sprayed concrete" as functional unit. Main data source is EcoInvent v2.2, with journal papers or EPDs as additional data sources, as stated in subsection 5.1.1 above. Economic value allocation is used, with mass allocation and the cut-off approach serving as sensitivity check, and EPD (2013) v1.03 is applied as LCIA method.

The results of the SLR show that methodological choices regarding data source, allocation (with sensitivity check), life cycle phases and functional unit are very common and widely accepted among LCA experts. Unfortunately, this is not true to the same extent for the LCIA method. It is, of course, an accepted method, but not very common in literature. As already mentioned, there was no other choice because the EPDs of the admixtures use this method.

5.2. Mix Designs

Six wet and five dry mix designs[2] are analysed by LCA. Of them, three wet and two dry designs are approved sprayed concrete mixes while the other three are currently under study for applicability. The proven ones include the term "Ref" for reference. The exact designs of the examined sprayed concretes can be found in the appendix. Also note that from now on the term "cement" always refers to CEM I.

Among the wet mixes, NRef1 is the simplest form of sprayed concrete, consisting of cement, gravel, water, set accelerator and superplasticizer. In NRef4, a certain amount of the cement is replaced by fly ash, blast furnace slag and a little content of limestone. NRef5 is the only wet mix which uses CEM I with 42,5 MPa. Additionally, the cement substitution is made with blast furnace slag and an inert Micro-Filler. N1 continues to lower the amount of cement, but in contrast to NRef4 it uses Metakaolin and a mix of Micro- and Meso-Fillers. In N3 and N4 the inert Meso-Fillers are excluded, but blast furnace slag is added. The difference, beside the composition of the Mix of Micro-Fillers and Metakaolin is the amount of cement used: While N3 possesses the smallest amount of all wet mixes with 210kg/m3, N4 contains with 281kg/m3 the same amount as NRef4.

The dry mixes, bearing in mind the differences between dry and wet mix designs, kind of behave like the same as the wet ones. TRef1 is - again - the simplest design, consisting only of cement and gravel. TRef2 substitutes some cement by fly ash, blast furnace slag and limestone. T1, T3

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[2] The mix designs are presented in the appendix.

and T6 reduce the cement amount further by adding Micro-Fillers and Metakaolin to the mix of cement and gravel.

5.3. Results of Mix Designs

This section shows the results of the LCA of sprayed concrete. The different mixes are analysed and compared. Absolute numbers always refer to the functional Unit of 1 m3 if not stated otherwise. To give a better view at the relations between different results, pictures are plotted on a relative basis. Base case is always the economic value allocation. 100% refers to the highest value of the corresponding impact indicator within the economic value allocation methodology. Lines are drawn to show the uncertainty of the results with regard to the cut-off approach and mass allocation. For some impact indicators and mix designs, mass allocation leads to absurd high values leading to unsuitable illustrations if also plotted. Therefore, again the graphs are cropped to show the essential findings. Pictures, where all results are shown can be found in the appendix.

5.3.1. Dry Mixes

As graph 5.1 illustrates, the substitution of cement leads to a reduction of five of the six impact indicators. TRef1, with the highest amount of cement, has the highest impact concerning acidification, eutrophication, global warming and ozone depletion. Also its photochemical ozone creation potential is very high. As a result of the high ADP associated with Metakaolin, the reference designs' abiotic depletion potentials are very small compared to the new dry mixes, because the new ones use Metakaolin while TRef1 and TRef2 don't. With the exception of ADP, the most environmentally friendly mix is T6 as it has lower impacts in every category than both reference mixes. Also T6 contains no uncertainty due to allocation because it uses an inert Micro-Filler and Metakaolin as partially cement replacement.

As already predicted during the description of the base materials, the substitution of cement indeed lowers the GWP[3], but this comes at some other impact's cost: So POCP increases if too much fly ash and blast furnace slag is used (TRef2). The usage of a mix of inert and active fillers is therefore preferable.

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[3] Also AP, EP and ODP decrease.

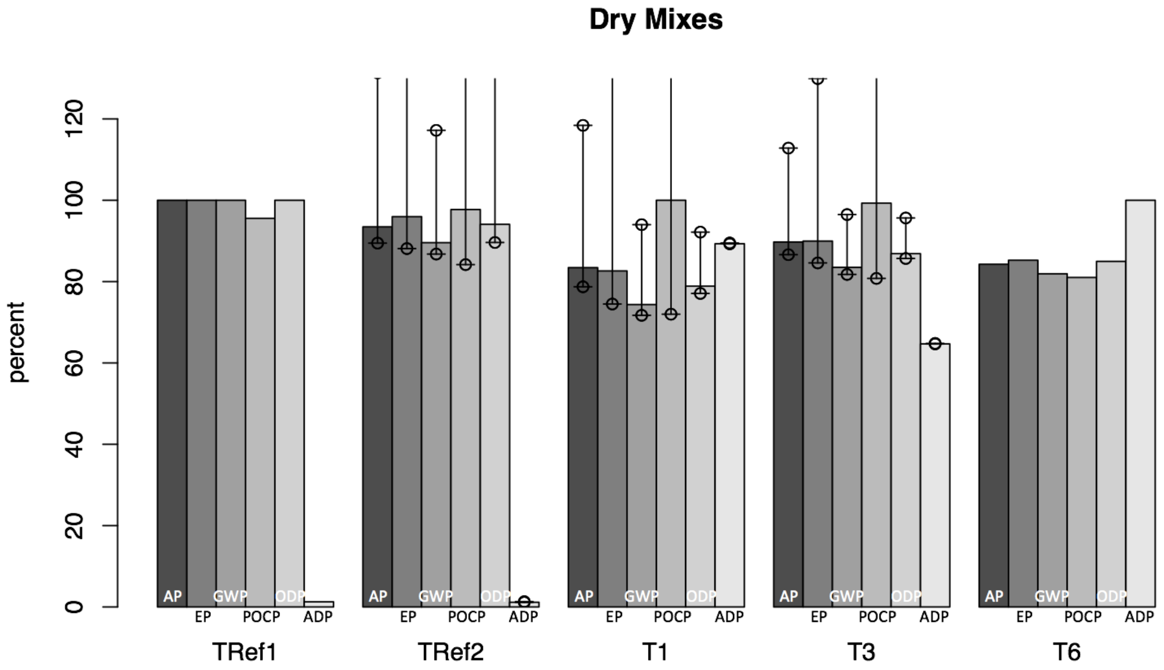

Figure 5.1.: *Impacts of Dry Mixes*

5.3.2. Wet Mixes

The impacts of wet mixes are higher than the dry ones because water and admixtures are not included in the assessment of the dry mix designs. As graph 5.2 indicates, the wet designs behave similar to the dry ones: NRef1, which has the highest amount of cement again bears the highest AP, EP, GWP and ODP, but the lowest ADP. The reason for the high ADP of the new designs is again Metakaolin. Fly Ash and Blast Furnace Slag are responsible for the higher POCP of all mixes compared to NRef1. Only N3 has a lower POCP than NRef1, because the substitution of cement is realized with a large amount of inert Micro-Filler.
Because the wet and dry mixes do not differ much in their environmental behaviour, a deeper look at the contribution of different base materials to the results of the whole mix design is provided just for the wet mixes. Also, only NRef1, NRef4 und N1 are compared. Anyway, N3 und N4 are similar to N1 because they differ just a little in the ratio of the different fillers.

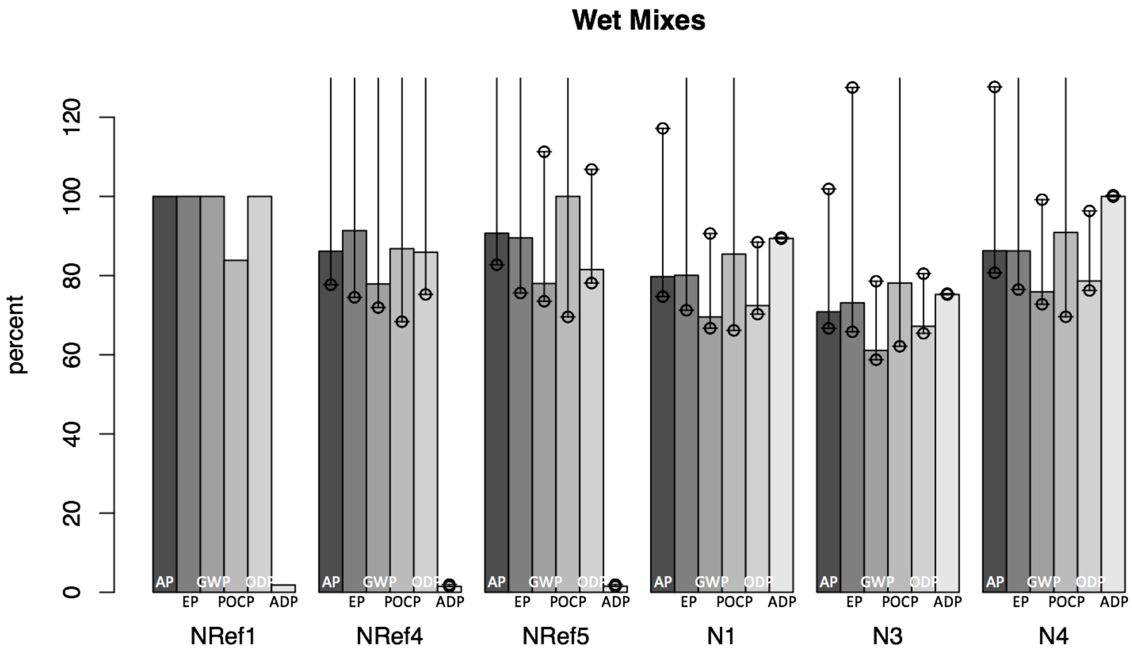

Figure 5.2.: *Impacts of Wet Mixes*

To give an immediate impression of the different materials' contribution to the examined impact indicators, the parts of the bars representing this are coloured on basis of their reactivity as follows: Materials with a hydraulic/pozzolanic reactivity[4] are illustrated with a grey background, admixtures[5] have got a black background and the others[6] have got a white one.

Graphs 5.3, 5.4 and 5.5 show the contribution of different base materials to acidification, eutrophication and global warming potential. They all look similar and invite one to draw the conclusion that the substitution of cement with fly ash and blast furnace slag or fillers is environmentally beneficial. NRef1 has the highest impacts in these categories while N1 has the smallest ones.

Looking at the traditional design NRef1 it becomes clear, that discarding admixtures in a LCA of sprayed concrete doesn't lead to solid results, as they add up to more than 10% of each of these three impact indicator values. The other two mixes reveal that it is more environmentally friendly to substitute cement with fillers, especially inert fillers[7], than a mixture of fly ash and blast furnace slag.

Graph 5.6 shows a different picture. Due to the high POCP of blast furnace slag the mixes NRef4 and N1 have a slightly higher POCP than NRef1. Also the mix designs are influenced a lot more by admixtures as they are at other indicators, because they are responsible for at least

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[4] CEM I, fly ash, blast furnace slag, Metakaolin and Meso-filler consisting of blast furnace slag

[5] set accelerator and superplasticizer

[6] water, aggregates, limestone and inert Meso- and Micro-Fillers

[7] Just relying on inert fillers by this amount is not possible due to technological reasons.

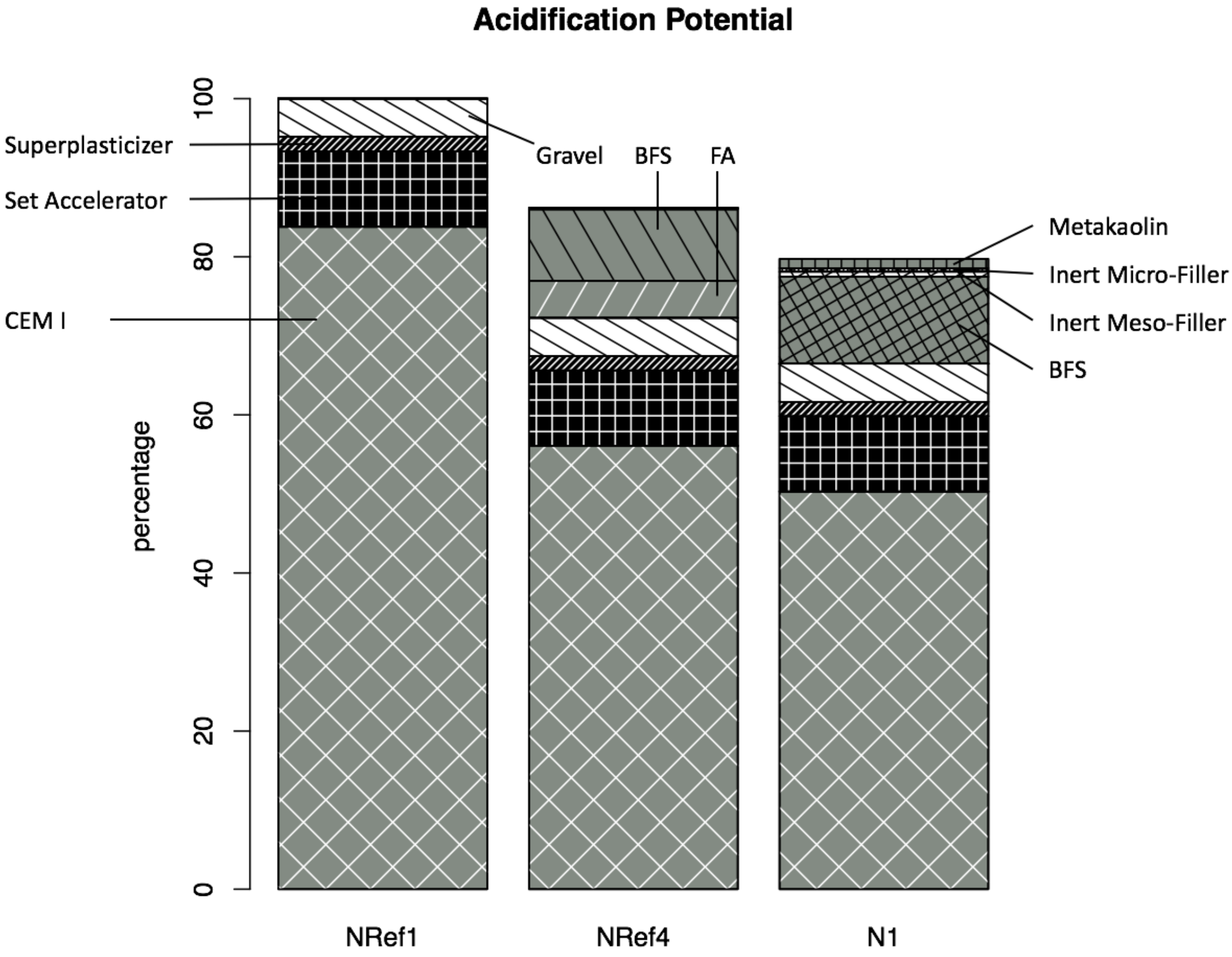


Figure 5.3.: *Acidification Potential of Wet Mixes - Contribution*

33% of each design's POCP.

As illustration 5.7 indicates, the ozone depletion potential behaves similar to AP, EP and GWP, as again NRef1 is the one with the highest and N1 the one with the lowest impact. A huge difference is the contribution of the admixtures: They are not even close to one per cent and therefore are not identifiable in the graph.

As already mentioned, the ADP is mainly dominated by Metakaolin. Because it is only used in N1 among the three examined mixes, NRef1 and NRef4 are assigned with a lot less ADP than N1. Graph 5.8 shows that their impact is just about two per cent of N1's. By discarding Metakaolin, also this indicator confirms that admixtures have to be included in sprayed concrete LCAs: The account for 20% of NRef1's ADP. Furthermore, the impact decreases if cement is substituted with fly ash and blast furnace slag.

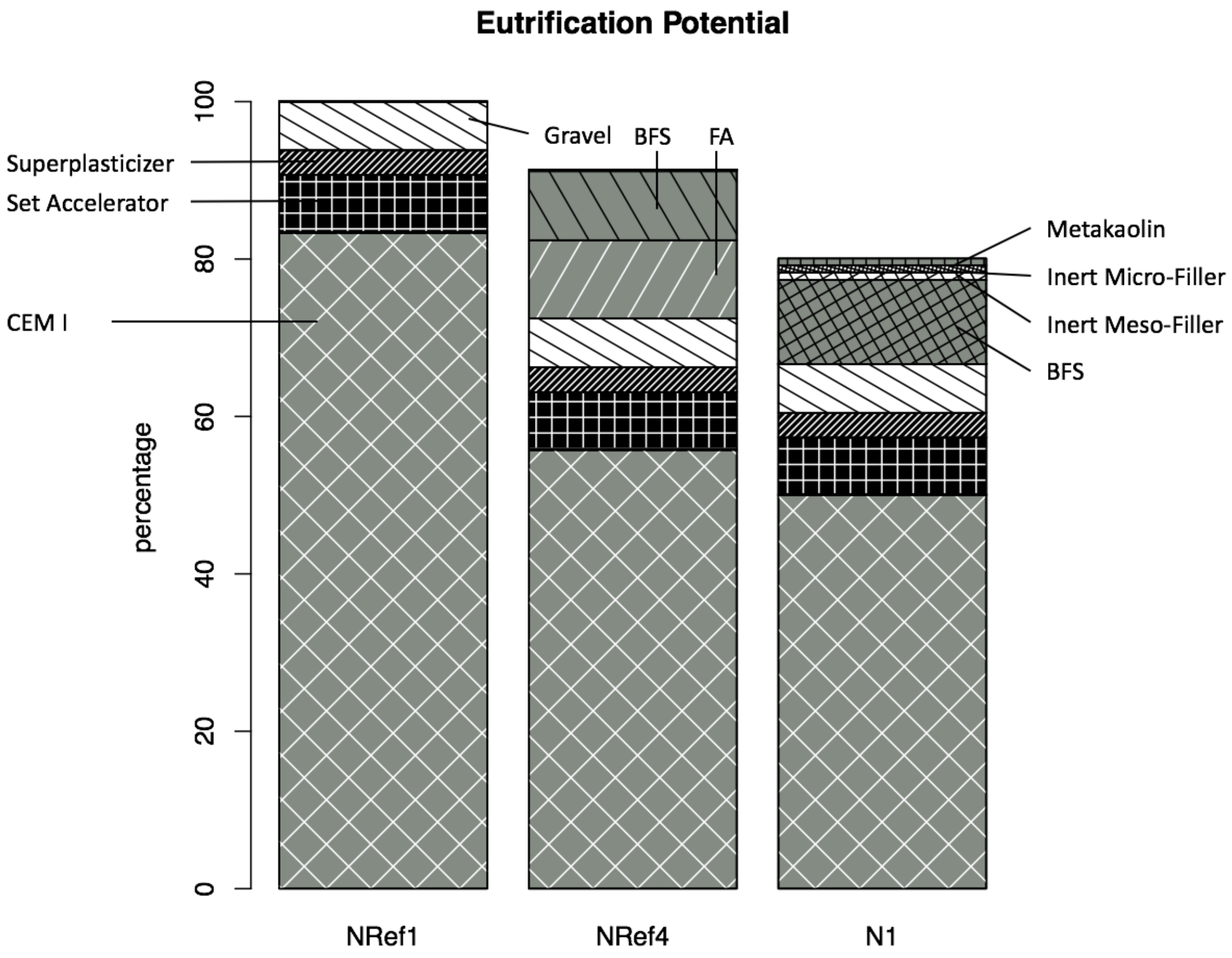


Figure 5.4.: *Eutrophication Potential of Wet Mixes - Contribution*

To summarize, except for POCP (and the ADP of Metakaolin), the substitution of cement is environmentally beneficial. The use of inert fillers is preferable from an environmental point of view, but also the use of fly ash and blast furnace slag proves to be advantageous. Unfortunately, the substitution slightly enhances the POCP if reactive materials are used. But, without willing to commit "weighting", a look at the previous graphs suggest the assumption that the environmental benefits clearly prevail.

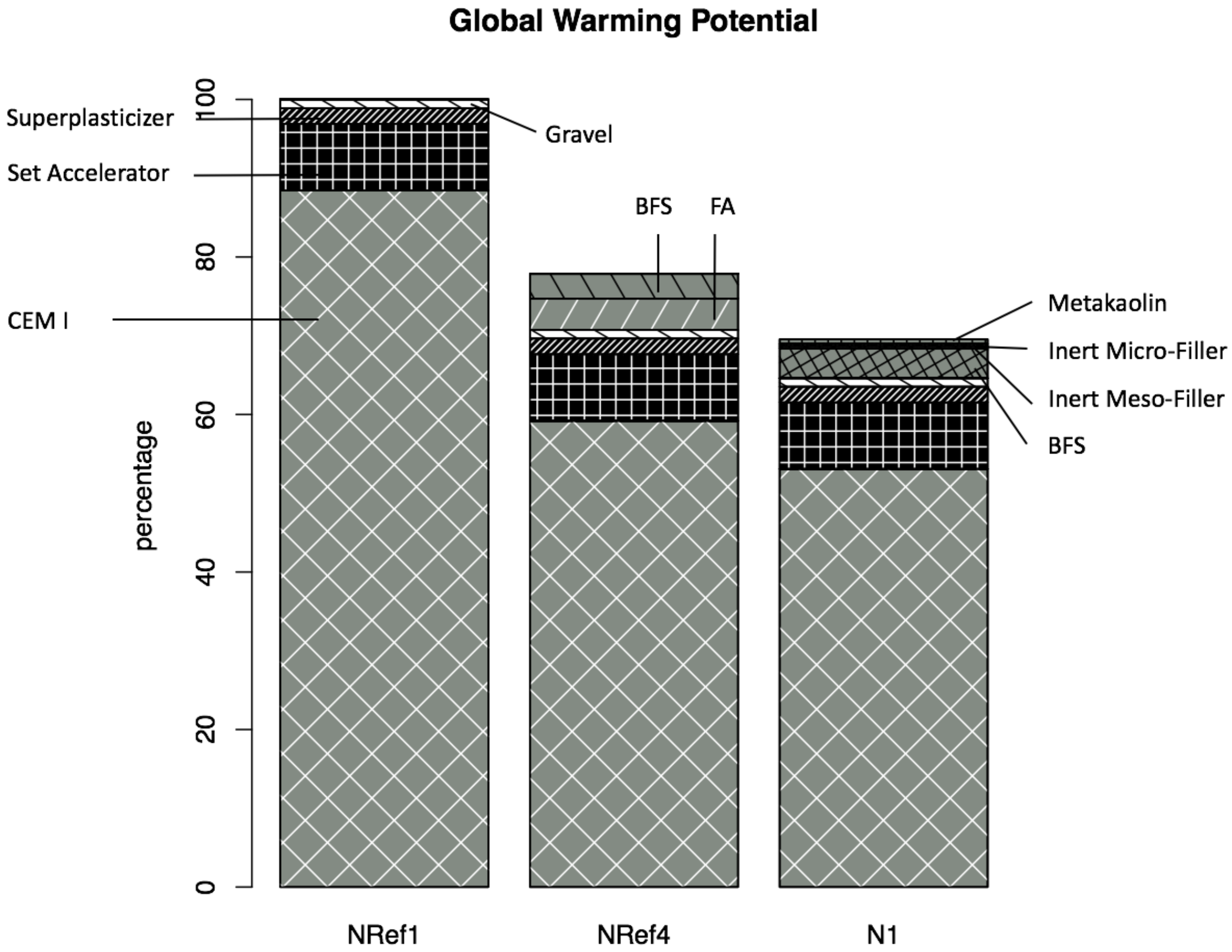


Figure 5.5.: *Global Warming Potential of Wet Mixes - Contribution*

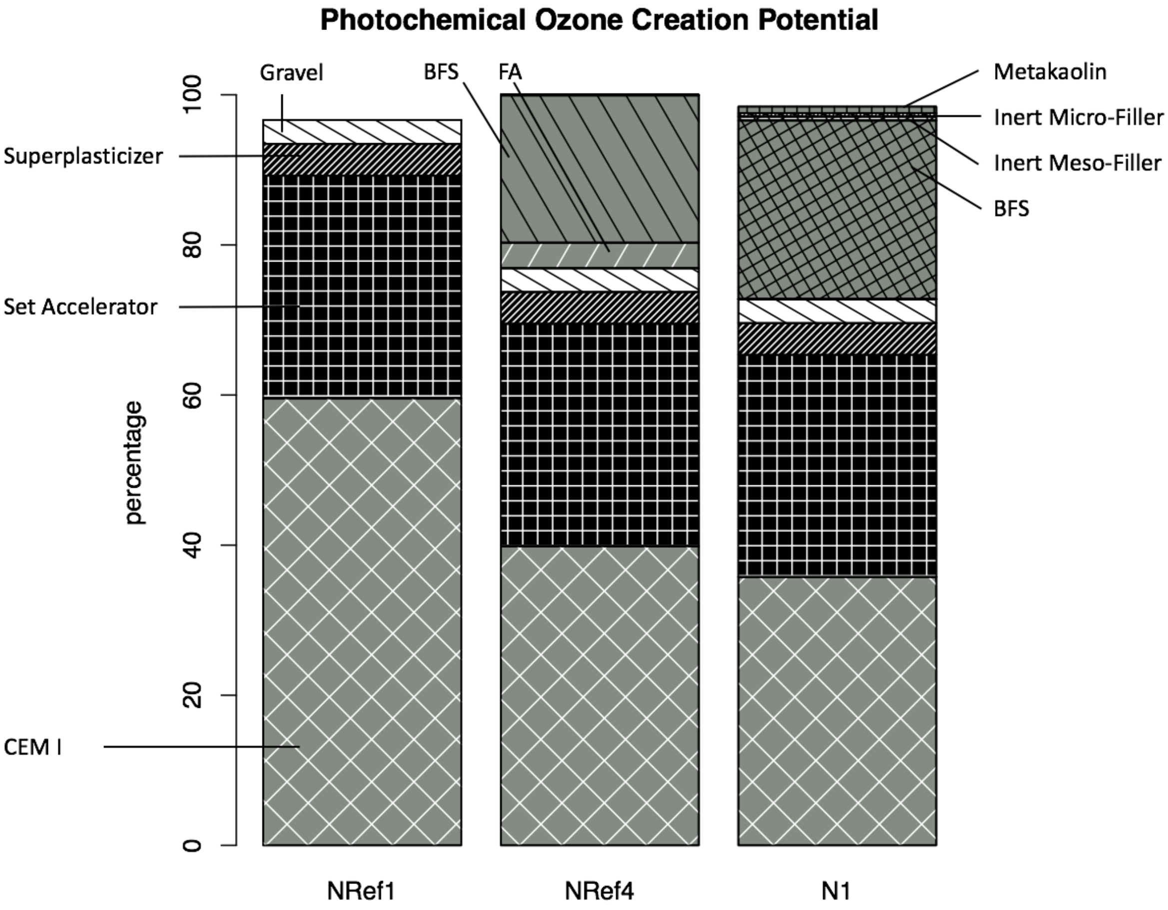


Figure 5.6.: *Photochemical Ozone Creation Potential of Wet Mixes - Contribution*

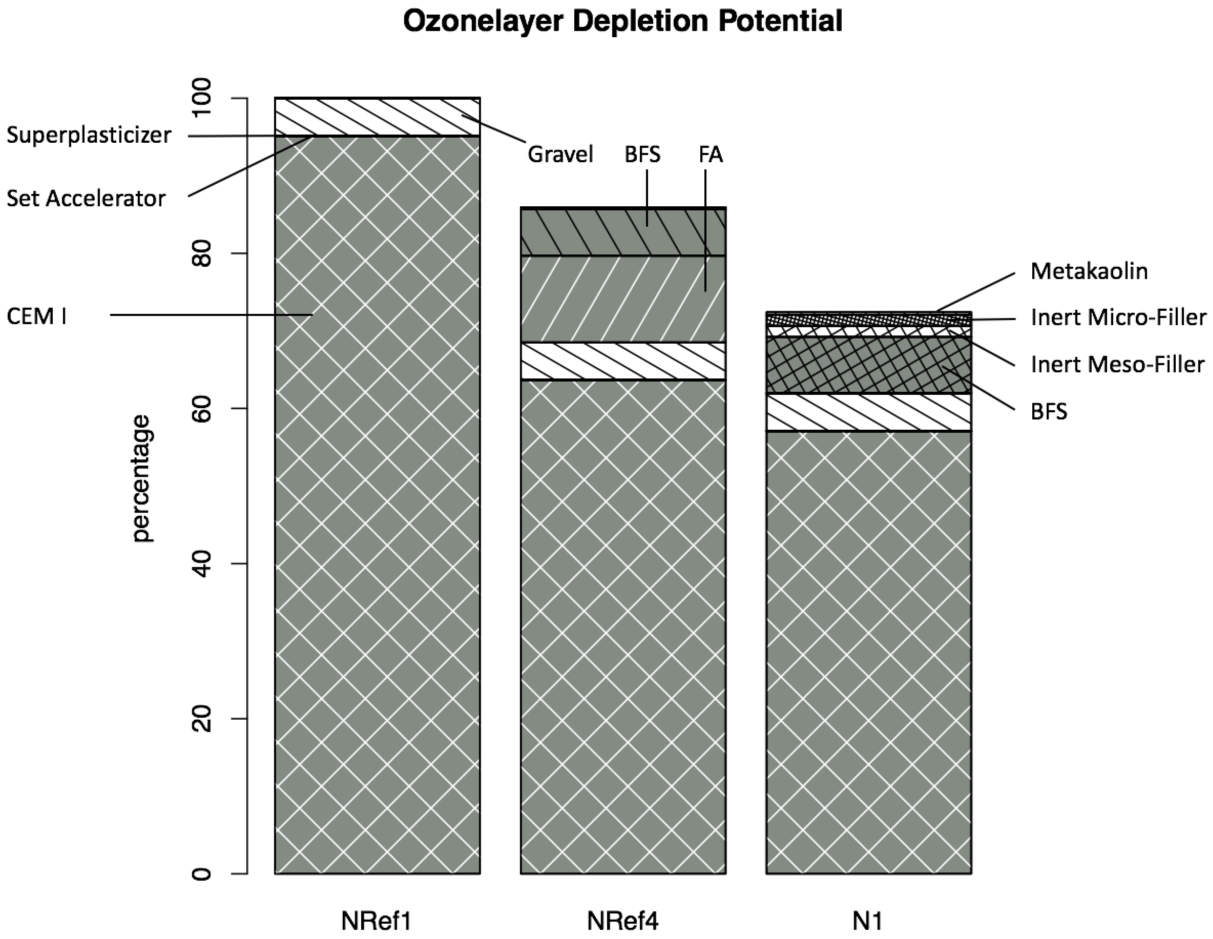


Figure 5.7.: *Ozone Depletion Potential of Wet Mixes - Contribution*

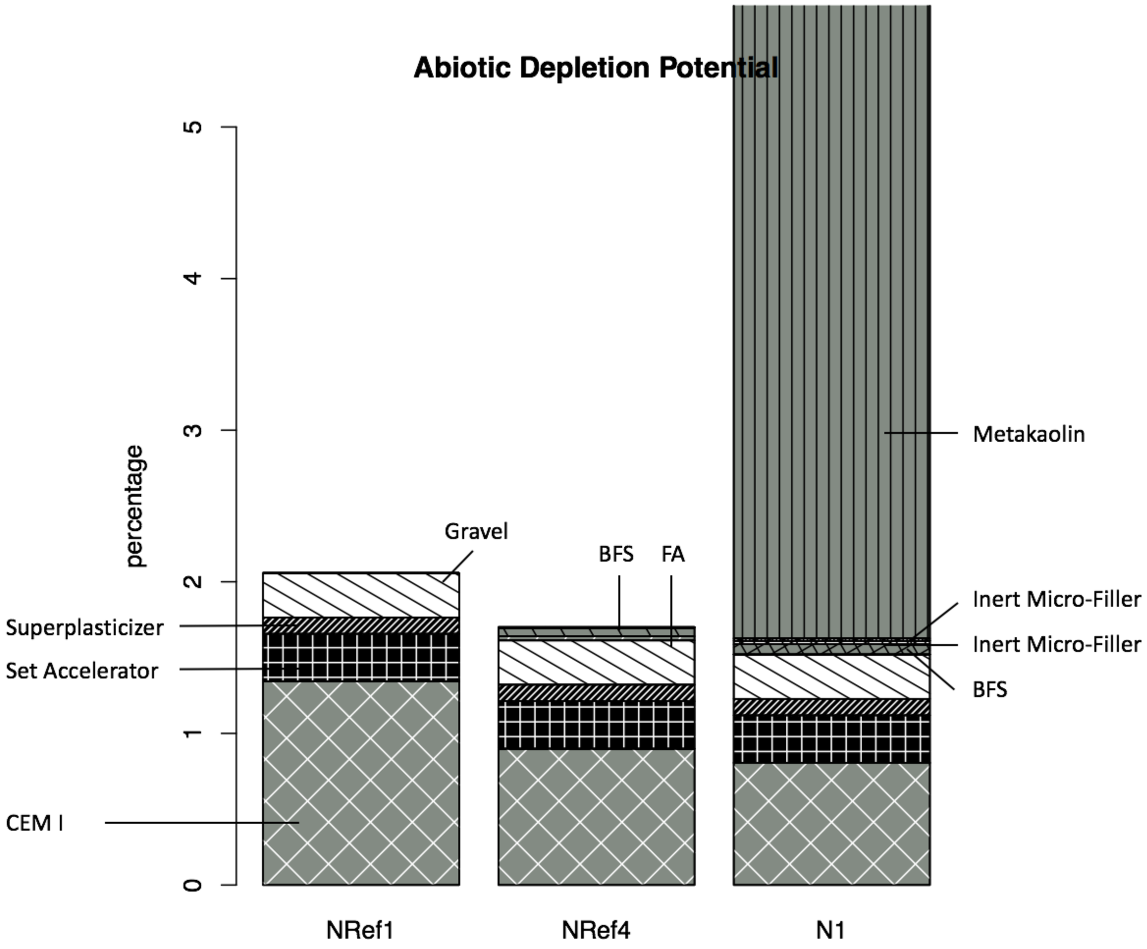


Figure 5.8.: *Abiotic Depletion Potential of Wet Mixes - Contribution*

6. Discussion and Uncertainty Analysis

Huijbregts (1998) identified six types of uncertainty common in LCA which inevitably lead to results also being afflicted by uncertainty. These are:[Huijbregts1998]

1. Parameter Uncertainty:
   Uncertainty due to inaccurate, incomplete or missing data in the LCI.
2. Model Uncertainty:
   Uncertainty due to the uncertainty of characterisation factors within the LCIA method.
3. Uncertainty due to Choices:
   Uncertainty caused by choices regarding the functional unit, system boundaries, allocation rules, etc.
4. Spatial Variability:
   Uncertainty due to not distinguishing between, for example, outdoor and indoor emissions, or emissions to land and emissions to water.
5. Temporal Variability:
   Uncertainty caused by changes in LCI and LCIA methods if data is collected over a long time period.
6. Variability between Sources and Objects:
   Uncertainty caused, for example, by the use of different technologies in two factories producing the same product.

In this section, the first type, and parts of the fifth and sixth type are addressed. Note that all activities in this section only address results' sensitivity with regard to background data, while foreground data is assumed to be fixed and certain, and therefore isn't changed or challenged throughout the whole thesis.

At first, the modelling of Fly Ash and Blast Furnace Slag in SimaPro is verified with with variations of the LCIA method and the process inputs "Hard Coal Supply Mix" and "Diesel". To deal with parameter uncertainty on a mixture basis, a Monte Carlo Simulation (MCS) of the three already well examined mix designs is performed. Uncertainty due to data source was already touched in chapter 4, where the different impacts for the examined base materials according to different sources was presented. To go one step further, in this section also a comparison of the sprayed concrete mixes modelled with EcoInvent v2.2 and v3.3 is made.

6.1. Sensitivity Analysis of the Modelling of FA and BFS

As already pointed out, SimaPro lacks environmental information regarding Fly Ash (FA) and Blast Furnace Slag (BFS). Therefore these materials were modelled with inputs and outputs presented by Chen et al (2010). As already shown and reasoned, derived impacts differ from the ones revealed in the paper. To verify if some inputs or outputs could be changed in order to reduce the gap, a deeper look at the contributors of the environmental impacts of FA and BFS is conducted.

Two inputs are revealed as mayor contributors: "Hard Coal Supply Mix" and "Diesel". Because there are more than one "Hard Coal Supply Mix" and "Diesel" available in SimaPro, these two inputs are varied in order to get an idea whether the differences to impacts according to Chen et al (2010) stem from them. Additionally, also the sensitivity of the results with regard to the LCIA method is checked.

6.1.1. LCIA Method

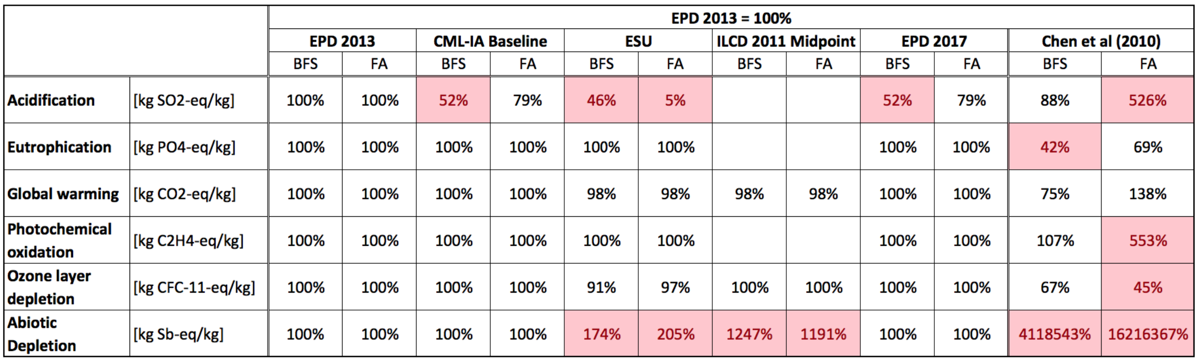
To validate the sensitivity of the results of FA and BFS regarding the LCIA method, four other LCIA methods are used and their results are compared. The calculations are done only within the economic value allocation methodology. The LCIA methods are:

- EPD (2013) v1.03
- CML-IA baseline v3.04 / EU25
- ESU (EPD prEN 15804:2010) v1.05
- ILCD 2011 Midpoint+ v1.09 / EC-JRC Global, equal weighting
- EPD (2017)

Table 6.1 shows the different results as a ratio of results derived with EPD (2013) v1.03, which was also used during the LCA of sprayed concrete. Big differences among the methods are only witnessed at AP and ADP. At the other four impact indicators, results don't vary much.

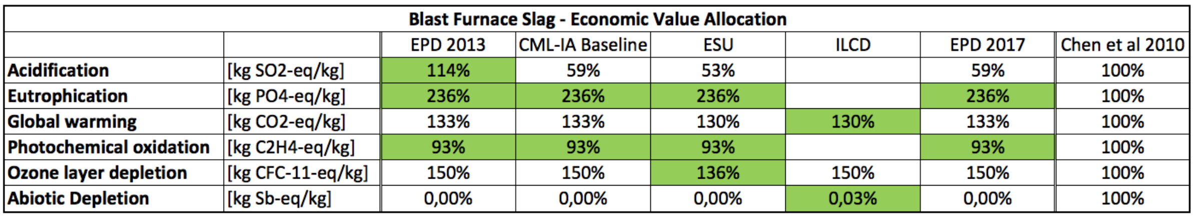
For comparison reasons, also the impacts according to Chen et al (2010), relative to the results derived in SimaPro with EPD (2013) v1.03, are plotted. Beside the big differences at ADP, the AP of Fly Ash conceals the most interesting discrepancy: While the additional LCIA methods all indicate that the used value is too high, results from Chen et al (2010) suggest quite the opposite. So, on the one hand, ESU v1.05 would use only 5% of the used AP, while Chen et al (2010) present a more than five times higher value than the used one.

Tables 6.2 and 6.3 answer the question, with which method results come closest to the results shown in Chen et al (2010). Therefore, keeping the huge deviations at ADP in mind, one can argue that the used method EPD (2013) v1.03 comes closest: For both FA and BFS, at AP, EP and POCP it is the method - or among the methods - which come closest to the results of Chen et al (2010). At GWP and ODP, deviations to the closest method are very small. So the used method is indeed the closest one among the examined LCIA methods, but differences to the results of Chen et al (2010) are nonetheless bigger than preferred.



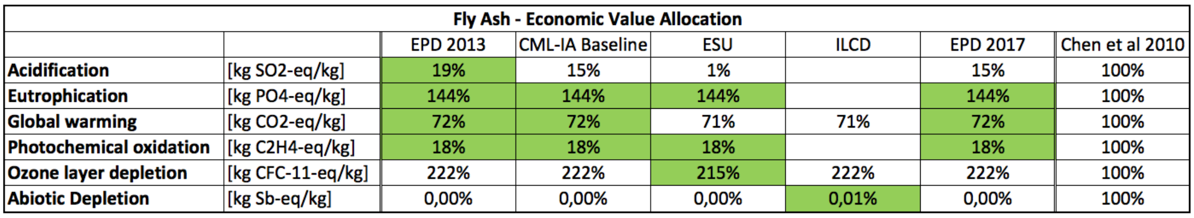
		EPD 2013 = 100%											
		EPD 2013		CML-IA Baseline		ESU		ILCD 2011 Midpoint		EPD 2017		Chen et al (2010)	
		BFS	FA	BFS	FA	BFS	FA	BFS	FA	BFS	FA	BFS	FA
Acidification	[kg SO2-eq/kg]	100%	100%	52%	79%	46%	5%			52%	79%	88%	526%
Eutrophication	[kg PO4-eq/kg]	100%	100%	100%	100%	100%	100%			100%	100%	42%	69%
Global warming	[kg CO2-eq/kg]	100%	100%	100%	100%	98%	98%	98%	98%	100%	100%	75%	138%
Photochemical oxidation	[kg C2H4-eq/kg]	100%	100%	100%	100%	100%	100%			100%	100%	107%	553%
Ozone layer depletion	[kg CFC-11-eq/kg]	100%	100%	100%	100%	91%	97%	100%	100%	100%	100%	67%	45%
Abiotic Depletion	[kg Sb-eq/kg]	100%	100%	100%	100%	174%	205%	1247%	1191%	100%	100%	4118543%	16216367%

Table 6.1.: *Sensitivity of FA and BFS Impacts - LCIA Method*



		Blast Furnace Slag - Economic Value Allocation					
		EPD 2013	CML-IA Baseline	ESU	ILCD	EPD 2017	Chen et al 2010
Acidification	[kg SO2-eq/kg]	114%	59%	53%		59%	100%
Eutrophication	[kg PO4-eq/kg]	236%	236%	236%		236%	100%
Global warming	[kg CO2-eq/kg]	133%	133%	130%	130%	133%	100%
Photochemical oxidation	[kg C2H4-eq/kg]	93%	93%	93%		93%	100%
Ozone layer depletion	[kg CFC-11-eq/kg]	150%	150%	136%	150%	150%	100%
Abiotic Depletion	[kg Sb-eq/kg]	0,00%	0,00%	0,00%	0,03%	0,00%	100%

Table 6.2.: *FA Impacts in relation to Chen et al (2010) - Variation of LCIA Method*



		Fly Ash - Economic Value Allocation					
		EPD 2013	CML-IA Baseline	ESU	ILCD	EPD 2017	Chen et al 2010
Acidification	[kg SO2-eq/kg]	19%	15%	1%		15%	100%
Eutrophication	[kg PO4-eq/kg]	144%	144%	144%		144%	100%
Global warming	[kg CO2-eq/kg]	72%	72%	71%	71%	72%	100%
Photochemical oxidation	[kg C2H4-eq/kg]	18%	18%	18%		18%	100%
Ozone layer depletion	[kg CFC-11-eq/kg]	222%	222%	215%	222%	222%	100%
Abiotic Depletion	[kg Sb-eq/kg]	0,00%	0,00%	0,00%	0,01%	0,00%	100%

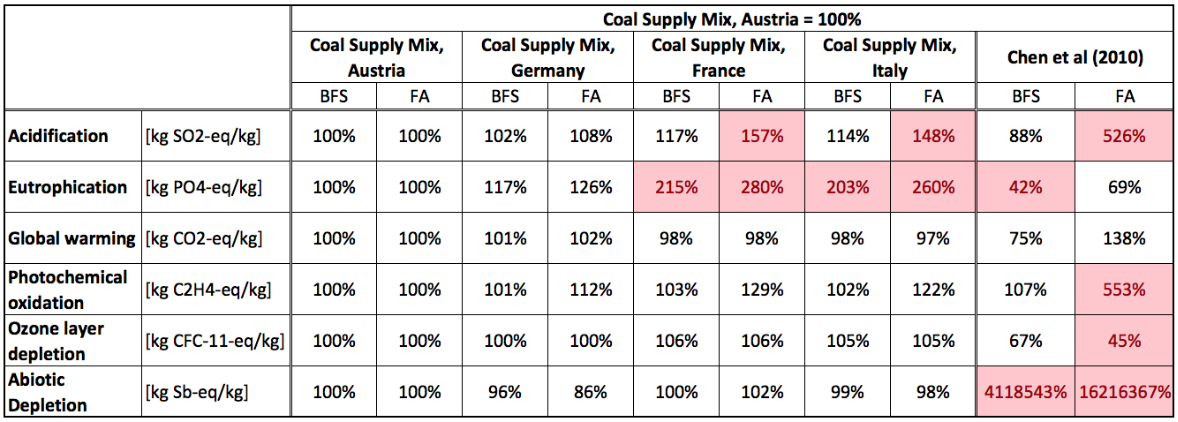
Table 6.3.: *BFS Impacts in relation to Chen et al (2010) - Variation of LCIA Method*

6.1.2. Coal

Besides variation of the LCIA method, variations of inputs and outputs with big influence on the results is another approach to gain more insights in the differences between the used results and results provided by Chen et al (2010) for FA and BFS. One of the inputs with a major effect on the results of both materials is "Hard Coal Supply Mix". In SimaPro, the Hard Coal Supply Mix is country-dependent, i.e. there exist processes for different countries. The processes used as inputs for BFS and FA are:

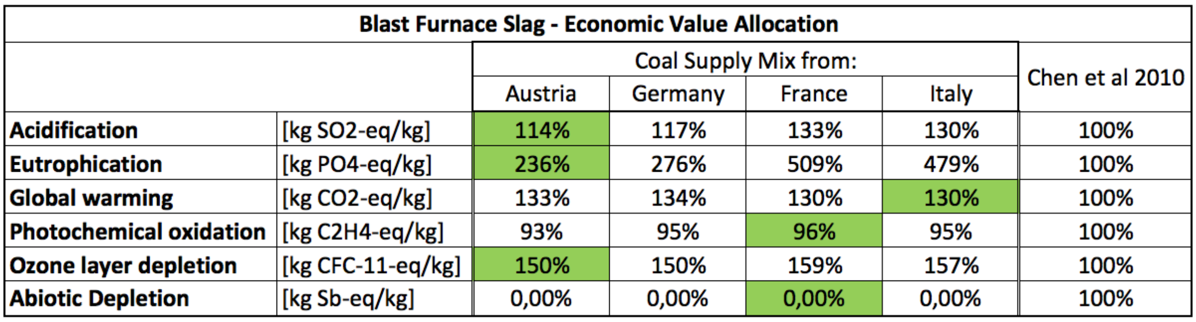
- Hard Coal Supply Mix, Austria
- Hard Coal Supply Mix, Germany
- Hard Coal Supply Mix, France
- Hard Coal Supply Mix, Italy

Unfortunately, there is no Hard Coal Supply Mix for Switzerland, and also no European Average available in SimaPro. Among the other Hard Coal Supply Mixes are processes from baltic nations or U.S., but since they are not comparable to Austria and therefore not within the boundary of this thesis, they are not considered in more detail.
Table 6.4 shows relative results with the used Supply Mix from Austria serving as basis. With coal from other states, results don't change much. The only bigger deviations occur at EP and AP if coal from Italy or France is considered. Interestingly, deviations at EP lie in the other direction than results from Chen et al (2010) would suggest. At the other four indicators, differences are small. Especially the similarity of Germany and Austria is remarkable.
A look at tables 6.5 and 6.6 show that the values derived with usage of the Austrian Coal Mix come closest to values from Chen et al (2010) at AP, EP and ODP, with differences to the closest Coal Mix at the other three impact indicators being negligible small, as long as BFS is considered. At FA, France comes closest in three categories, with a large deviation to Austria at AP. Its only shortcoming is that it assigns more than four times the EP to FA than Chen et al (2010) do. Due to the large differences at AP and EP to the Austrian coal, it's impossible to state which Supply Mix comes closest to Chen et al (2010) without weighting, which is avoided throughout the whole thesis.



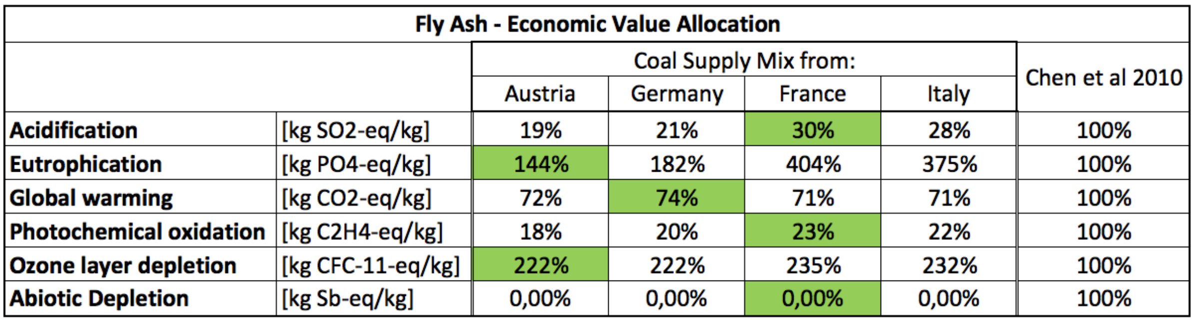
		Coal Supply Mix, Austria = 100%									
		Coal Supply Mix, Austria		Coal Supply Mix, Germany		Coal Supply Mix, France		Coal Supply Mix, Italy		Chen et al (2010)	
		BFS	FA	BFS	FA	BFS	FA	BFS	FA	BFS	FA
Acidification	[kg SO2-eq/kg]	100%	100%	102%	108%	117%	157%	114%	148%	88%	526%
Eutrophication	[kg PO4-eq/kg]	100%	100%	117%	126%	215%	280%	203%	260%	42%	69%
Global warming	[kg CO2-eq/kg]	100%	100%	101%	102%	98%	98%	98%	97%	75%	138%
Photochemical oxidation	[kg C2H4-eq/kg]	100%	100%	101%	112%	103%	129%	102%	122%	107%	553%
Ozone layer depletion	[kg CFC-11-eq/kg]	100%	100%	100%	100%	106%	106%	105%	105%	67%	45%
Abiotic Depletion	[kg Sb-eq/kg]	100%	100%	96%	86%	100%	102%	99%	98%	4118543%	16216367%

Table 6.4.: *Sensitivity of FA and BFS Impacts - Coal*



Blast Furnace Slag - Economic Value Allocation						
		Coal Supply Mix from:				Chen et al 2010
		Austria	Germany	France	Italy	
Acidification	[kg SO2-eq/kg]	114%	117%	133%	130%	100%
Eutrophication	[kg PO4-eq/kg]	236%	276%	509%	479%	100%
Global warming	[kg CO2-eq/kg]	133%	134%	130%	130%	100%
Photochemical oxidation	[kg C2H4-eq/kg]	93%	95%	96%	95%	100%
Ozone layer depletion	[kg CFC-11-eq/kg]	150%	150%	159%	157%	100%
Abiotic Depletion	[kg Sb-eq/kg]	0,00%	0,00%	0,00%	0,00%	100%

Table 6.5.: *FA Impacts in relation to Chen et al (2010) - Variation of Coal*



Fly Ash - Economic Value Allocation						
		Coal Supply Mix from:				Chen et al 2010
		Austria	Germany	France	Italy	
Acidification	[kg SO2-eq/kg]	19%	21%	30%	28%	100%
Eutrophication	[kg PO4-eq/kg]	144%	182%	404%	375%	100%
Global warming	[kg CO2-eq/kg]	72%	74%	71%	71%	100%
Photochemical oxidation	[kg C2H4-eq/kg]	18%	20%	23%	22%	100%
Ozone layer depletion	[kg CFC-11-eq/kg]	222%	222%	235%	232%	100%
Abiotic Depletion	[kg Sb-eq/kg]	0,00%	0,00%	0,00%	0,00%	100%

Table 6.6.: *BFS Impacts in relation to Chen et al (2010) - Variation of Coal*

6.1.3. Diesel

Another input with a big influence on the results for BFS and FA is "Diesel". SimaPro provides eight different kinds of Diesel, and all of them are used in this sensitivity analysis:

- Diesel, at regional storage, CH[1]
- Diesel, at regional storage, RER[2]

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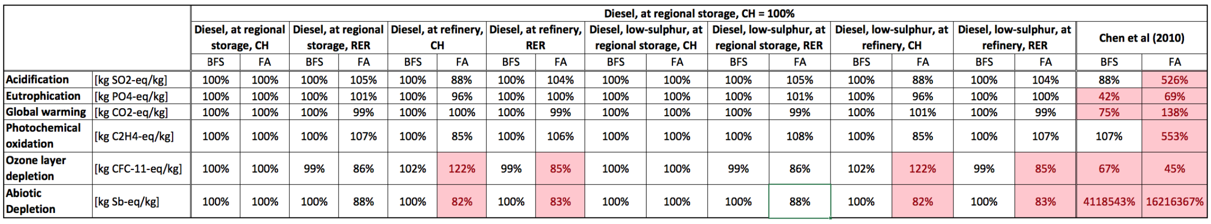
[1] Ch refers to Switzerland.

[2] RER refers to European Average.

- Diesel, at refinery, CH
- Diesel, at refinery, RER
- Diesel, low-sulphur, at regional storage, CH
- Diesel, low-sulphur, at regional storage, RER
- Diesel, low-sulphur, at refinery, CH
- Diesel, low-sulphur, at refinery, RER

As table 6.7 shows, differences in the results are small compared to differences derived with variations of LCIA method or Coal Supply Mix. The only noteworthy deviations occur if kinds of "Diesel, at refinery" and Fly Ash are considered. Looking at ODP, the indicator most affected by Diesel, it is interesting that deviations occur in both directions.
For BFS, the variation of "Diesel" has almost no effect. This is because for BFS less Diesel than for FA is used. So due to the small quantity of fuel used, the already small differences between the kinds of Diesel lead to almost no differences in the simulated slags.
To summarize, significant differences of the results only occur at AP and ADP if the LCIA method is varied, AP and EP if the coal comes from Italy or France, and ODP and and ADP if Diesel "at refinery" is used. Nevertheless, a variation of the LCIA method doesn't close the gap to results from Chen et al (2010), as other methods assign less burden, and Chen et al (2010) assign more to FA and BFS as the used method EPD (2013) v1.03 does. The same is true for EP if different Coal Supply Mixes are considered and ODP if different kinds of Diesel are used.
The only indicator, where results come closer to results presented in Chen et al (2010), is AP if Coal Supply Mix from France or Italy is used. But since this would come at the cost of a unreasonable high EP, also the use of one of these inputs would not be satisfying.



		Diesel, at regional storage, CH = 100%																	
		Diesel, at regional storage, CH		Diesel, at regional storage, RER		Diesel, at refinery, CH		Diesel, at refinery, RER		Diesel, low-sulphur, at regional storage, CH		Diesel, low-sulphur, at regional storage, RER		Diesel, low-sulphur, at refinery, CH		Diesel, low-sulphur, at refinery, RER		Chen et al (2010)	
		BFS	FA	BFS	FA	BFS	FA	BFS	FA	BFS	FA	BFS	FA	BFS	FA	BFS	FA	BFS	FA
Acidification	[kg SO2-eq/kg]	100%	100%	100%	105%	100%	88%	100%	104%	100%	100%	100%	105%	100%	88%	100%	104%	88%	526%
Eutrophication	[kg PO4-eq/kg]	100%	100%	100%	101%	100%	96%	100%	100%	100%	100%	100%	101%	100%	96%	100%	100%	42%	69%
Global warming	[kg CO2-eq/kg]	100%	100%	100%	99%	100%	100%	100%	99%	100%	100%	100%	99%	100%	101%	100%	99%	75%	138%
Photochemical oxidation	[kg C2H4-eq/kg]	100%	100%	100%	107%	100%	85%	100%	106%	100%	100%	100%	108%	100%	85%	100%	107%	107%	553%
Ozone layer depletion	[kg CFC-11-eq/kg]	100%	100%	99%	86%	102%	122%	99%	85%	100%	100%	99%	86%	102%	122%	99%	85%	67%	45%
Abiotic Depletion	[kg Sb-eq/kg]	100%	100%	100%	88%	100%	82%	100%	83%	100%	100%	100%	88%	100%	82%	100%	83%	4118543%	16216367%

Table 6.7.: *Sensitivity of FA and BFS Impacts - Diesel*

6.2. Sensitivity Check with LCIA method EPD (2017)

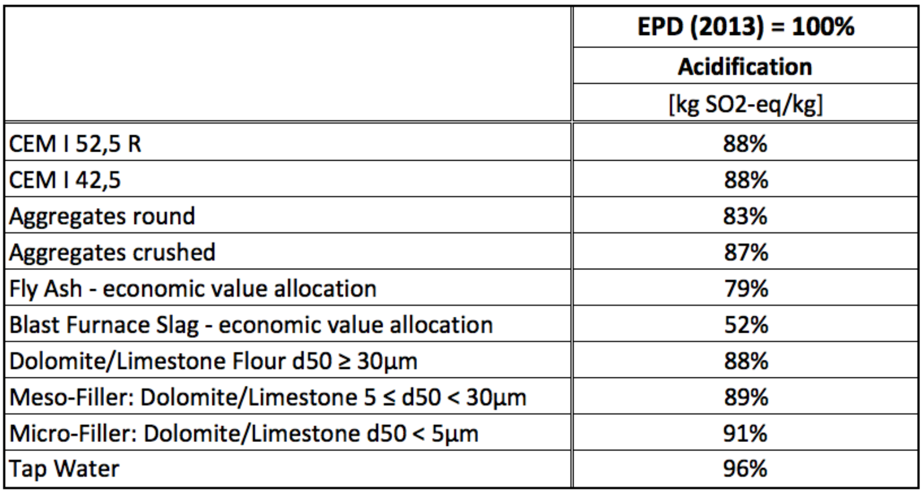
The EPD method in its newest version emerged during the work on this thesis. In order to align with the latest state of the art, a sensitivity check with EPD (2017) on a mix design basis is provided. The previous section showed that only characterisation factors with regard to Acidification Potential (AP) changed. So the other five examined indicators stay the same, and a look at the AP of different mixes with the new LCIA method is committed.

Table 6.8 shows the proportion of the assigned AP under EPD (2017) in comparison to EPD (2013) for all used materials which were modelled in SimaPro, with the impact under EPD (2013) serving as 100%. The table shows that most materials' AP was cut by 12 to 17 per cent. For BFS and FA the reduction is even bigger, while the reduction is smaller for Meso- and Micro-Fillers, and tap water.

So compared to earlier findings under EPD (2013), it now looks like a substitution of cement with FA and BFS is even more environmentally beneficial with regard to AP. Because the reduction of Meso- and Micro-Fillers' AP is less than the one from FA and BFS, there may be a position shift within this indicator. Earlier findings showed that mix designs with FA and BFS (e.g. NRef4) have higher APs than mix designs with Meso- and Micro-Fillers (e.g. N1).

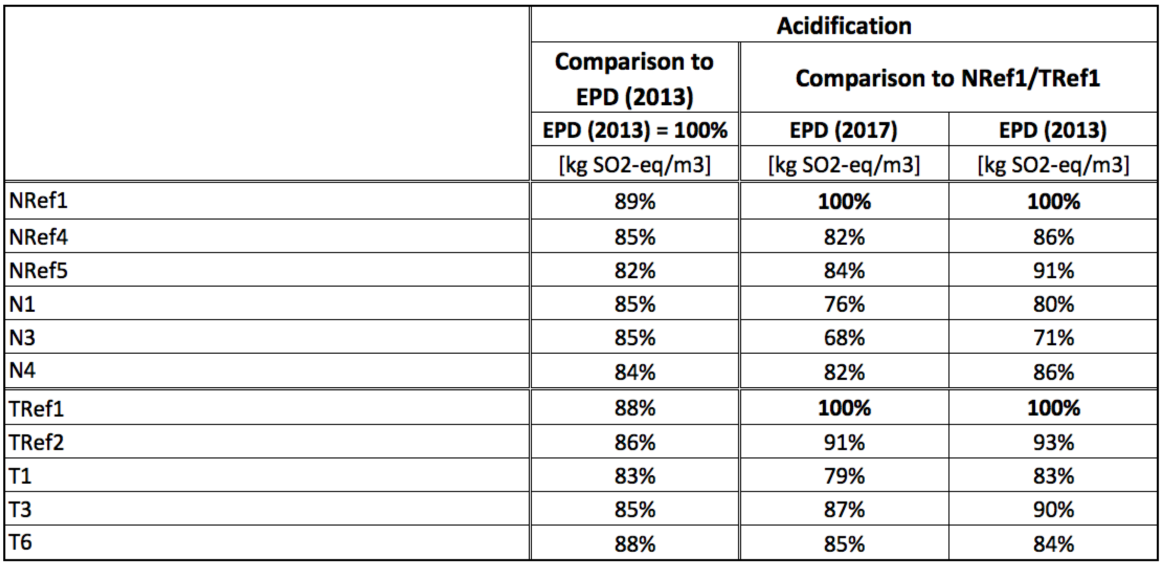
But table 6.9 shows that no position changes occur, as the positions with regard to AP stay the same regardless which EPD version is used. This can be derived by looking at the middle and the right column. The column in the middle compares a mix design's AP with the AP of NRef1 or TRef1 (depending whether the mix is a dry or wet one) under the use of EDP (2017). The right column does the same under use of EPD (2013). It can be seen that the mix with the lowest AP under EPD (2017) is also the one with the lowest under EPD (2013) and so on. Indeed, the proportions change, but not much.

The left column in table 6.9 shows how the mix designs' AP change if EPD (2017) is used, i.e it shows the same like table 6.8 did, but on a mix design basis. So, for example, under EPD (2017) only 89% of AP under EPD (2013) is assigned to 1 m3 of NRef1. All values lie within the range of 82 to 89%, evening out the bigger deviations on a material basis.



	EPD (2013) = 100%
	Acidification
	[kg SO2-eq/kg]
CEM I 52,5 R	88%
CEM I 42,5	88%
Aggregates round	83%
Aggregates crushed	87%
Fly Ash - economic value allocation	79%
Blast Furnace Slag - economic value allocation	52%
Dolomite/Limestone Flour d50 ≥ 30µm	88%
Meso-Filler: Dolomite/Limestone 5 ≤ d50 < 30µm	89%
Micro-Filler: Dolomite/Limestone d50 < 5µm	91%
Tap Water	96%

Table 6.8.: *Sensitivity of Materials' AP - Comparison of EPD (2017) to EPD (2013)*



	Acidification		
	Comparison to EPD (2013)	Comparison to NRef1/TRef1	
	EPD (2013) = 100%	EPD (2017)	EPD (2013)
	[kg SO2-eq/m3]	[kg SO2-eq/m3]	[kg SO2-eq/m3]
NRef1	89%	**100%**	**100%**
NRef4	85%	82%	86%
NRef5	82%	84%	91%
N1	85%	76%	80%
N3	85%	68%	71%
N4	84%	82%	86%
TRef1	88%	**100%**	**100%**
TRef2	86%	91%	93%
T1	83%	79%	83%
T3	85%	87%	90%
T6	88%	85%	84%

Table 6.9.: *Sensitivity of Mix Designs' AP - Comparison of EPD (2017) to EPD (2013) and Comparison to Reference Mix 1*

6.3. Monte Carlo Simulation

A Monte Carlo Simulation is one of the tools capable to address parameter uncertainty in LCA [Huijbregts1998]. It uses the distribution of all parameters to vary their values, arriving at different results for each run. By repeating this very often, MCS reveals the distribution of the examined product system's results.

The distribution of the parameters in SimaPro is calculated on basis of the parameters' pedigree-matrices. The pedigree-matrix was introduced by Weidema/Wesnaes in 1996 [Weidema1996]. It is a vector consisting of five numbers, whereby each ranges from one to five. The five numbers represent the uncertainty of the parameter regarding reliability, completeness, temporal correlation, geographical correlation and further technological correlation.

In SimaPro, each input and output of the unit processes is valued with a pedigree matrix. Unit processes available in EcoInvent usually already have been valued, but new modelled materials, like fly ash and blast furnace slag, are certainly not. Therefore, each input and output in the models of FA and BFS was given a pedigree-matrix.

The MCS is performed in SimaPro and parameters are varied based on the pedigree-matrices. 10.000 iterations are ran, which is a number also found in other LCA studies which contain a MCS, e.g. [Pang2015; Blengini2010]. Additionally, Ciroth et al, who deal with uncertainty in LCAs, recommend the use of 10.000 runs in MCS [Ciroth2004]. Because SimaPro uses a log-normal distribution for each parameter if pedigree-matrices are used, the distributions of the whole sprayed concrete mix designs are also positive skewed.

Because not every base material used was modelled in SimaPro, an adjustment is necessary to derive at the sprayed concrete mix designs' results: Results of the MCS, i.e. means and standard deviations, as well as the 2,5% and 97,5%-percentiles of impact indicator results are transferred to Excel, where the impacts of the materials, which are not modelled in SimaPro, are added to mean and percentiles. These materials are the admixtures and Metakaolin. Then, it is possible to plot graph 6.1, which shows the results. The standard deviation of the mixes do not change by this adjustment, which means it is assumed that the impacts of superplasticizer, set accelerator and Metakaolin are certain[3] or very small compared to the uncertainty of the other materials.

Graph 6.1 shows the results of the MCS for three wet mix designs: NRef1, NRef4 and N1. 100% outlines the highest mean value within each impact category of the three mixes. Also the value "mean +/- one standard deviation" is plotted and connected with lines. Furthermore, the 2,5% and 97,5%-percentiles are drawn as circles. Looking at their positions identifies the positive

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[3] This is of course an untenable assumption. But, it avoids an estimation of a distribution of these Materials and problems associated with the superposition of different distributions.

skewness of the results.

For GWP, the range of the possible results is small compared to the range of the ODP indicator. There, the 97,5%-percentile, which means that 97,5% of the possible results are below it, is more than two times higher than the mean value for NRef1. Unfortunately, the range of the ADP indicator is not illustrated well, because the ADP of the used Metakaolin is very big compared to all other materials.

By looking at all impact indicators but ADP, it looks like overlaps of the distributions of the different mix designs are possible. For example, while the means state for GWP that NRef4 has a lower environmental burden than NRef1, their distributions indicate that also the opposite - with a lower probability - could be true. In this example, approximating both distributions by normal distributions with the same means and standard deviations, one could conclude that this is true with the probability of approximately 6%. But that's a fallacy. At least as long as the exact same materials are used for the different mix designs:

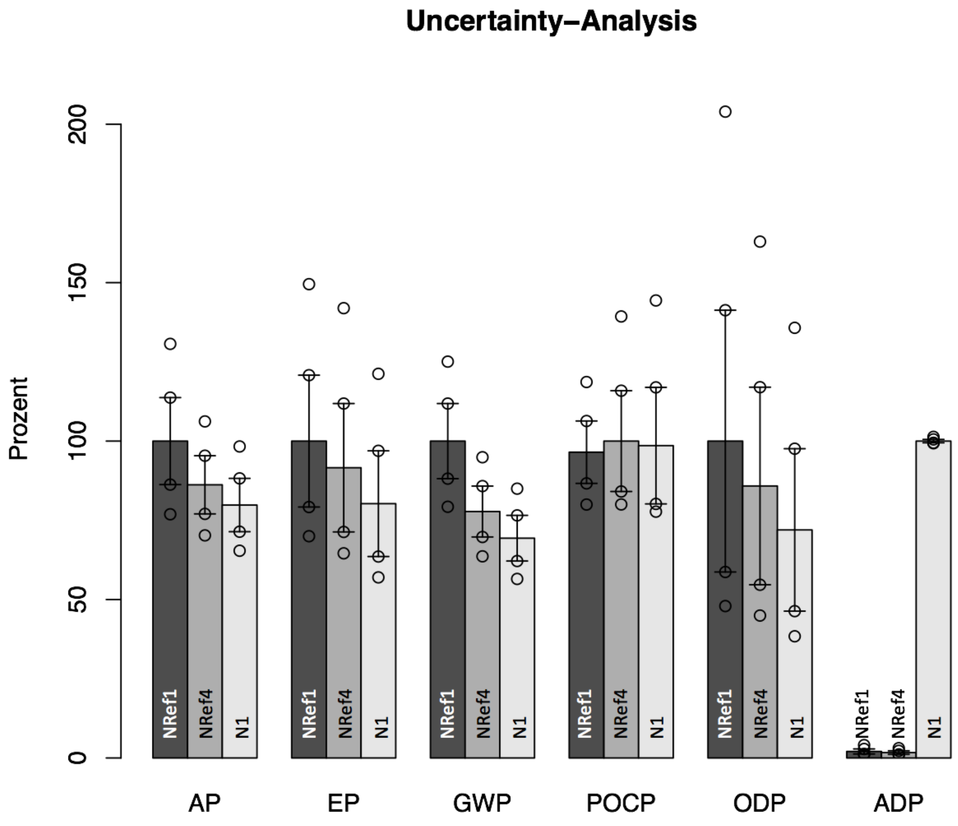


Figure 6.1.: *Impact Indicators of Wet Mix Designs under Uncertainty*

This is illustrated briefly by the example of one base material, in this case CEM I (cement). The true values for the used cement may differ from the mean used in the simulation according to the distribution assumed in SimaPro. If the real value for the used cement is higher than it's

mean, it will lead to a higher value for the whole mix NRef1 according to picture 6.1. But if the same cement is used for the other mix designs, these will also have higher impacts, preventing one mix design from becoming suddenly more environmentally friendly than the other.
So, a change in position due to the simulation can only become true if the mix designs use different materials, which they do. To arrive at the true probabilities of one sprayed concrete mix having bigger environmental impacts than another, materials used by more than one mix design have to be varied in the same way in the different mixes in each run of the MCS. This is what SimaPro automatically does. It also provides numbers of the probability, that one mix design has a higher impact indicator as the other. Graph 6.2 shows a comparison of NRef1 and NRef4.

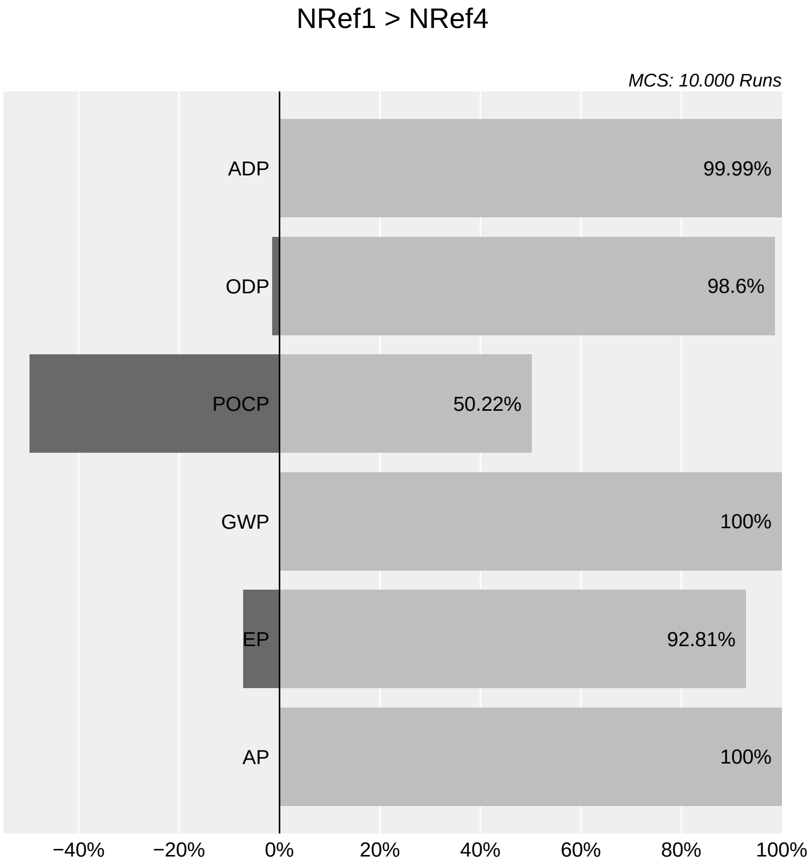


Figure 6.2.: *Probability of NRef1 having bigger impacts then NRef4*

It can be seen that the true overlaps are much smaller than originally thought, if even existent. Turning back to the example of GWP, graph 6.2 shows that the actual probability of NRef4 having a higher impact on GWP than NRef1 is not 6%, but 0%. It is also illustrated that this is true for AP, and in terms of almost certainty for ODP and ADP. While for EP the overlap is about 7,2%, the situation is very interesting for POCP. On the one hand, the means of NRef1 and NRef4 state that NRef1 has the lower POCP, but according to graph 6.2, it is slightly more possible that NRef1 has the higher POCP. This can be true because of the standard deviation and skewness of the distributions. To summarize, the picture emphasizes what was told in the previous section: For five of the six examined impact categories, NRef4 environmentally dominates NRef1. For the sixth, POCP, this is not true because their values don't differ much and no mix design is clearly more environmentally friendly than the other.

The comparison between NRef1 and NRef4 is only legitimate because SimaPro lacks the same amount of the same materials of both mixes: superplasticizer and set accelerator. Because they are part of both designs in the exact same amount, their absence in the MCS does not influence the presented results. Unfortunately a comparison of N1 with both of them is consequently not possible, because also Metakaolin is not modelled in SimaPro which would make results useless.

6.4. Sensitivity Check with EcoInvent v3.3

LCA results differ depending on the background data source used. For example, as already noted in chapter 4, Ökobaudat, ELCD and EcoInvent v2.2 associate different impacts to several base materials for sprayed concrete. These differences are a result of varying measurements, different system processes, dates, technologies, etc.

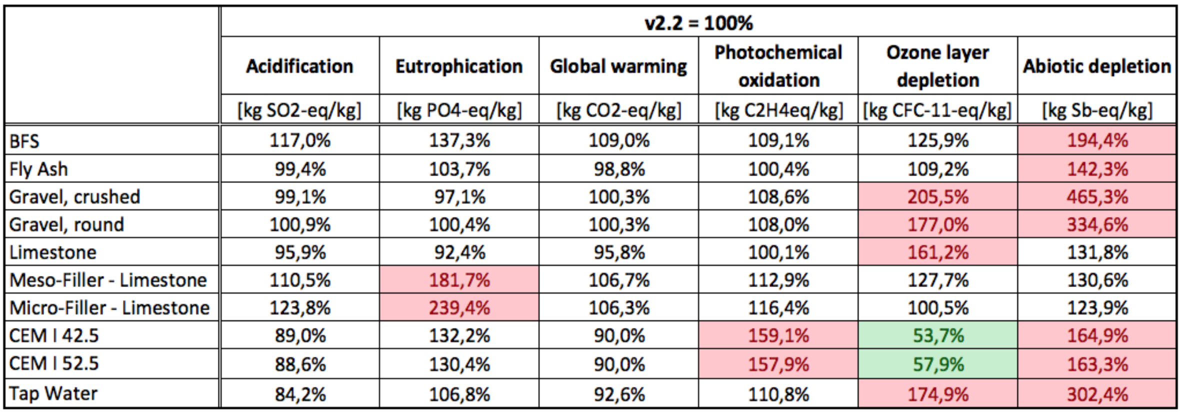
To check whether results vary massively if another data source is used, a sensitivity check is done with EcoInvent version 3.3 with the system model "Allocation, recycled content". Differences between the two versions are mainly existent because of updates of already existing processes, implementation of new activities, changes of allocation methods used and transportation data, and a better global coverage and completeness [Steubing2016].

At first, differences between the two version regarding the base materials of sprayed concrete are presented. Then, these differences are outlined on basis of sprayed concrete mix designs. Finally, results of v2.2 and v3.3 for the three wet mixes NRef1, NRef4 and N1 are compared. This third activity will answer the crucial question behind this subsection, whether the environmental advantage of one mix over the other disappears if another source is used.

6.4.1. Materials

In table 6.10 the base materials which were modelled or available in SimaPro are presented. Their associated environmental impact under v3.3 is plotted as percentage of the corresponding impact under v2.2. Impacts with a higher discrepancy than 40% are marked.

Acidification and Global Warming Potential do not differ much between the versions. Looking at these impact categories with regard to cement, which is the main contributor to both, it is found that v3.3 associates less AP and GWP to it. This indicates that also the whole mix designs of sprayed concrete will have lower AP and GWP under the new version. Exactly the opposite should be true for ADP, because every material has a higher ADP in the new version. Before turning to that, a deeper look at the deviations of the different materials is provided[4].



	v2.2 = 100%					
	Acidification	Eutrophication	Global warming	Photochemical oxidation	Ozone layer depletion	Abiotic depletion
	[kg SO2-eq/kg]	[kg PO4-eq/kg]	[kg CO2-eq/kg]	[kg C2H4eq/kg]	[kg CFC-11-eq/kg]	[kg Sb-eq/kg]
BFS	117,0%	137,3%	109,0%	109,1%	125,9%	194,4%
Fly Ash	99,4%	103,7%	98,8%	100,4%	109,2%	142,3%
Gravel, crushed	99,1%	97,1%	100,3%	108,6%	205,5%	465,3%
Gravel, round	100,9%	100,4%	100,3%	108,0%	177,0%	334,6%
Limestone	95,9%	92,4%	95,8%	100,1%	161,2%	131,8%
Meso-Filler - Limestone	110,5%	181,7%	106,7%	112,9%	127,7%	130,6%
Micro-Filler - Limestone	123,8%	239,4%	106,3%	116,4%	100,5%	123,9%
CEM I 42.5	89,0%	132,2%	90,0%	159,1%	53,7%	164,9%
CEM I 52.5	88,6%	130,4%	90,0%	157,9%	57,9%	163,3%
Tap Water	84,2%	106,8%	92,6%	110,8%	174,9%	302,4%

Table 6.10.: *Comparison of v3.3 to v2.2 on Basis of 1 kg of Material*

Gravel has quite the same AP, EP and GWP as under v2.2, but the new ODP and ADP are much higher. The high ODP comes from different impacts of the energy providing materials during the production of the gravel, i.e. diesel and electricity. The high ADP roots in a new valuation of gravel/sand quarry or mine and the building hall.

With version 3.3, limestone also has a higher ODP. As for gravel, the reason is also the used electricity. Electricity is also respnsable for the high Eutrophication Potential of Meso- and Micro-Fillers.

Cement varies much in EP, POCP, ODP and ADP, but not always in the same direction. While for three indicators, the impacts go up under the new version, it cuts the ODP almost in half. All four indicators are dominated by the production of clinker, which comes with corresponding different impacts in version 3.3. Furthermore, the valuation of the cement factory has also changed, contributing to the now higher ADP of CEM I.

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[4] Network graphs for material's impacts which have changed much are provided in the appendix. They show the contributions of processes to the materials indicator results.

Also the impacts of the tap water changes. The two highest discrepancies come at ODP and ADP. For ODP here the same is true as for Gravel and Limestone: The new electricity valuation pushes it higher. ADP is mainly influenced by the water supply network and water works and impacts of both processes have increased in the new version.
The look at the materials has identified three processes, which contribute much to the results and also have changed in version 3.3 significantly: These are Diesel, Electricity and Clinker production[5].

6.4.2. General Comparison of v3.3 to v2.2 in the Context of Sprayed Concrete

Due to the interaction of differences of constituents between version 2.2 and 3.3, and the amount of material used within the different mix designs, deviations of impact indicators occur in both directions. Figures 6.3 to 6.9 show the comparison of both EcoInvent versions. The impact indicator value if version 3.3 is used is plotted on the abscissa, while the corresponding impact indicator value under usage of version 2.2 is printed on the ordinate. A 45-Degree-Line is drawn to detect whether deviations of all mixes lie in the same direction and whether all six examined impact indicators experience them in the same direction.
As the graphs show, the first question can be easily answered with "yes". The second question is much more interesting, as deviations lie in different directions among the impact indicators: The use of EcoInvent v2.2 assigns more environmental burden to all examined mix designs in terms of AP, GWP and ODP, while the opposite is true for EP, POCP and ADP[6]. Reasons for this can be traced back to the statements above.

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[5] Processes influencing ADP are excluded here, because there aren't any processes which are involved in more than one material and ADP is, anyway, a very sensitive indicator where results can easily change dramatically.

[6] Graph 6.8 on ADP doesn't show the deviations between v2.2 and v3.3 in full extent because Metakaolin, which is not modelled in SimaPro and therefore experiences no changes, dominates the mix designs which use this material. This is seen on the right/above section of the graph. A deeper look at mix designs which do not use Metakaolin, which is provided with picture 6.9, shows that deviations are not that small as a look at graph 6.8 would suggest.

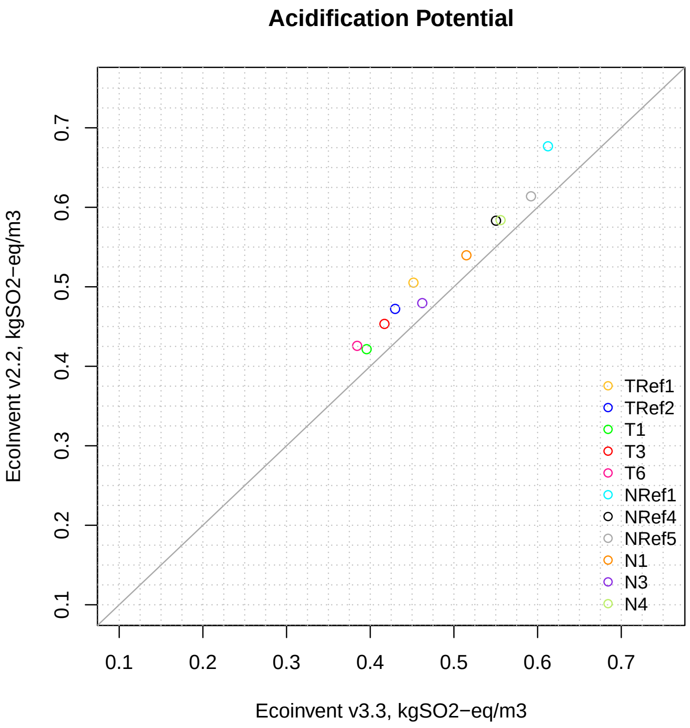


Figure 6.3.: *AP of Sprayed Concrete Mix Designs - Comparison of v3.3 to v2.2*

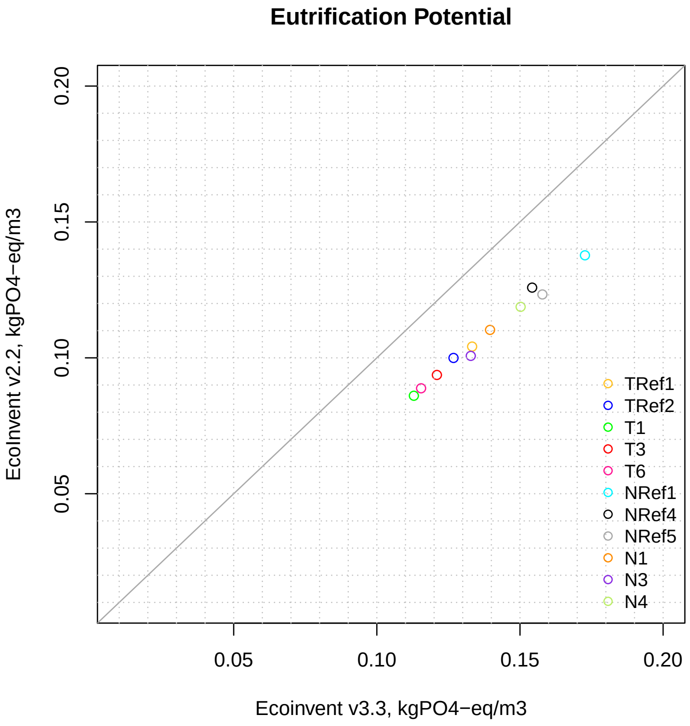


Figure 6.4.: *EP of Sprayed Concrete Mix Designs - Comparison of v3.3 to v2.2*

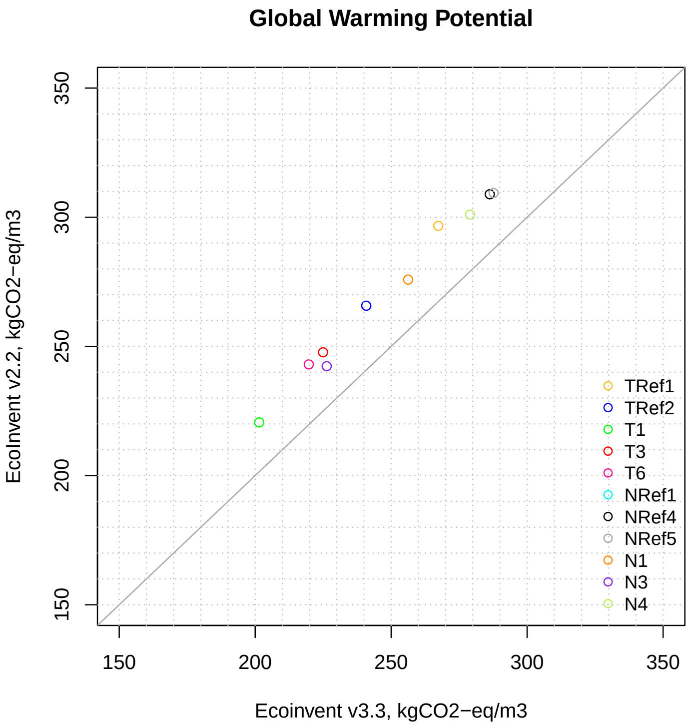


Figure 6.5.: *GWP of Sprayed Concrete Mix Designs - Comparison of v3.3 to v2.2*

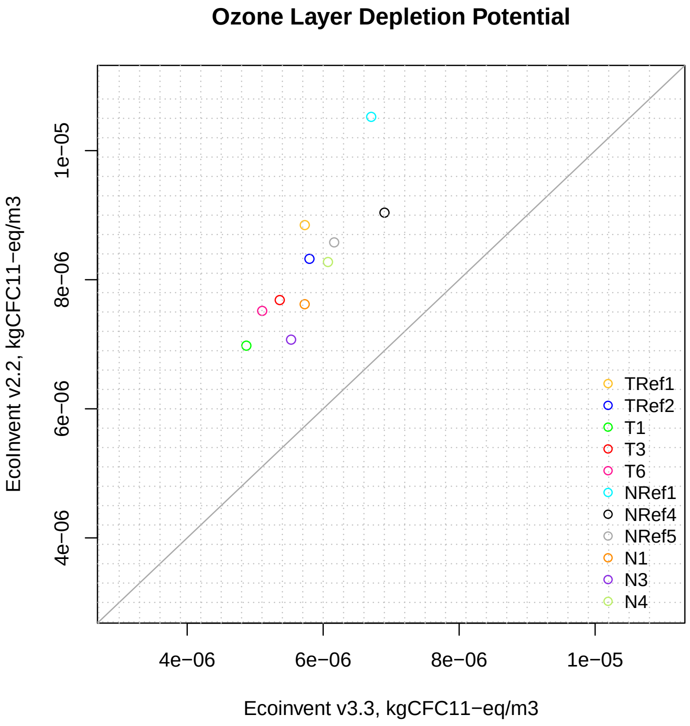


Figure 6.6.: *ODP of Sprayed Concrete Mix Designs - Comparison of v3.3 to v2.2*

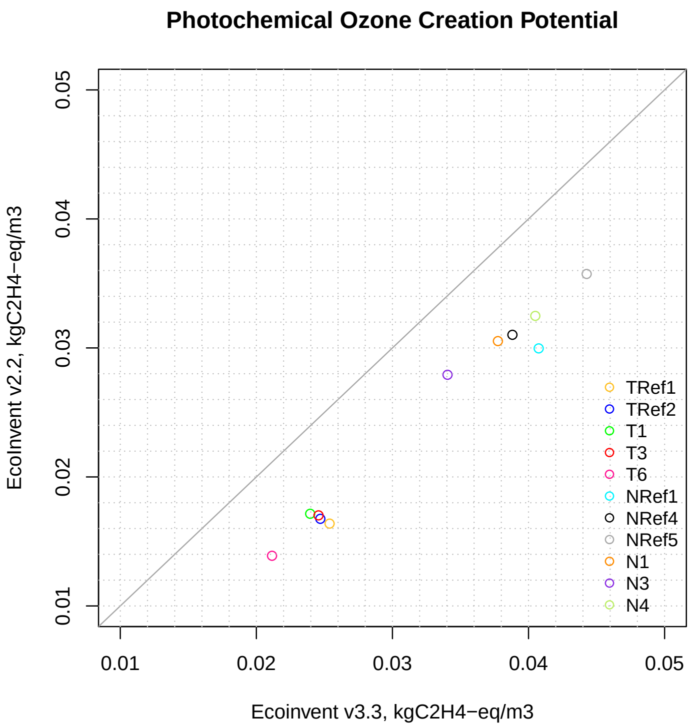


Figure 6.7.: *POCP of Sprayed Concrete Mix Designs - Comparison of v3.3 to v2.2*

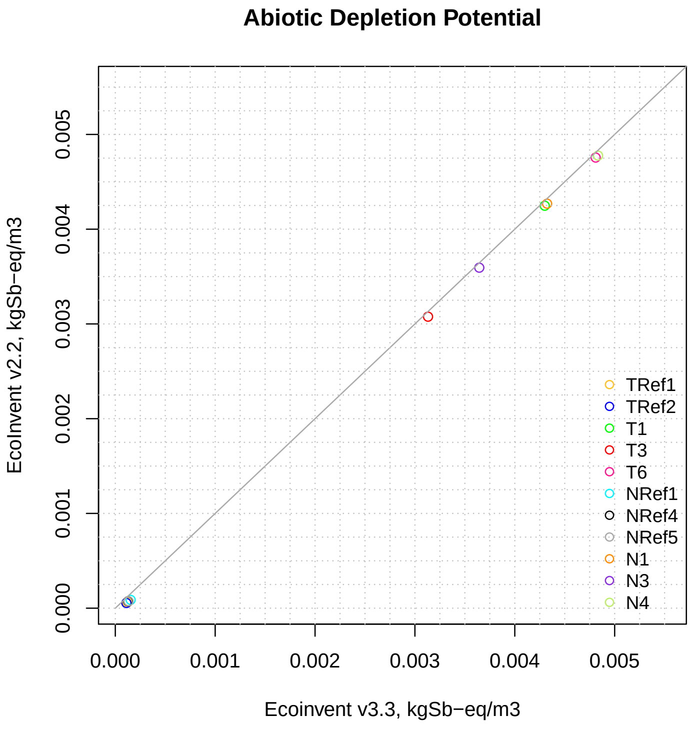


Figure 6.8.: *ADP of Sprayed Concrete Mix Designs - Comparison of v3.3 to v2.2*

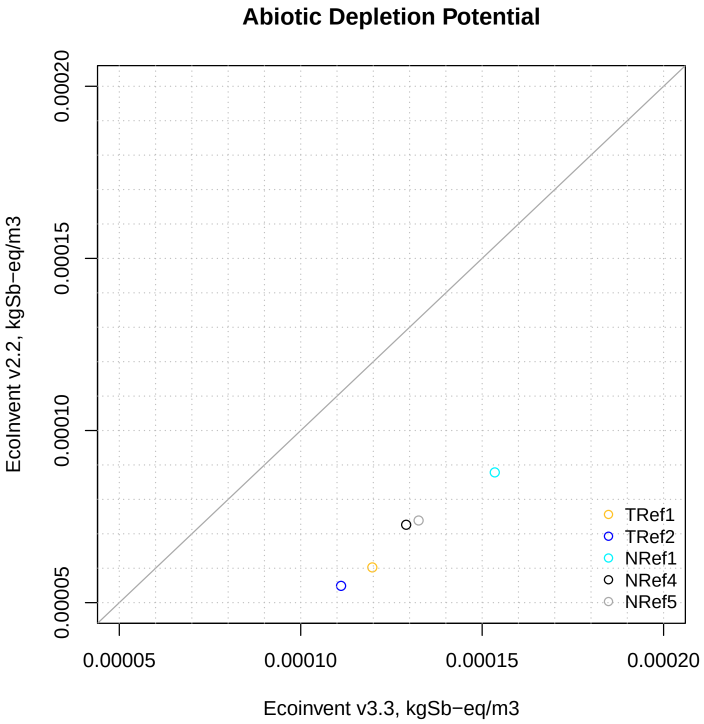
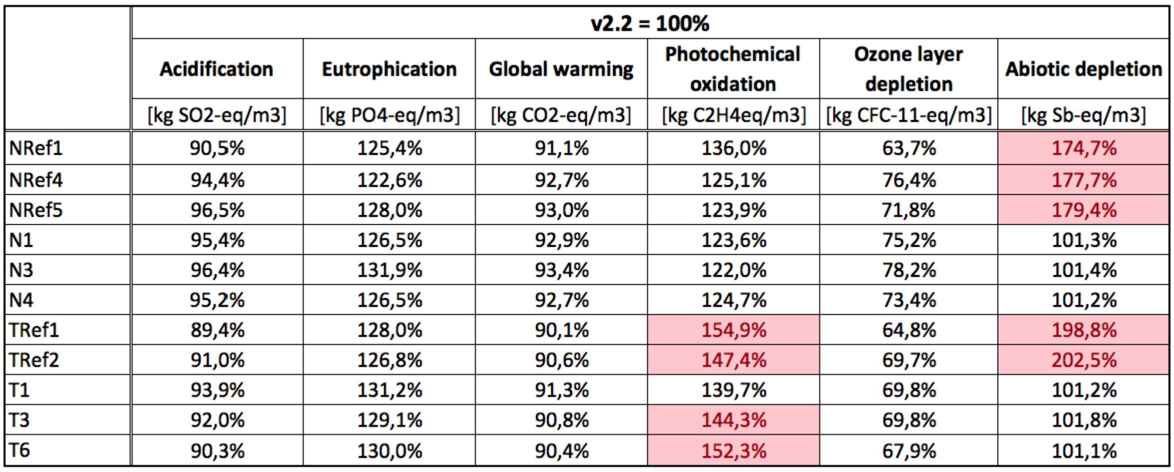


Figure 6.9.: *ADP of Sprayed Concrete Mix Designs without Metakaolin - Comparison of v3.3 to v2.2*

6.4.3. Mix Designs

Table 6.11 shows the changes of wet and dry mixes if version 3.3 is used. Several impact indicators alter in the same directions: On the one hand using v3.3 assigns less AP, GWP and ODP to sprayed concrete. The reason for this are the changed impacts of CEM I. On the other hand, EP, POCP and ADP increase by using the new version. This is no surprise because every base material has higher impacts in these three categories. The only exception is the EP of limestone, but this material is not used in big amounts.

The ADPs of N1, N3, N4, T1, T3 and T6 do not change as much as expected by looking at table 6.10, where the ADPs of the materials have increased dramatically. The reason for this is the use of Metakaolin in these mix designs. Metakaolin is not modelled in SimaPro as impacts are directly taken from the paper by Habert et al (2011), where the assigned ADP is very high compared to all other materials used in this LCA. Therefore, and as already pointed out in section 5.3, the ADP of these mixes are dominated by it and since it experiences no change under the use of version 3.3, also the results for the whole mixes do not vary much.



	v2.2 = 100%					
	Acidification	Eutrophication	Global warming	Photochemical oxidation	Ozone layer depletion	Abiotic depletion
	[kg SO2-eq/m3]	[kg PO4-eq/m3]	[kg CO2-eq/m3]	[kg C2H4eq/m3]	[kg CFC-11-eq/m3]	[kg Sb-eq/m3]
NRef1	90,5%	125,4%	91,1%	136,0%	63,7%	174,7%
NRef4	94,4%	122,6%	92,7%	125,1%	76,4%	177,7%
NRef5	96,5%	128,0%	93,0%	123,9%	71,8%	179,4%
N1	95,4%	126,5%	92,9%	123,6%	75,2%	101,3%
N3	96,4%	131,9%	93,4%	122,0%	78,2%	101,4%
N4	95,2%	126,5%	92,7%	124,7%	73,4%	101,2%
TRef1	89,4%	128,0%	90,1%	154,9%	64,8%	198,8%
TRef2	91,0%	126,8%	90,6%	147,4%	69,7%	202,5%
T1	93,9%	131,2%	91,3%	139,7%	69,8%	101,2%
T3	92,0%	129,1%	90,8%	144,3%	69,8%	101,8%
T6	90,3%	130,0%	90,4%	152,3%	67,9%	101,1%

Table 6.11.: *Comparison of v3.3 to v2.2 on Basis of 1 m3 Sprayed Concrete*

Every indicator of all different mix designs changes in the same direction, but not with the same magnitude. Therefore it is possible, that one mix with a higher indicator than another mix under v2.2 now derives at a lower one under v3.3. But is this true? Picture 6.10 gives the answer: The left part of graph 6.10 shows the environmental impacts of one m3 of the three already well examined wet mixes NRef1, NRef4 and N1 if EcoInvent version 2.2 is used. As already found in section 5.3, NRef1 has the highest environmental impacts while N1 has the lowest ones. The two exceptions are POCP, where the substitution of cement by fly ash and blast furnace slag does not lead to lower impacts, and therefore the largest burden is assigned to NRef4, and ADP, where N1 has the highest impacts due to the use of Metakaolin.

On the right hand side, the same graph is plotted, but version 3.3 is used. Comparing both graphs answers the question whether the environmental advantage of one mix design over the other disappears if versions change: The relative positions of the three mixes do not change if AP, EP, GWP and ADP are considered. The positions regarding POCP change in order that this indicator aligns itself with the former mentioned four indicators in terms that NRef1 has the highest POCP. The reason for this is the high POCP of CEM I under version 3.3: While using version 2.2 the substitution of cement in mix NRef4 is not advantageous due to the high POCP of fly ash. The new version assigns nearly as much as 60% more POCP to CEM I, but the impact of fly ash does not increase. This leads to the lower POCP of NRef4 than NRef1 in version 3.3. If nothing else would change, all six examined indicators in v3.3 would prefer NRef4 over NRef1. Also N1 would be the one with the lowest environmental burden with the exception of ADP. But this is not true, as graph 6.10 shows, because NRef4 now has the highest ozone depletion potential. Again, the reason for this is CEM I. With version 3.3 the cement's ODP decreases dramatically and the fly ash's ODP increases slightly. This leads to a situation where the replacement of cement with fly ash does not decrease the mix designs' ODP.

Deeper insights in differences between v2.2 and v3.3 with regard to the mix designs NRef1, NRef4 and N1 shows appendix H. There, sections of contribution networks relating to the ambiguous indicators ODP and POCP are plotted. Main differences can be traced back to changes on an inventory level. For example, differences at ODP, which mainly come from the clinker production process, are caused primarily by the replacement of "heavy fuel oil" with variety of other fuels with less ODP.

To summarize, the two examined versions agree at the environmental positions of the three mix designs if AP, EP, GWP and ADP are considered. However, with regard to POCP and ODP, the use of the new version alters the positions of them, again making it not possible to prefer one mix over the other in all addressed impact categories.

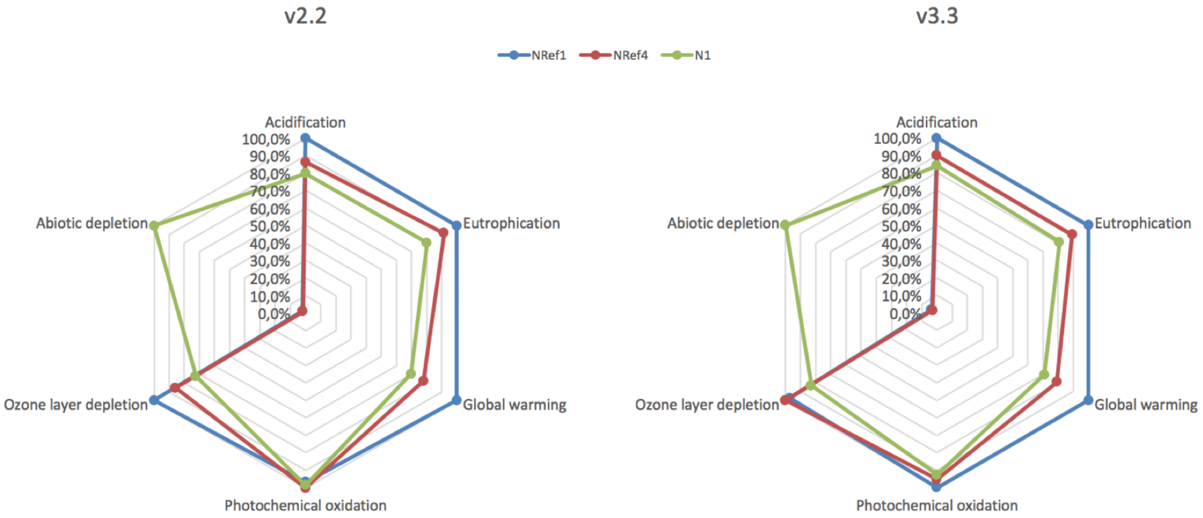


Figure 6.10.: *Impacts of Wet Mixes - Comparison of v3.3 to v2.2*

7. Conclusion

In this thesis, a Systematic Literature Review (SLR) of sprayed concrete's constituents and an LCA of sprayed concrete was conducted. During the SLR a research gap regarding LCAs of sprayed concrete was identified, affirming hypothesis 1[1]. Furthermore, EcoInvent was identified as the most utilized environmental database, most used in its version 2.2.

It was found that the scientific community and used data sources[2] agree to a different extent at the six addressed impact indicators[3] of sprayed concrete's base materials: At AP, EP and GWP using different data sources doesn't change results significantly, with GWP being the one indicator where the agreement is the strongest. At POCP and ODP, impacts of materials change a lot among the different data sources. But the indicator, where the highest discrepancy was found, is by far ADP.

Beside data sources, the used allocation rule is very important. It was shown that results for different materials which are by-products (fly ash and blast furnace slag), and impacts of whole sprayed concrete mixes can change dramatically between the addressed allocation rules. With this in mind it is also clear that statements in literature which claim that, for example, the substitution of cement with FA is environmentally beneficial, should be enjoyed with care. As shown and affirming hypothesis 4[4], this is not true if mass allocation is used.

In this LCA of sprayed concrete, where six wet mixes and five dry mixes were examined, economic value allocation was used as the base case. Affirming hypothesis 2[5], cement was clearly identified as the material with the biggest environmental burden within sprayed concrete mix designs. Furthermore, it was found that the its substitution with FA, BFS and limestone, or a mix of Meso- and Micro-Fillers is beneficial regarding AP, EP and GWP. If POCP and ODP are considered, this substitution decreases or slightly increases the environmental burden depending on the EcoInvent version used. Moreover, these kinds of substitution also have a

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[1] Hypothesis 1: In literature, LCAs on sprayed concrete are scarce.

[2] EcoInvent v2.2, EcoInvent v3.3, Ökobaudat, ELCD and EPDs

[3] Acidification Potential (AP), Eutrophication Potential (EP), Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Photochemical Ozone Creation Potential (POCP) and Abiotic Depletion Potential (ADP)

[4] Hypothesis 4: The environmental advantage of substituting cement with materials like fly ash and/or blast furnace slag depends on the allocation rule used.

[5] Hypothesis 2: Among the base materials of sprayed concrete, cement is responsible for the largest environmental burden.

positive effect on ADP. Here the only exception is the use of Metakaolin, which is the main contributor to ADP. This rather - but not to a full extent - affirms hypothesis 5[6], as it proves validity throughout all impact indicators, but the small changes were enough to alter the positions in terms of environmental advantage of different mix designs at ODP and POCP.

It was clearly pointed out, that admixtures play an important role in an LCA of sprayed concrete[7], as they are responsible for at least 10% of each impact indicator[8] in each examined mix design. But, like stated above, CEM I was identified as the environmental hot spot. As briefly touched in this study, its substitution has not only the potential to lower the environmental burden of sprayed concrete, it also has the ability to improve its technical properties.

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[6] Hypothesis 5: The use of other data sources doesn't change the results much.

[7] This affirms hypothesis 3: Admixtures play an important role in quantifying the environmental burden of sprayed concrete.

[8] Exceptions are ODP, and ADP if Metakaolin was used.

8. Outlook

To gain more environmental information on sprayed concrete in general and especially the new designed mix designs within the ASSpC project, the present LCA study should be expanded in three dimensions:

The first one deals with data quality and reliability. As discussed, environmental impacts of Metakaolin are directly taken from [Habert2011] where they are calculated using a different LCIA method. To improve its reliability, companies fabricating this material could provide information of its production, making it possible to simulate Metakaolin in SimaPro. Also the modelling of FA and BFS could be verified in this way.

The second dimension which should be tackled addresses the examined impact indicators. To gain more insights in the environmental burden caused by sprayed concrete, it would be beneficial to include more indicators. Especially the toxicity indicators within the CML methodology[1] could be of interest: On the one hand, admixtures are suspected to have a strong influence on these indicators. To better understand the environmental role of admixtures, toxicity indicator values should be published, for example by the EFCA. On the other hand, also the environmental advantage of substituting cement may become less clearer as pointed out in this thesis, because both FA and BFS have their highest relative impact indicator value relative to CEM I in one of the toxicity indicators [Chen2010; Habert2013]. In this thesis, its environmental advantage is only ambiguous at POCP[2], but including toxicity indicators may - in the worst case - point out a clear disadvantage of the substitution. Then, one has to commit *weighting* to derive at an answer to the question of the substitution of cement with FA and BFS leads to less environmental burden.

The third dimension, from a present-day perspective, is the one to be achieved "easiest": It is the expansion of the cradle-to-gate study to a cradle-to-grave study. Currently and within the next couple of years, there are experiments going on within the ASSpC project at TU Graz, ranging from large-scale spray tests to durability test procedures. These should provide information on technical properties which should make a solid cradle-to-grave LCA study possible. For example, longevity, maintenance intervals or End-of-Life characteristics could be estimated on basis of

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[1] Human Toxicity, Fresh Water Ecotoxicity, Marine Aquatic Ecotoxicity and Terrestrial Ecotoxicity

[2] or ODP, if EcoInvent v3.3 is used

experiments' results. Beside that, there is another obstacle to overcome if the whole life cycle phase is addressed: The choice of an appropriate functional unit. Because new developed mixes are, for example supposed to be less vulnerable to leaching or thaumasite sulfate attack, and therefore "better" than traditional mix designs in technical terms, one has to call into question whether they fulfill the same function. First solution approaches plan to include a technical parameter in the functional unit, like early strength or calcium leaching.

How these and other issues will be tackled in detail is yet to be seen. The ASSpC will deal with these topics in the next three years and there is no doubt that obstacles will be cleared and solid results attained.

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A. Appendix 1: SLR: Impacts of Sand and Gravel

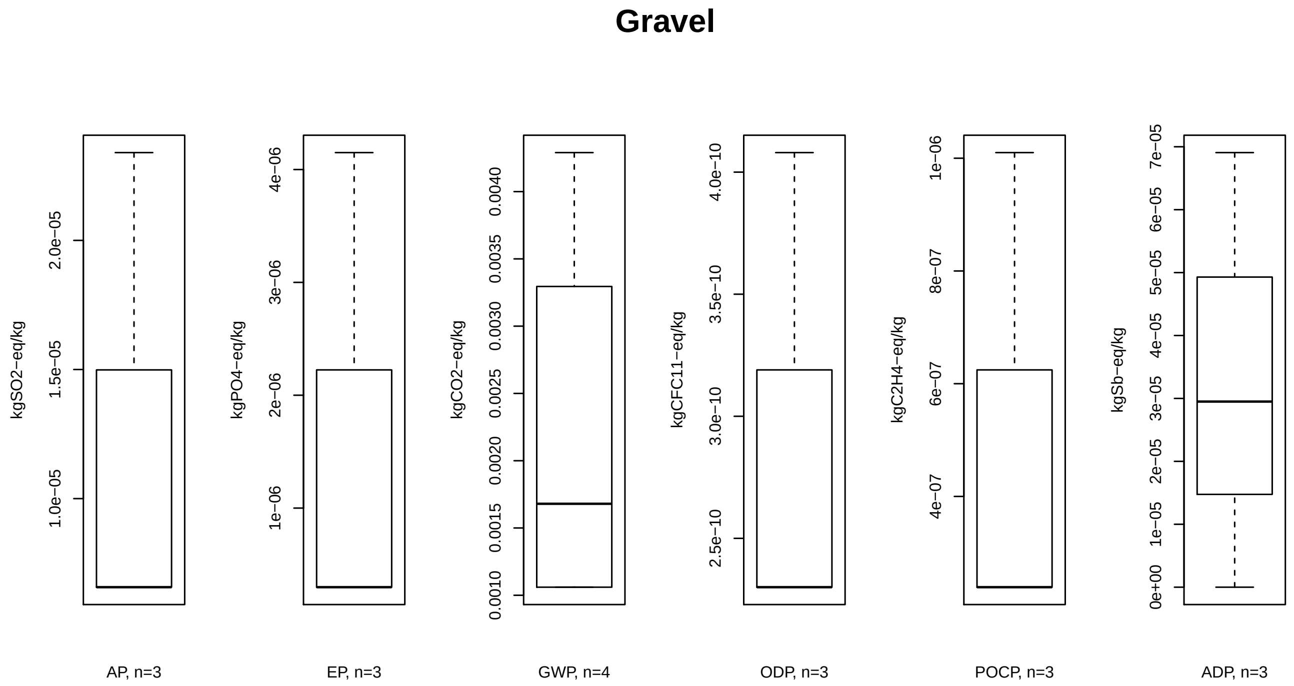


Figure A.1.: *Impacts of 1 kg Gravel*

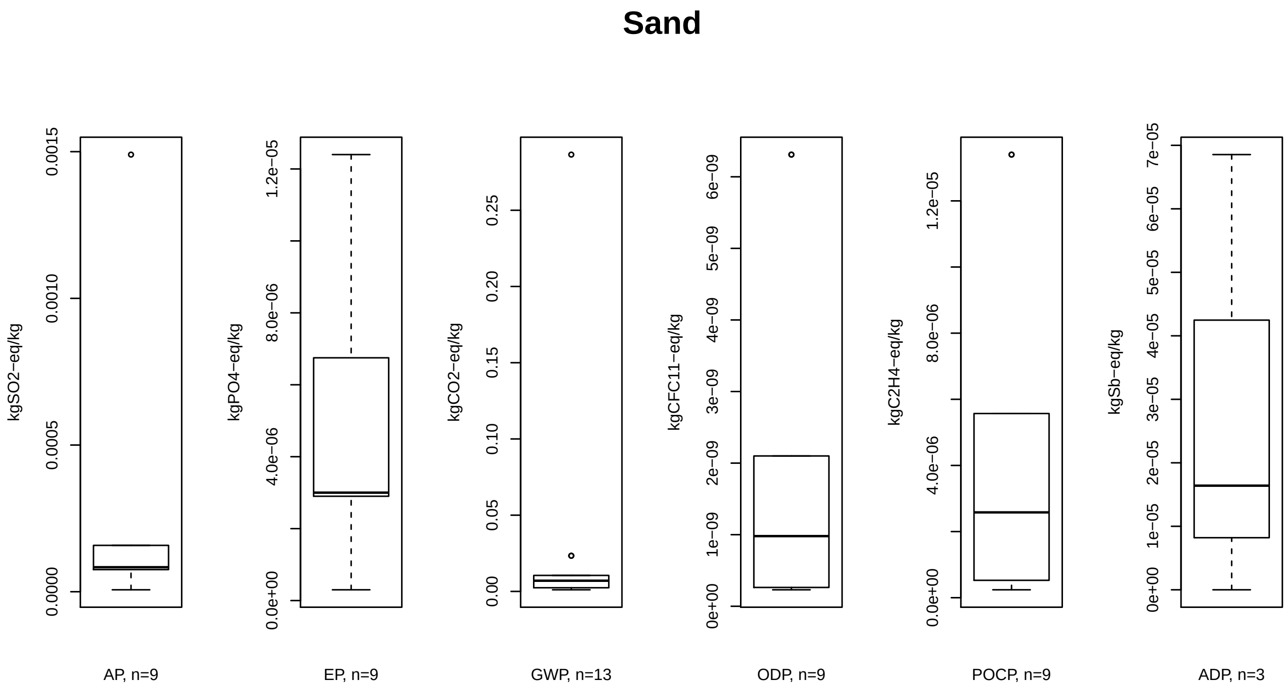


Figure A.2.: *Impacts of 1 kg Sand*

B. Appendix 2: Impact Comparisons of Base Materials

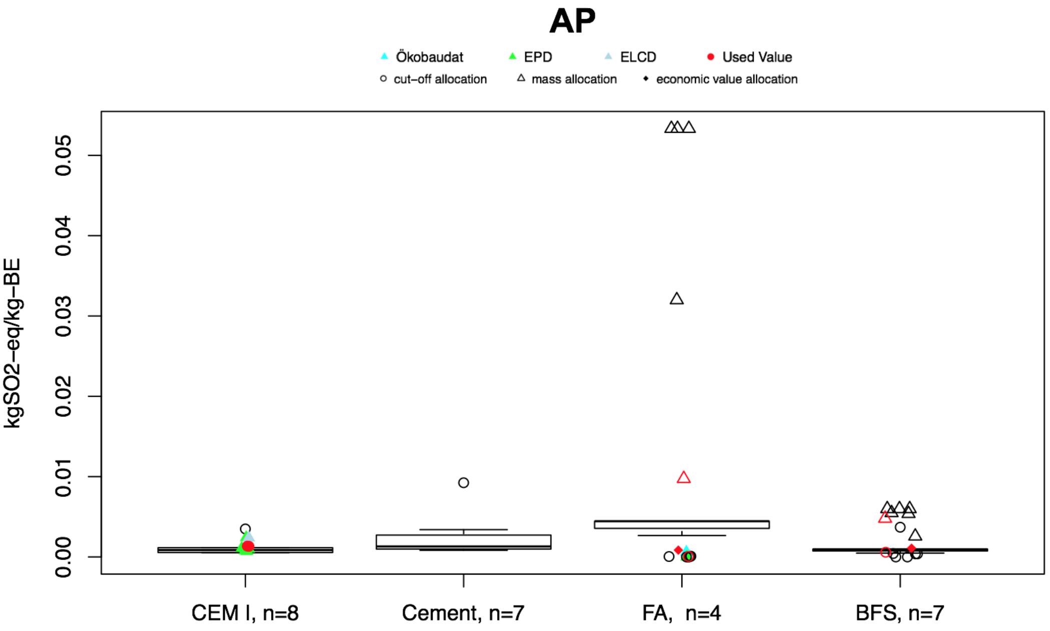


Figure B.1.: *AP of Different Materials*

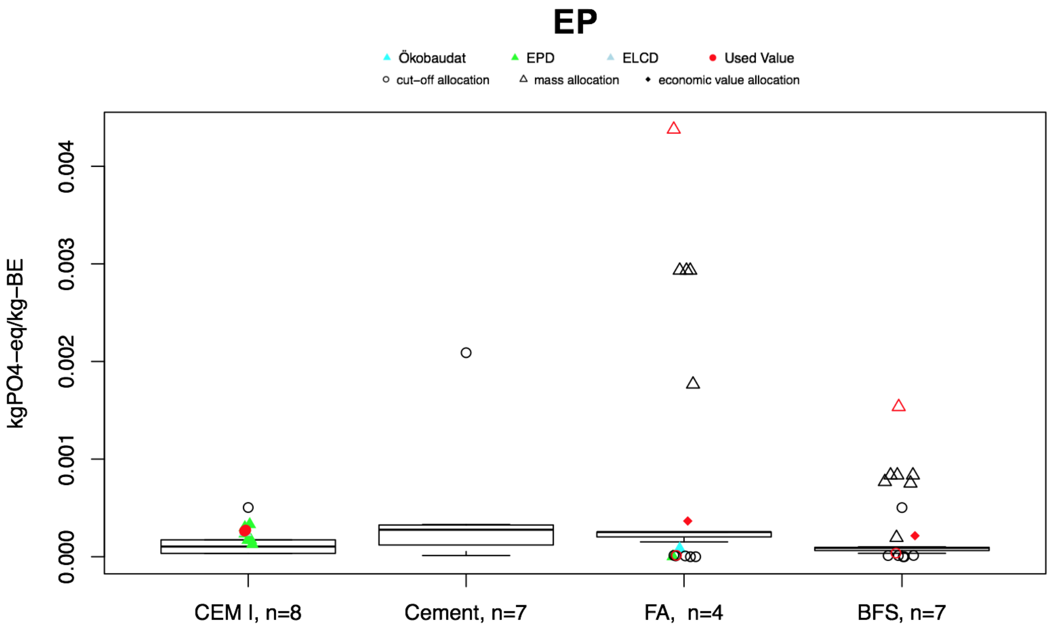


Figure B.2.: *EP of Different Materials*

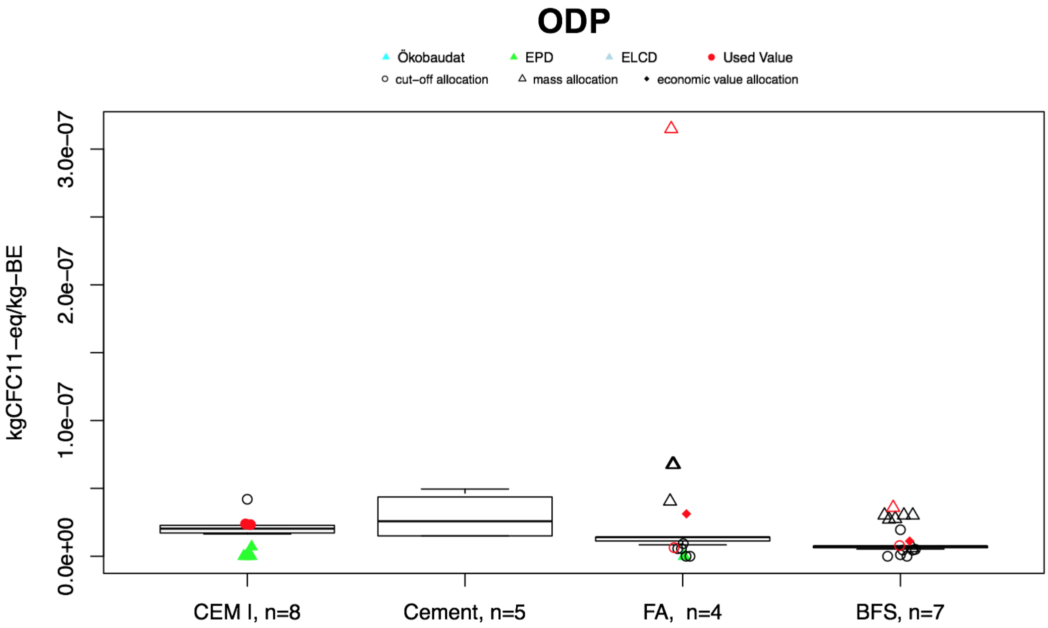


Figure B.3.: *ODP of Different Materials*

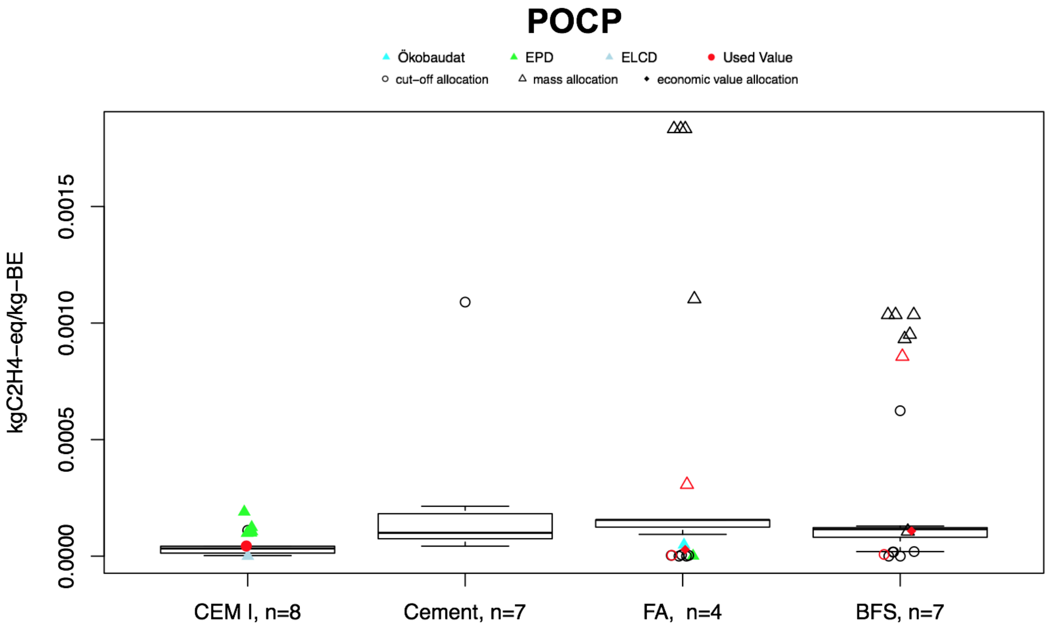
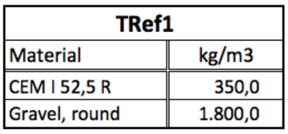


Figure B.4.: *POCP of Different Materials*

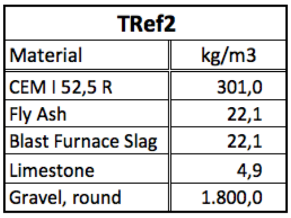
C. Appendix 3: Mix Designs

C.1. Dry Mixes



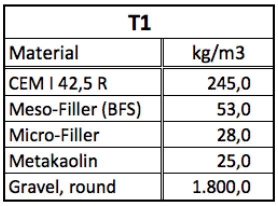
TRef1	
Material	kg/m3
CEM I 52,5 R	350,0
Gravel, round	1.800,0

Table C.1.: *Mix Design of 1m3 TRef1*



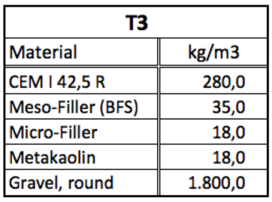
TRef2	
Material	kg/m3
CEM I 52,5 R	301,0
Fly Ash	22,1
Blast Furnace Slag	22,1
Limestone	4,9
Gravel, round	1.800,0

Table C.2.: *Mix Design of 1m3 TRef2*



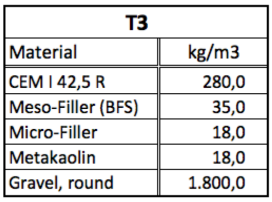
T1	
Material	kg/m3
CEM I 42,5 R	245,0
Meso-Filler (BFS)	53,0
Micro-Filler	28,0
Metakaolin	25,0
Gravel, round	1.800,0

Table C.3.: *Mix Design of 1m3 T1*



T3	
Material	kg/m3
CEM I 42,5 R	280,0
Meso-Filler (BFS)	35,0
Micro-Filler	18,0
Metakaolin	18,0
Gravel, round	1.800,0

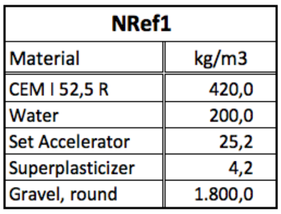
Table C.4.: *Mix Design of 1m3 T3*



T3	
Material	kg/m3
CEM I 42,5 R	280,0
Meso-Filler (BFS)	35,0
Micro-Filler	18,0
Metakaolin	18,0
Gravel, round	1.800,0

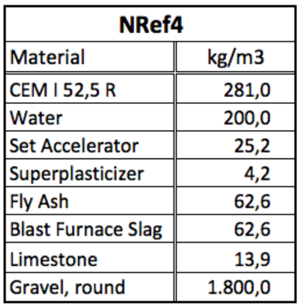
Table C.5.: *Mix Design of 1m3 T3*

C.2. Wet Mixes



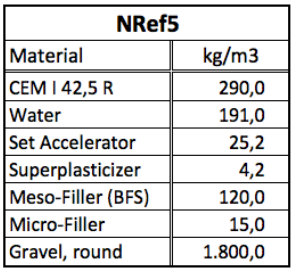
NRef1	
Material	kg/m3
CEM I 52,5 R	420,0
Water	200,0
Set Accelerator	25,2
Superplasticizer	4,2
Gravel, round	1.800,0

Table C.6.: *Mix Design of 1m3 NRef1*



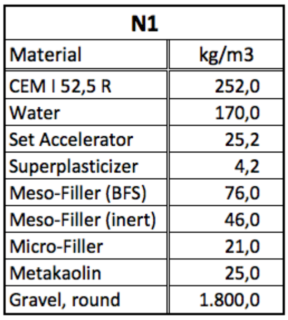
NRef4	
Material	kg/m3
CEM I 52,5 R	281,0
Water	200,0
Set Accelerator	25,2
Superplasticizer	4,2
Fly Ash	62,6
Blast Furnace Slag	62,6
Limestone	13,9
Gravel, round	1.800,0

Table C.7.: *Mix Design of 1m3 NRef4*



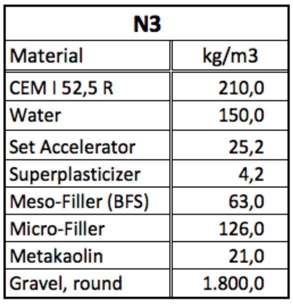
NRef5	
Material	kg/m3
CEM I 42,5 R	290,0
Water	191,0
Set Accelerator	25,2
Superplasticizer	4,2
Meso-Filler (BFS)	120,0
Micro-Filler	15,0
Gravel, round	1.800,0

Table C.8.: *Mix Design of 1m3 NRef5*



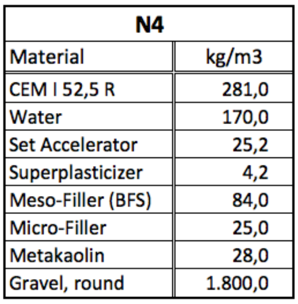
N1	
Material	kg/m3
CEM I 52,5 R	252,0
Water	170,0
Set Accelerator	25,2
Superplasticizer	4,2
Meso-Filler (BFS)	76,0
Meso-Filler (inert)	46,0
Micro-Filler	21,0
Metakaolin	25,0
Gravel, round	1.800,0

Table C.9.: *Mix Design of 1m3 N1*



N3	
Material	kg/m3
CEM I 52,5 R	210,0
Water	150,0
Set Accelerator	25,2
Superplasticizer	4,2
Meso-Filler (BFS)	63,0
Micro-Filler	126,0
Metakaolin	21,0
Gravel, round	1.800,0

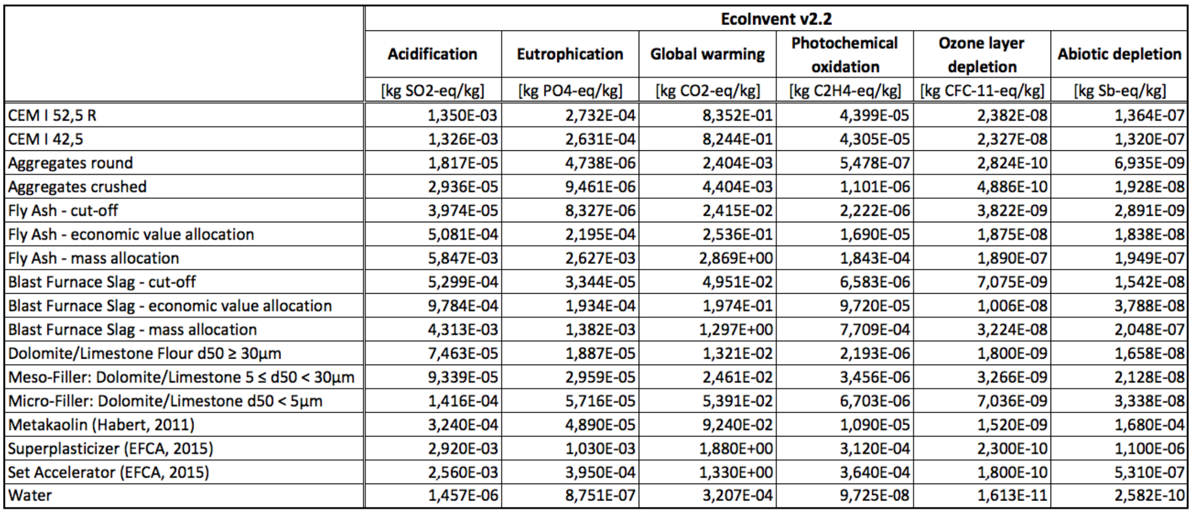
Table C.10.: *Mix Design of 1m3 N3*



N4	
Material	kg/m3
CEM I 52,5 R	281,0
Water	170,0
Set Accelerator	25,2
Superplasticizer	4,2
Meso-Filler (BFS)	84,0
Micro-Filler	25,0
Metakaolin	28,0
Gravel, round	1.800,0

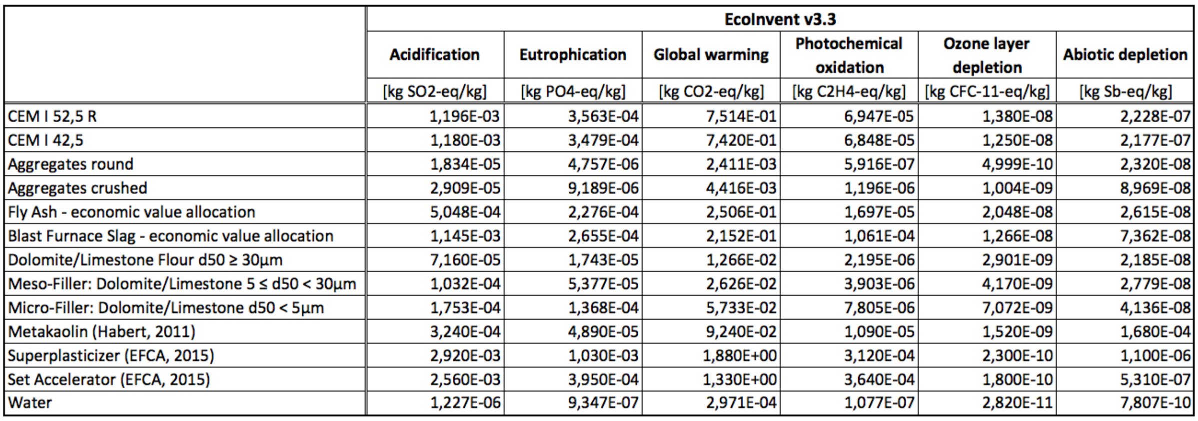
Table C.11.: *Mix Design of 1m3 N4*

D. Appendix 4: Used Impacts of Materials



	EcoInvent v2.2					
	Acidification	Eutrophication	Global warming	Photochemical oxidation	Ozone layer depletion	Abiotic depletion
	[kg SO2-eq/kg]	[kg PO4-eq/kg]	[kg CO2-eq/kg]	[kg C2H4-eq/kg]	[kg CFC-11-eq/kg]	[kg Sb-eq/kg]
CEM I 52,5 R	1,350E-03	2,732E-04	8,352E-01	4,399E-05	2,382E-08	1,364E-07
CEM I 42,5	1,326E-03	2,631E-04	8,244E-01	4,305E-05	2,327E-08	1,320E-07
Aggregates round	1,817E-05	4,738E-06	2,404E-03	5,478E-07	2,824E-10	6,935E-09
Aggregates crushed	2,936E-05	9,461E-06	4,404E-03	1,101E-06	4,886E-10	1,928E-08
Fly Ash - cut-off	3,974E-05	8,327E-06	2,415E-02	2,222E-06	3,822E-09	2,891E-09
Fly Ash - economic value allocation	5,081E-04	2,195E-04	2,536E-01	1,690E-05	1,875E-08	1,838E-08
Fly Ash - mass allocation	5,847E-03	2,627E-03	2,869E+00	1,843E-04	1,890E-07	1,949E-07
Blast Furnace Slag - cut-off	5,299E-04	3,344E-05	4,951E-02	6,583E-06	7,075E-09	1,542E-08
Blast Furnace Slag - economic value allocation	9,784E-04	1,934E-04	1,974E-01	9,720E-05	1,006E-08	3,788E-08
Blast Furnace Slag - mass allocation	4,313E-03	1,382E-03	1,297E+00	7,709E-04	3,224E-08	2,048E-07
Dolomite/Limestone Flour d50 ≥ 30µm	7,463E-05	1,887E-05	1,321E-02	2,193E-06	1,800E-09	1,658E-08
Meso-Filler: Dolomite/Limestone 5 ≤ d50 < 30µm	9,339E-05	2,959E-05	2,461E-02	3,456E-06	3,266E-09	2,128E-08
Micro-Filler: Dolomite/Limestone d50 < 5µm	1,416E-04	5,716E-05	5,391E-02	6,703E-06	7,036E-09	3,338E-08
Metakaolin (Habert, 2011)	3,240E-04	4,890E-05	9,240E-02	1,090E-05	1,520E-09	1,680E-04
Superplasticizer (EFCA, 2015)	2,920E-03	1,030E-03	1,880E+00	3,120E-04	2,300E-10	1,100E-06
Set Accelerator (EFCA, 2015)	2,560E-03	3,950E-04	1,330E+00	3,640E-04	1,800E-10	5,310E-07
Water	1,457E-06	8,751E-07	3,207E-04	9,725E-08	1,613E-11	2,582E-10

Table D.1.: *Used Impacts of 1 kg Material - EcoInvent v2.2*



	EcoInvent v3.3					
	Acidification	Eutrophication	Global warming	Photochemical oxidation	Ozone layer depletion	Abiotic depletion
	[kg SO2-eq/kg]	[kg PO4-eq/kg]	[kg CO2-eq/kg]	[kg C2H4-eq/kg]	[kg CFC-11-eq/kg]	[kg Sb-eq/kg]
CEM I 52,5 R	1,196E-03	3,563E-04	7,514E-01	6,947E-05	1,380E-08	2,228E-07
CEM I 42,5	1,180E-03	3,479E-04	7,420E-01	6,848E-05	1,250E-08	2,177E-07
Aggregates round	1,834E-05	4,757E-06	2,411E-03	5,916E-07	4,999E-10	2,320E-08
Aggregates crushed	2,909E-05	9,189E-06	4,416E-03	1,196E-06	1,004E-09	8,969E-08
Fly Ash - economic value allocation	5,048E-04	2,276E-04	2,506E-01	1,697E-05	2,048E-08	2,615E-08
Blast Furnace Slag - economic value allocation	1,145E-03	2,655E-04	2,152E-01	1,061E-04	1,266E-08	7,362E-08
Dolomite/Limestone Flour d50 ≥ 30µm	7,160E-05	1,743E-05	1,266E-02	2,195E-06	2,901E-09	2,185E-08
Meso-Filler: Dolomite/Limestone 5 ≤ d50 < 30µm	1,032E-04	5,377E-05	2,626E-02	3,903E-06	4,170E-09	2,779E-08
Micro-Filler: Dolomite/Limestone d50 < 5µm	1,753E-04	1,368E-04	5,733E-02	7,805E-06	7,072E-09	4,136E-08
Metakaolin (Habert, 2011)	3,240E-04	4,890E-05	9,240E-02	1,090E-05	1,520E-09	1,680E-04
Superplasticizer (EFCA, 2015)	2,920E-03	1,030E-03	1,880E+00	3,120E-04	2,300E-10	1,100E-06
Set Accelerator (EFCA, 2015)	2,560E-03	3,950E-04	1,330E+00	3,640E-04	1,800E-10	5,310E-07
Water	1,227E-06	9,347E-07	2,971E-04	1,077E-07	2,820E-11	7,807E-10

Table D.2.: *Used Impacts of 1 kg Material - EcoInvent v3.3*

E. Appendix 5: Impacts of Dry and Wet Mixes

	EcoInvent v2.2					
	Acidification	Eutrophication	Global warming	Photochemical oxidation	Ozone layer depletion	Abiotic depletion
	[kg SO2-eq/m3]	[kg PO4-eq/m3]	[kg CO2-eq/m3]	[kg C2H4-eq/m3]	[kg CFC-11-eq/m3]	[kg Sb-eq/m3]
NRef1	0,6768	0,1377	396,60	0,02997	1,052E-05	8,784E-05
NRef4	0,5831	0,1258	308,90	0,03102	9,039E-06	7,263E-05
NRef5	0,6139	0,1233	309,38	0,03574	8,578E-06	7,387E-05
N1	0,5397	0,1103	275,85	0,03053	7,621E-06	4,269E-03
N3	0,4795	0,1007	242,36	0,02792	7,071E-06	3,594E-03
N4	0,5839	0,1188	301,01	0,03249	8,274E-06	4,777E-03
TRef1	0,5052	0,1042	296,66	0,01638	8,847E-06	6,024E-05
TRef2	0,4722	0,1000	265,74	0,01675	8,323E-06	5,487E-05
T1	0,4215	0,0861	220,59	0,01715	6,978E-06	4,248E-03
T3	0,4533	0,0937	247,74	0,01702	7,685E-06	3,077E-03
T6	0,4257	0,0888	243,04	0,01389	7,517E-06	4,756E-03

Table E.1.: *Impacts of 1 m3 Sprayed Concrete - EcoInvent v2.2*

	EcoInvent v3.3					
	Acidification	Eutrophication	Global warming	Photochemical oxidation	Ozone layer depletion	Abiotic depletion
	[kg SO2-eq/m3]	[kg PO4-eq/m3]	[kg CO2-eq/m3]	[kg C2H4-eq/m3]	[kg CFC-11-eq/m3]	[kg Sb-eq/m3]
NRef1	0,6124	0,1727	361,39	0,04075	6,707E-06	1,535E-04
NRef4	0,5503	0,1542	286,26	0,03882	6,902E-06	1,291E-04
NRef5	0,5921	0,1578	287,68	0,04427	6,162E-06	1,325E-04
N1	0,5149	0,1395	256,23	0,03775	5,728E-06	4,324E-03
N3	0,4622	0,1328	226,31	0,03405	5,528E-06	3,645E-03
N4	0,5557	0,1502	279,04	0,04050	6,070E-06	4,834E-03
TRef1	0,4516	0,1333	267,32	0,02538	5,729E-06	1,197E-04
TRef2	0,4298	0,1268	240,84	0,02470	5,798E-06	1,111E-04
T1	0,3957	0,1129	201,46	0,02396	4,870E-06	4,300E-03
T3	0,4170	0,1210	224,95	0,02457	5,361E-06	3,131E-03
T6	0,3844	0,1155	219,72	0,02115	5,103E-06	4,810E-03

Table E.2.: *Impacts of 1 m3 Sprayed Concrete - EcoInvent v3.3*

F. Appendix 6: Impacts of Dry and Wet Mixes - Graphs

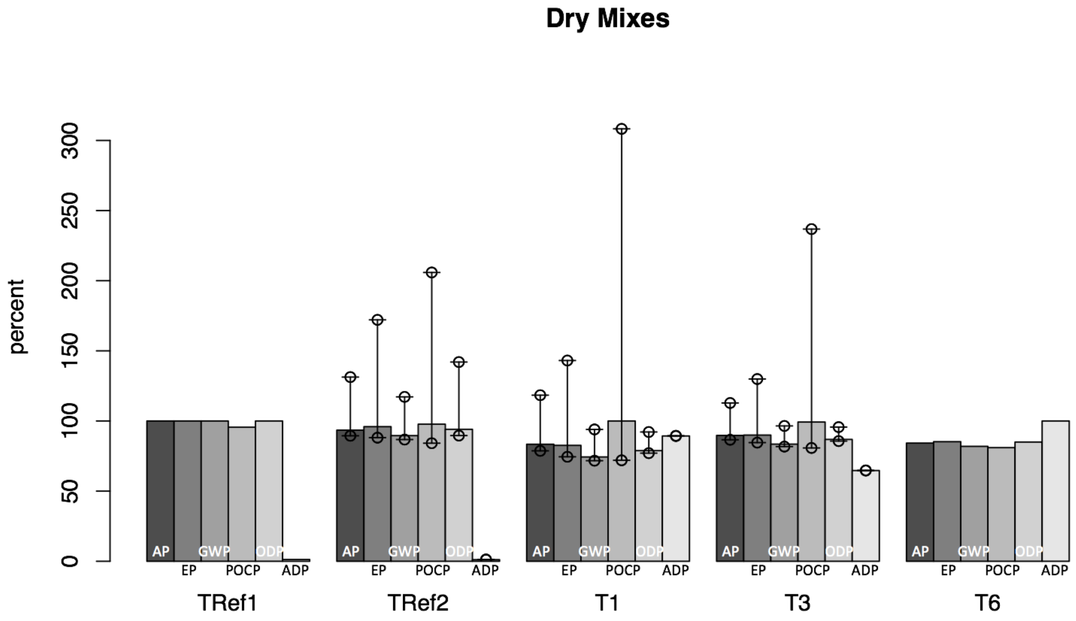


Figure F.1.: *All Impacts of Dry Mixes*

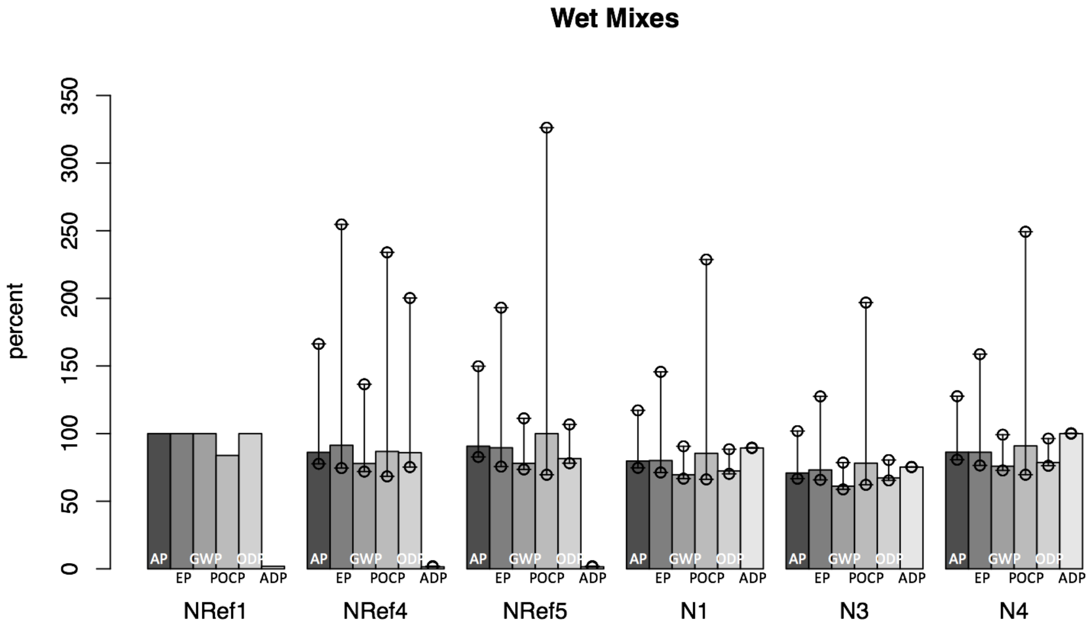


Figure F.2.: *All Impacts of Wet Mixes*

G. Appendix 7: Contribution Networks

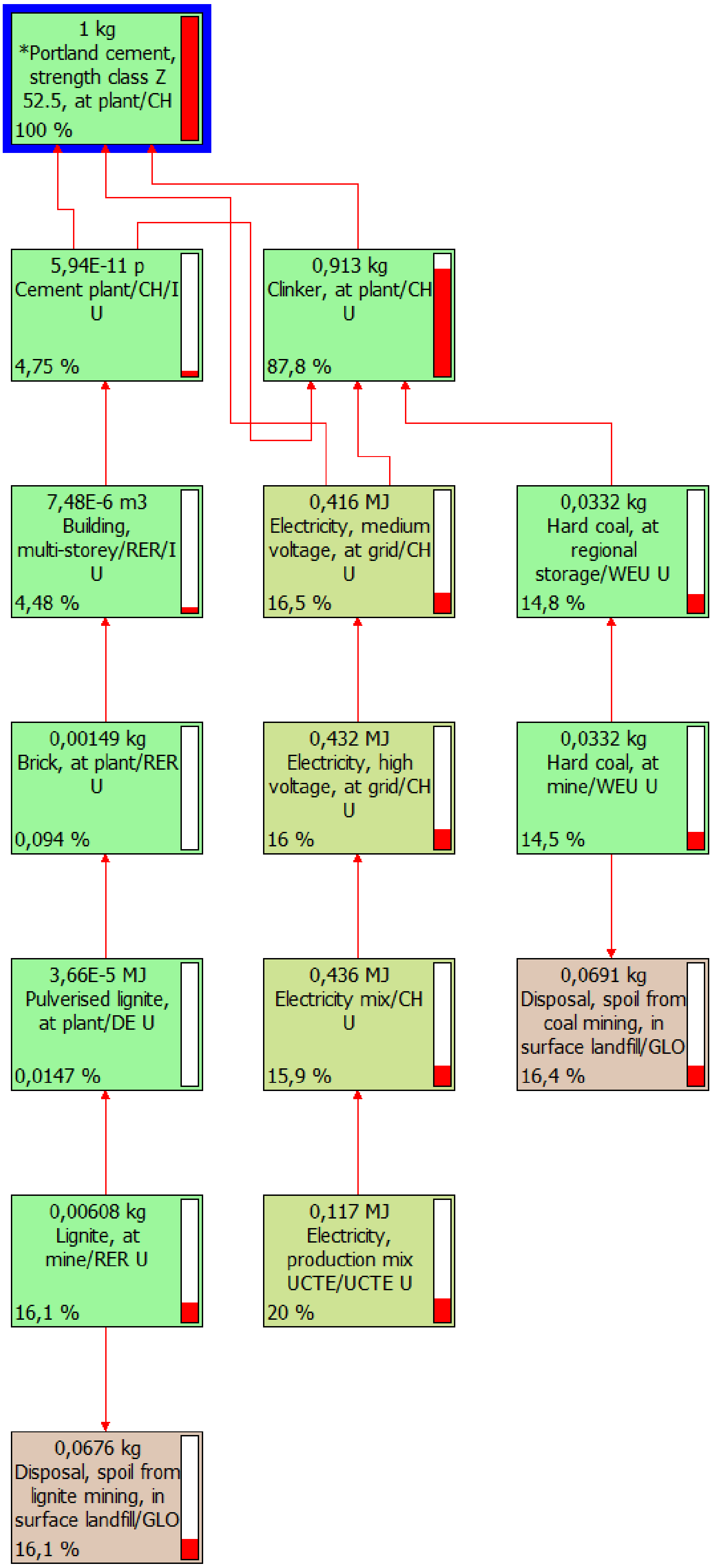


Figure G.1.: *EP of CEM I 52.5 v2.2 - Network*

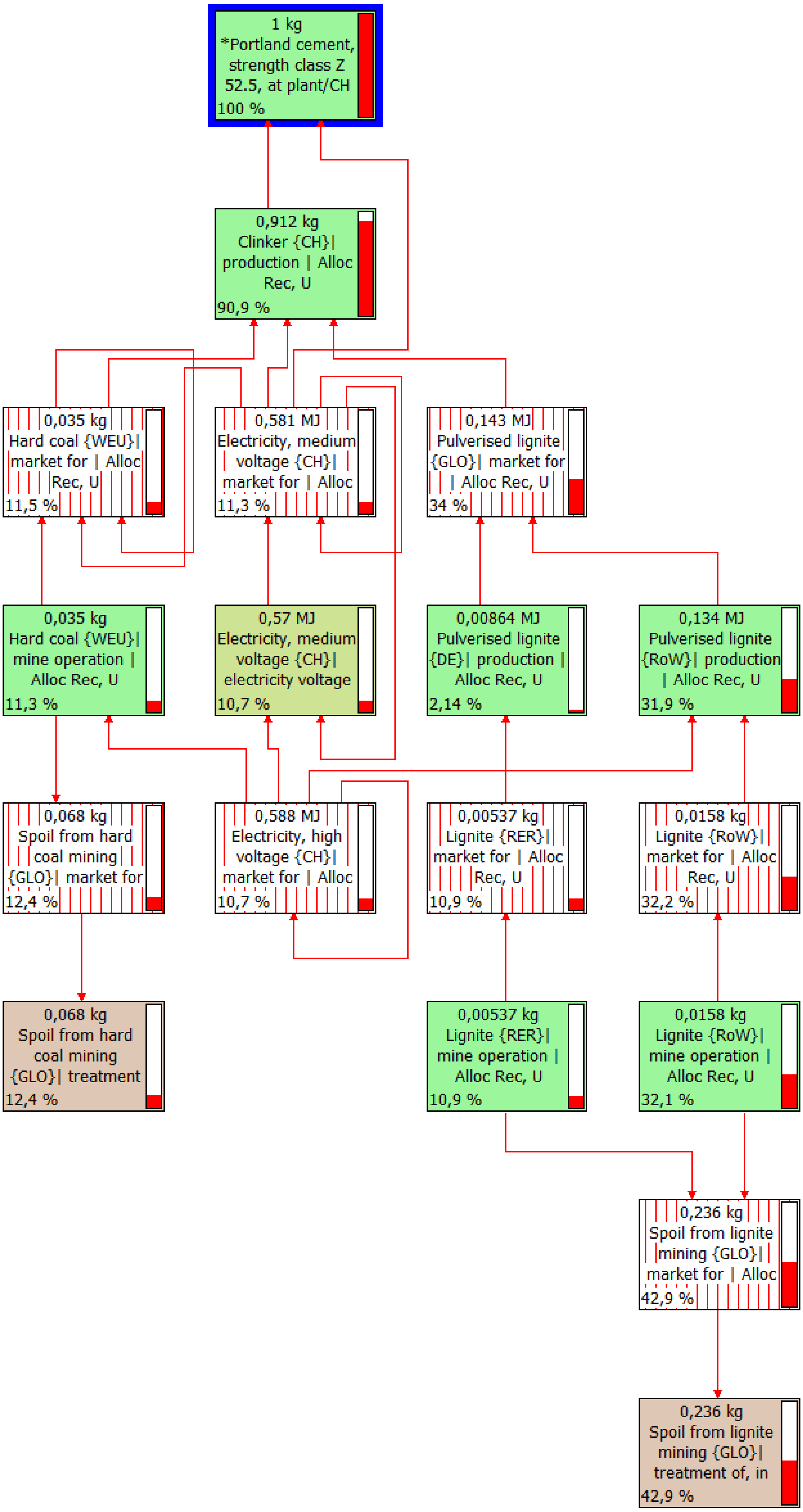


Figure G.2.: *EP of CEM I 52.5 v3.3 - Network*

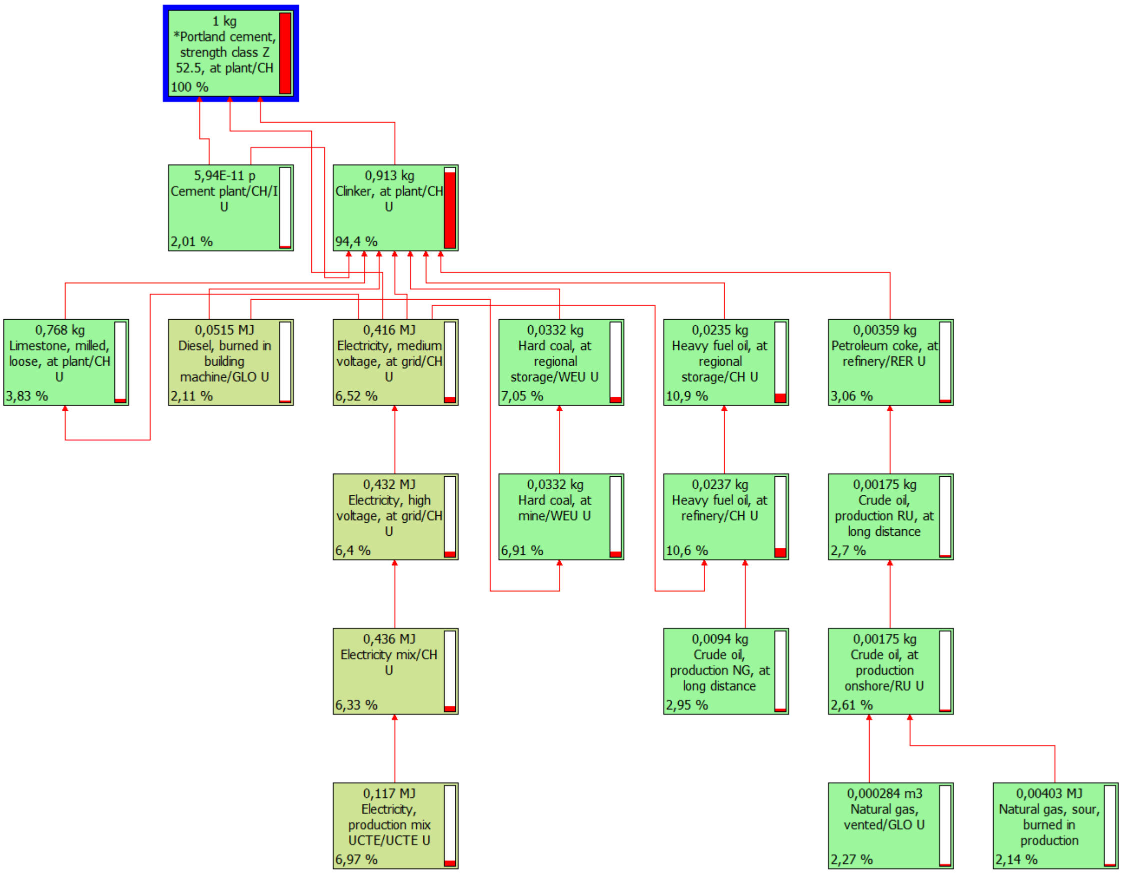


Figure G.3.: *POCP of CEM I 52.5 v2.2 - Network*

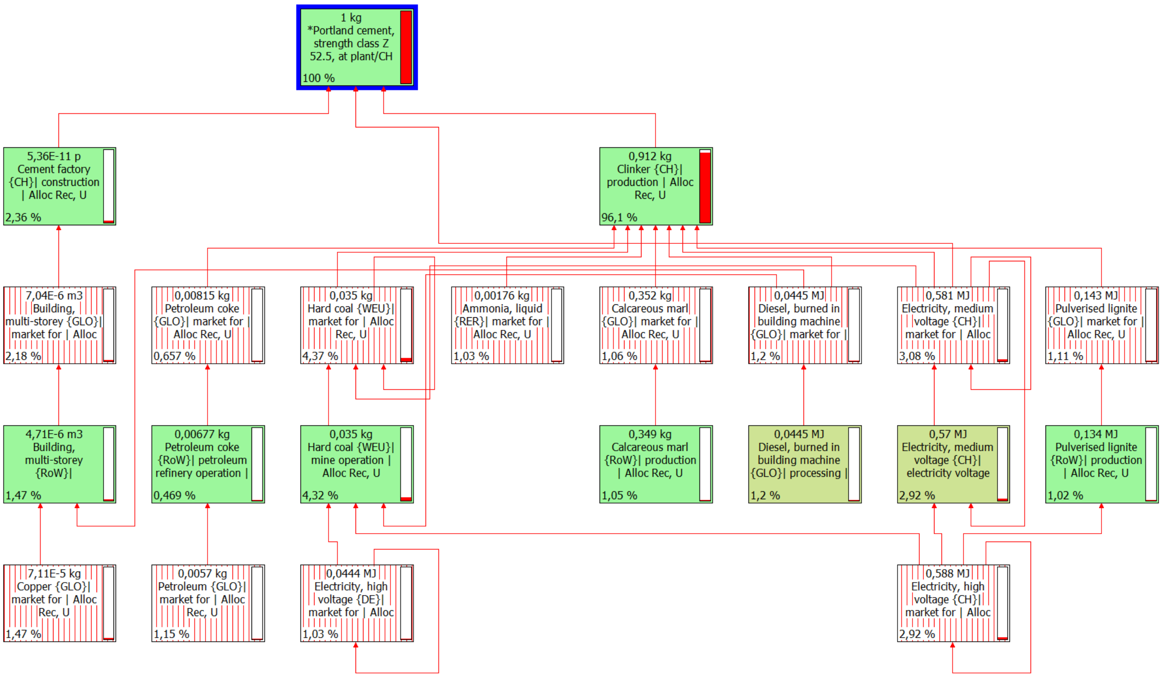


Figure G.4.: *POCP of CEM I 52.5 v3.3 - Network*

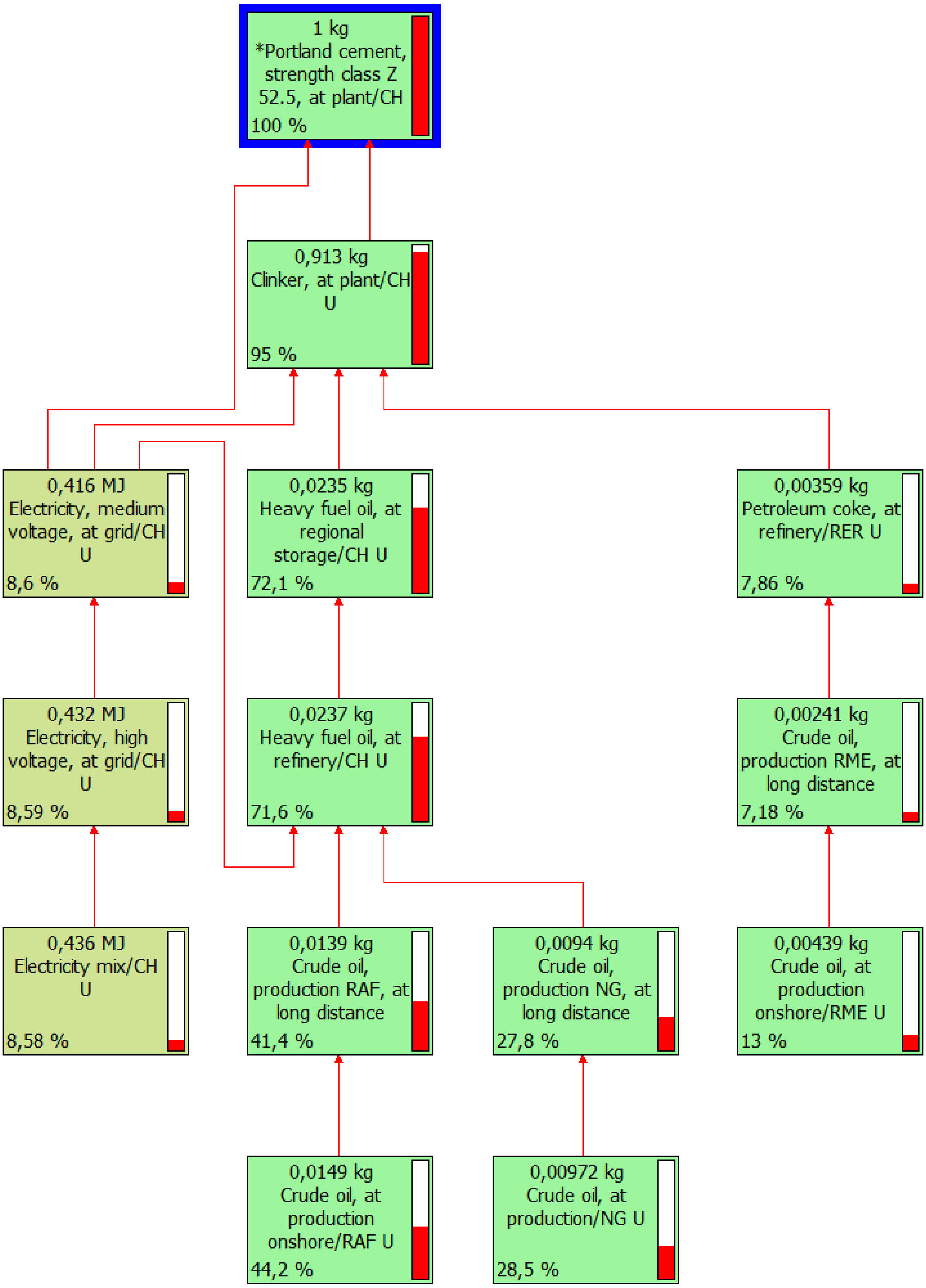


Figure G.5.: *ODP of CEM I 52.5 v2.2 - Network*

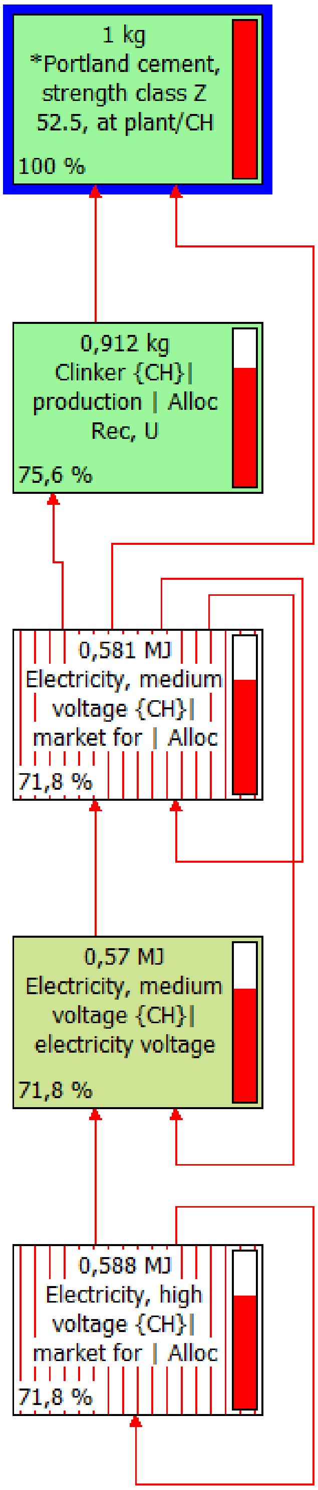


Figure G.6.: *ODP of CEM I 52.5 v3.3 - Network*

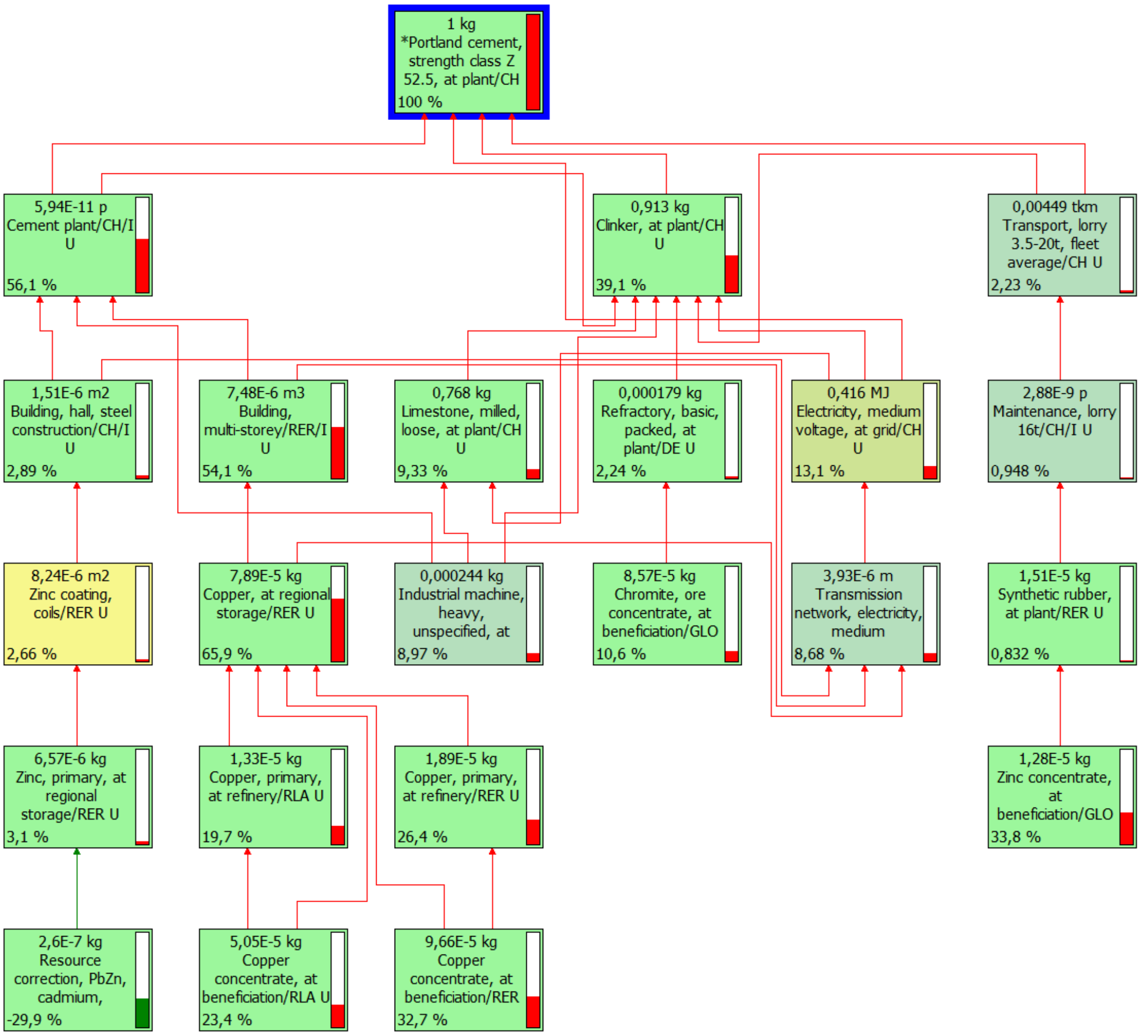


Figure G.7.: *ADP of CEM I 52.5 v2.2 - Network*

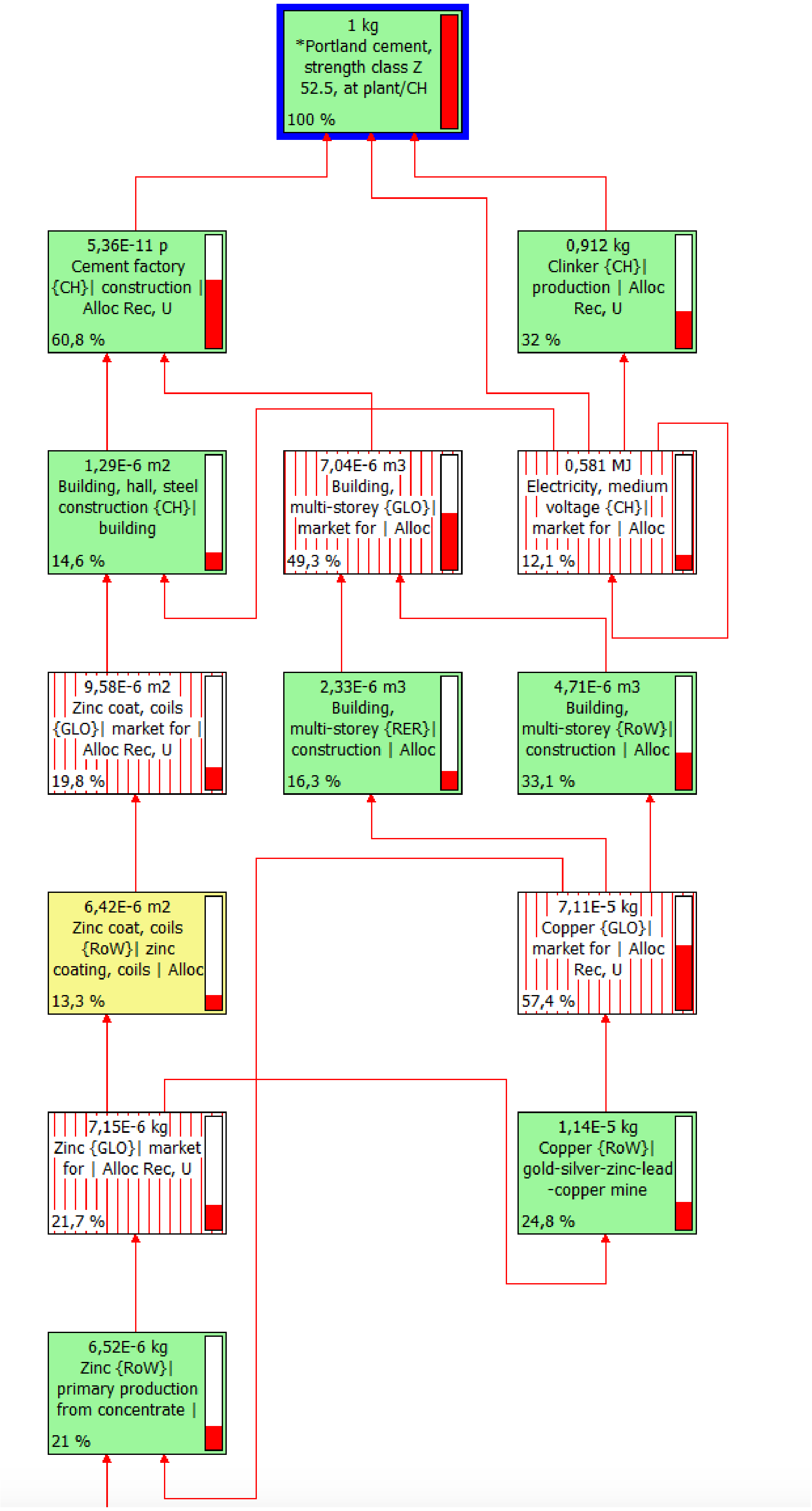


Figure G.8.: *ADP of CEM I 52.5 v3.3 - Network*

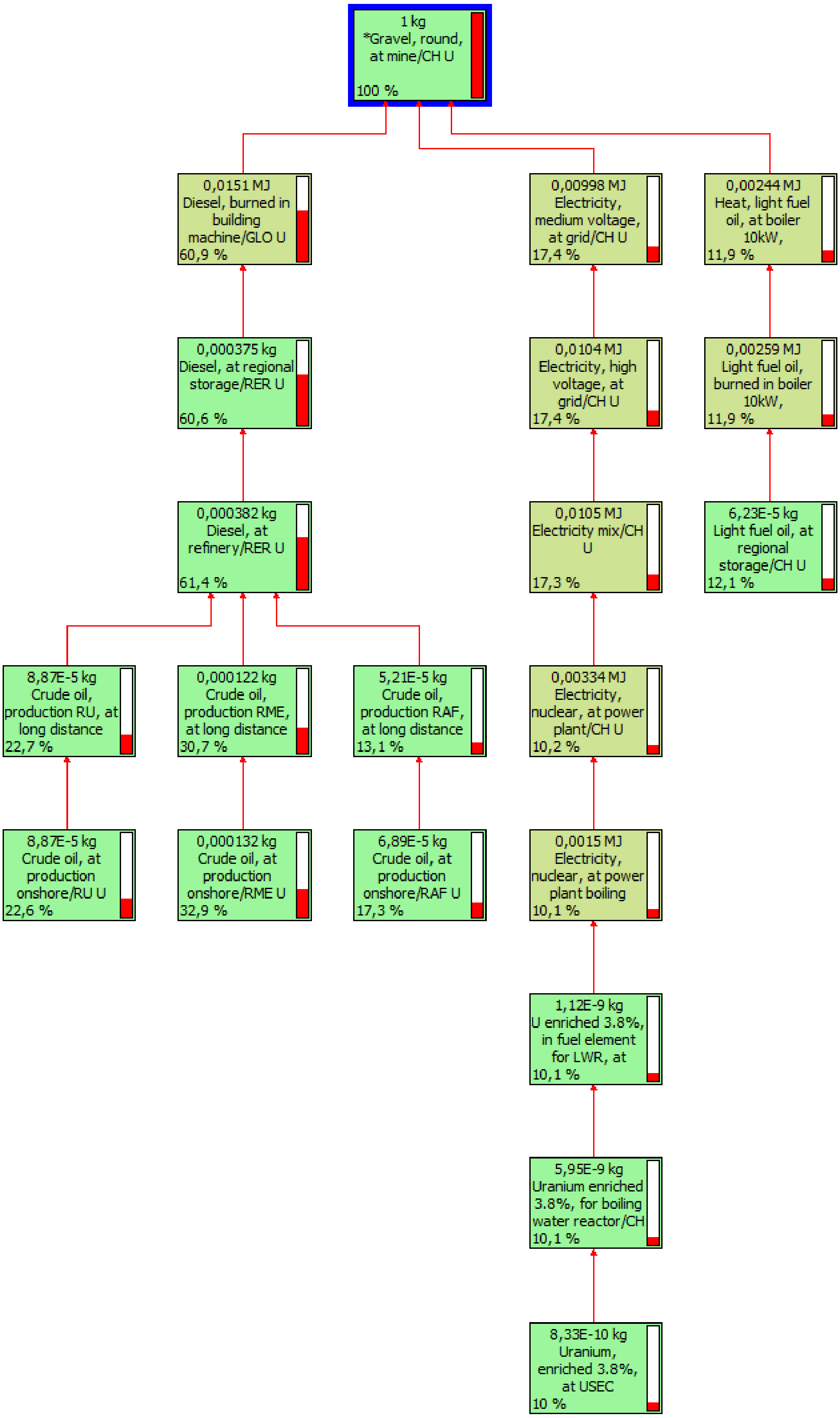


Figure G.9.: *ODP of Gravel v2.2 - Network*

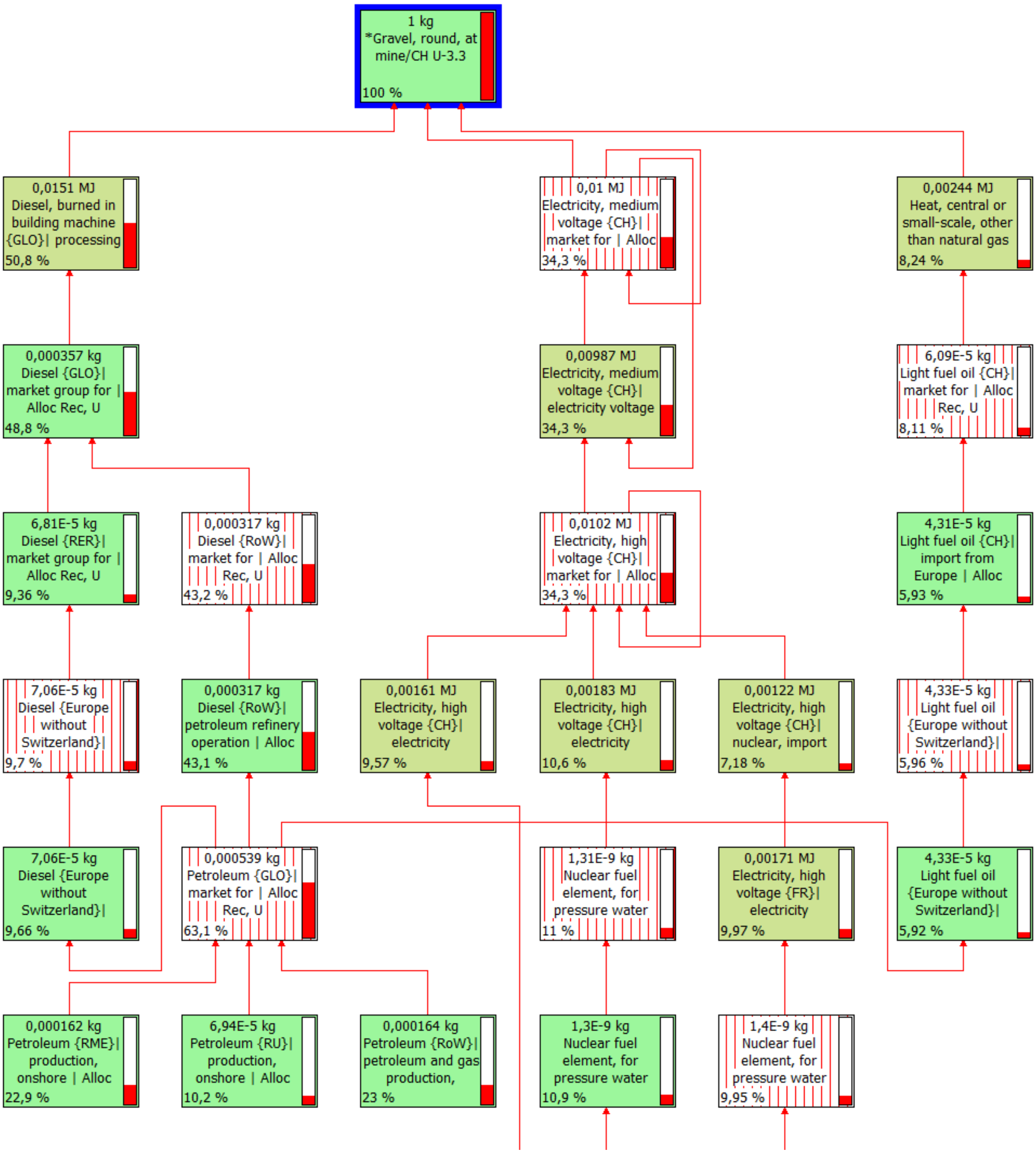


Figure G.10.: *ODP of Gravel v3.3 - Network*

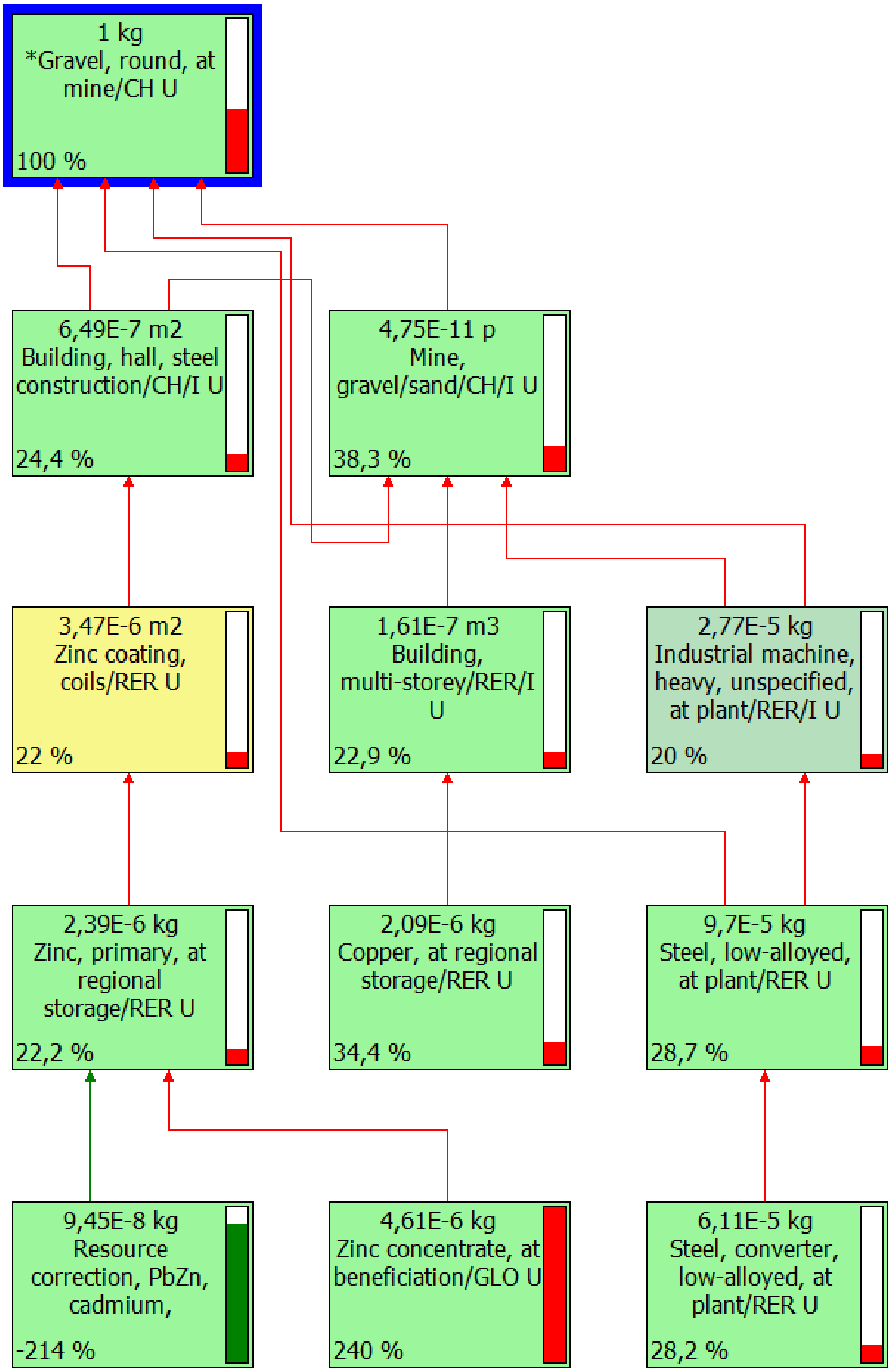


Figure G.11.: *ADP of Gravel v2.2 - Network*

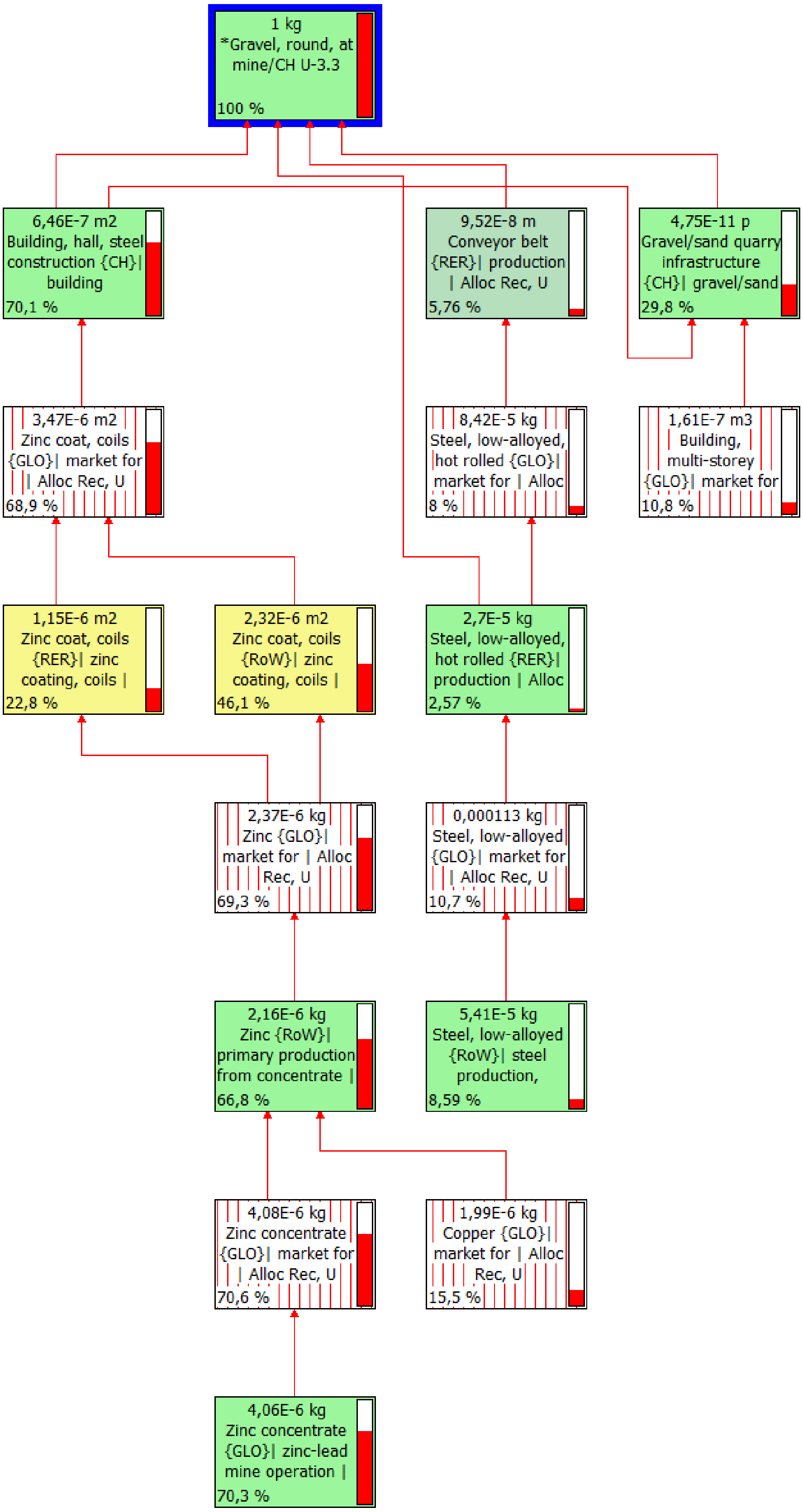


Figure G.12.: *ADP of Gravel v3.3 - Network*

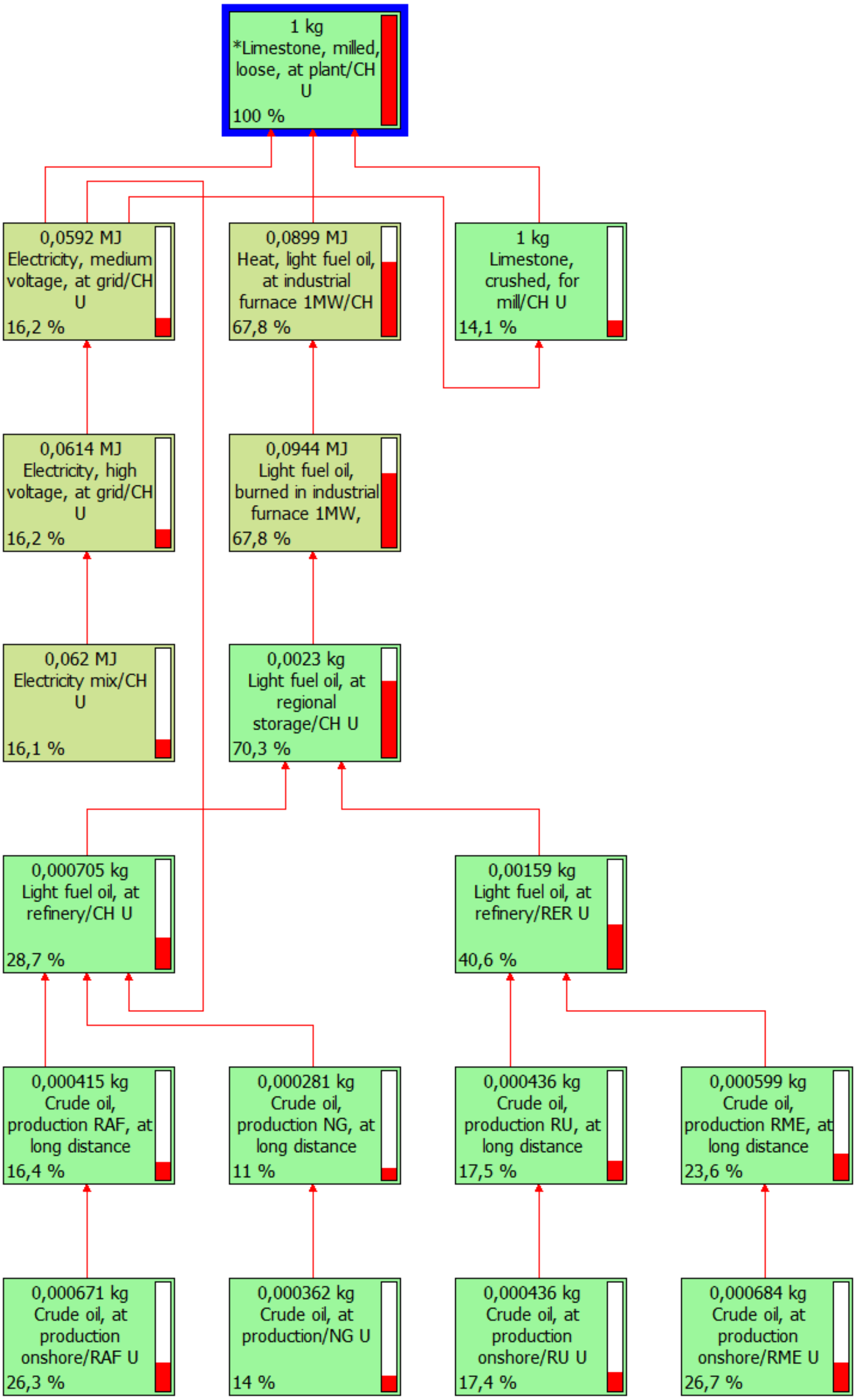


Figure G.13.: *ODP of Limestone v2.2 - Network*

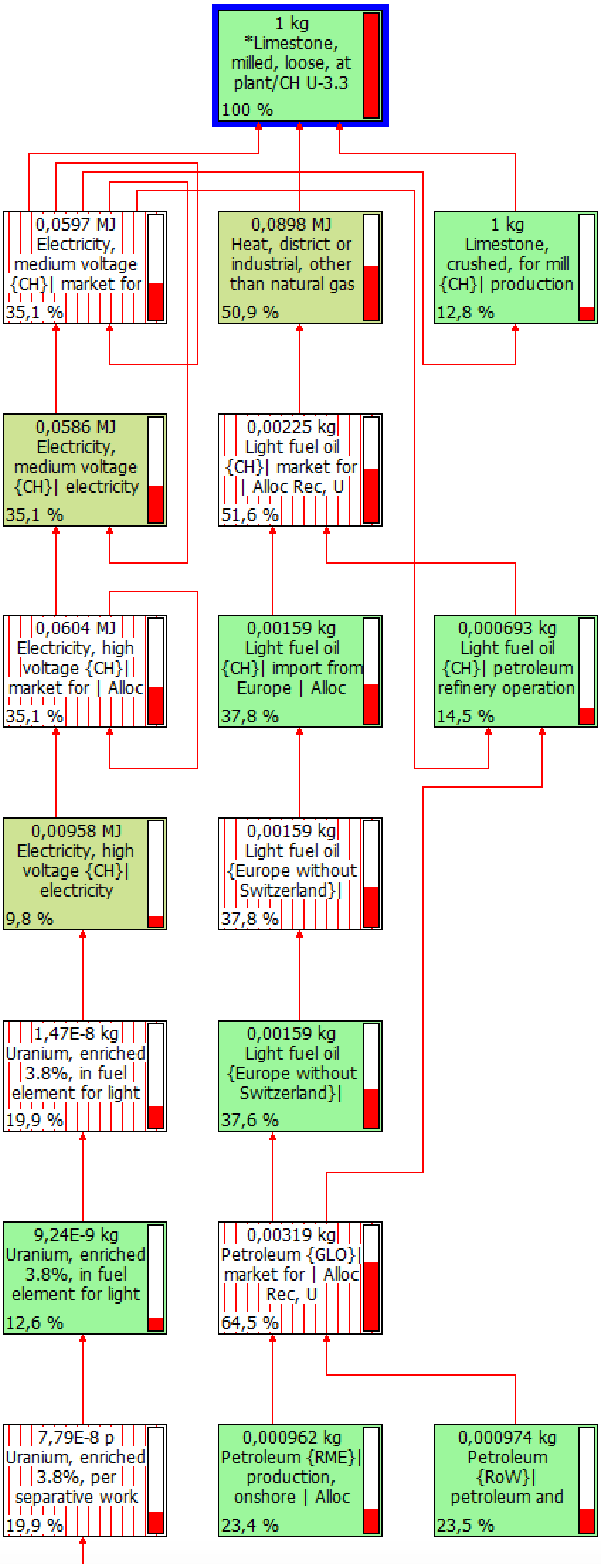


Figure G.14.: *ODP of Limestone v3.3 - Network*

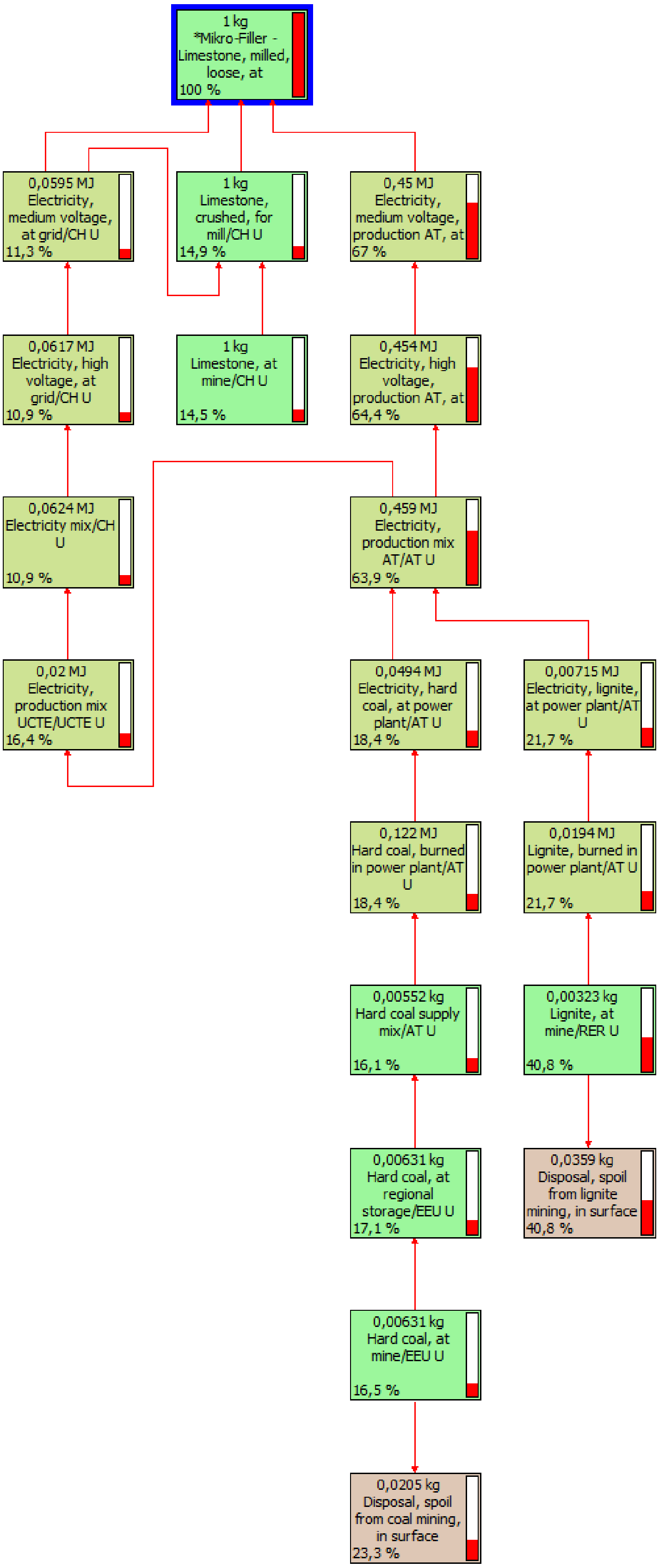


Figure G.15.: *EP of Micro-Filler v2.2 - Network*

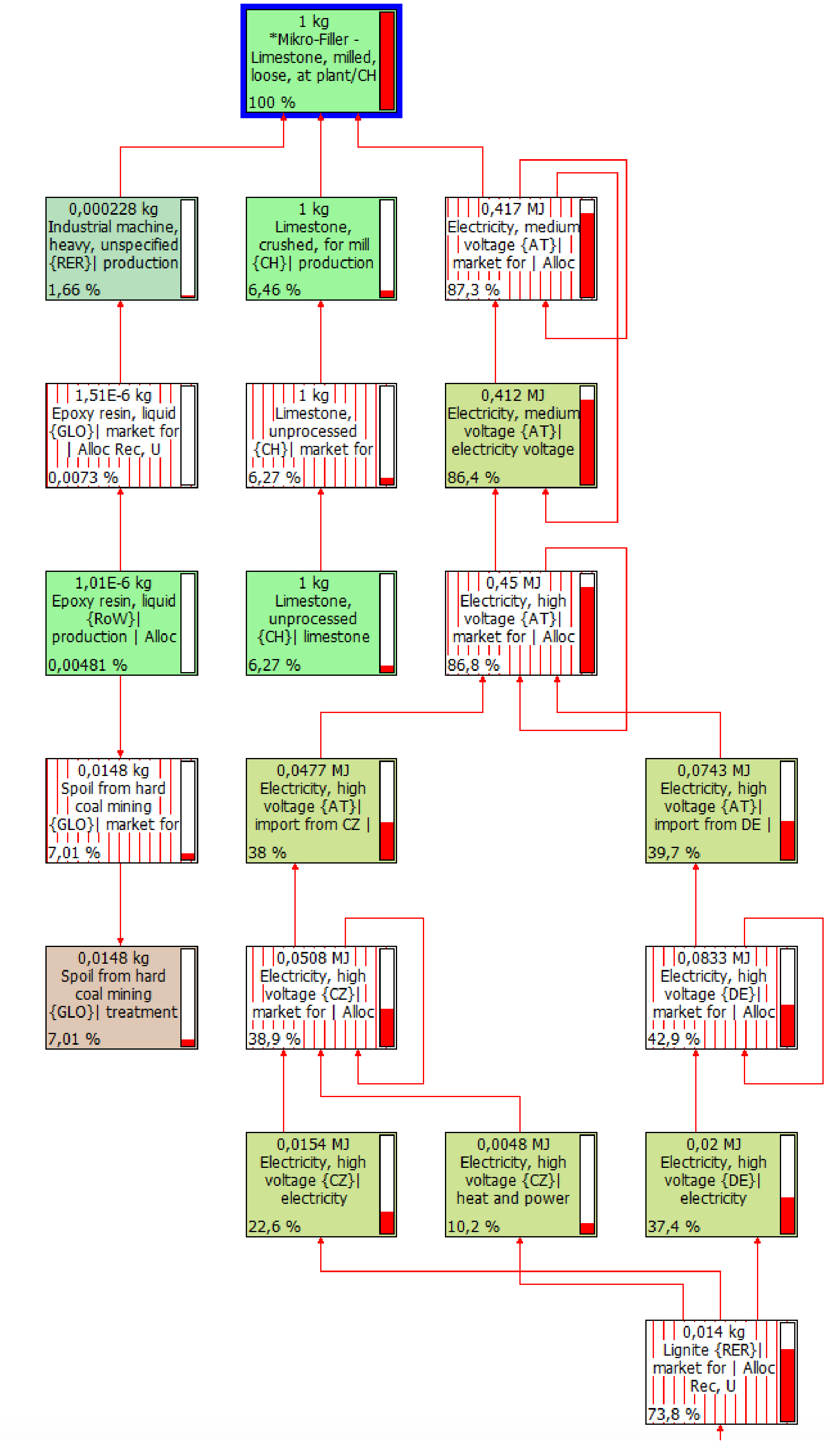


Figure G.16.: *EP of Micro-Filler v3.3 - Network*

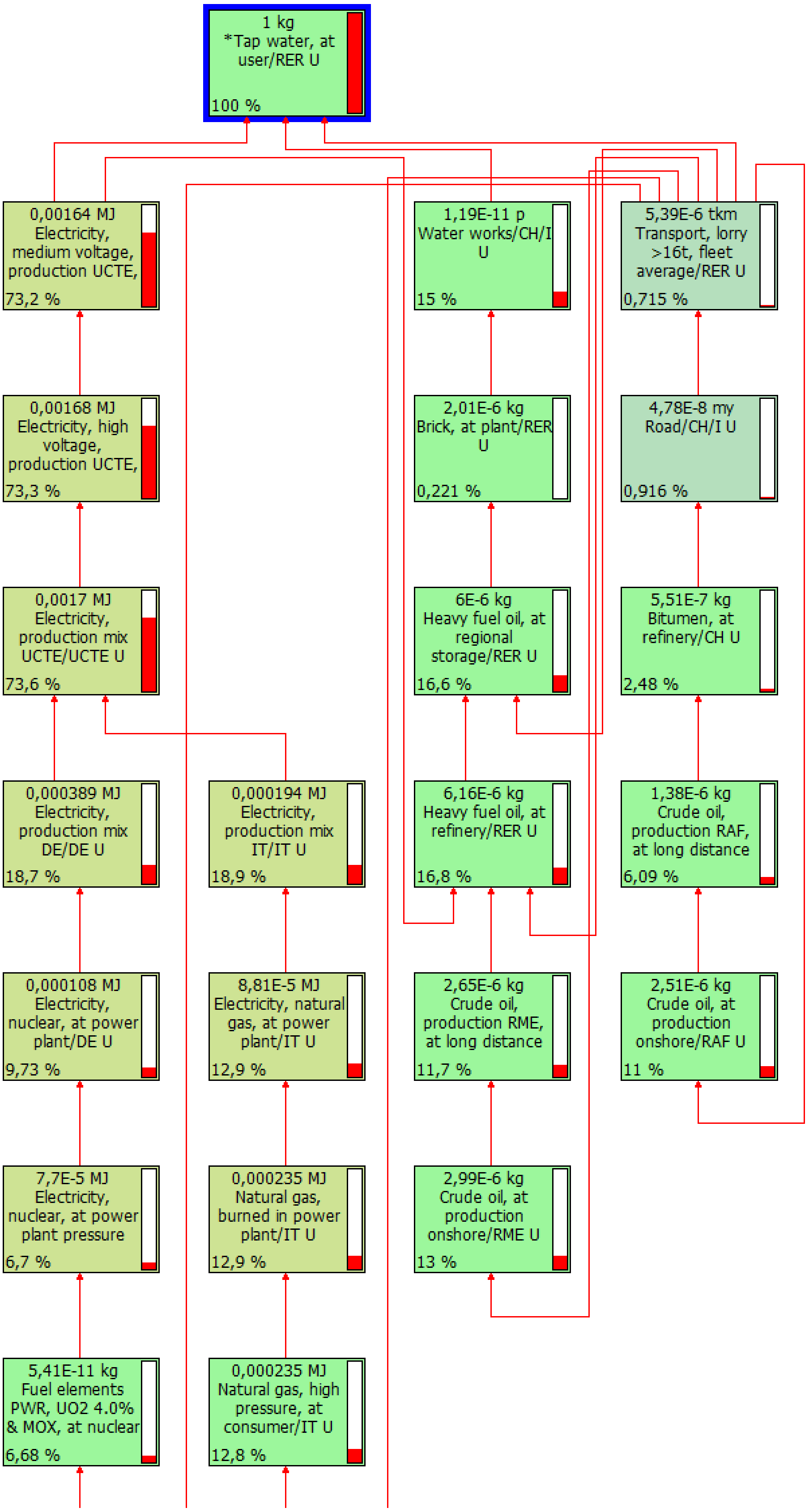


Figure G.17.: *ODP of Tap Water v2.2 - Network*

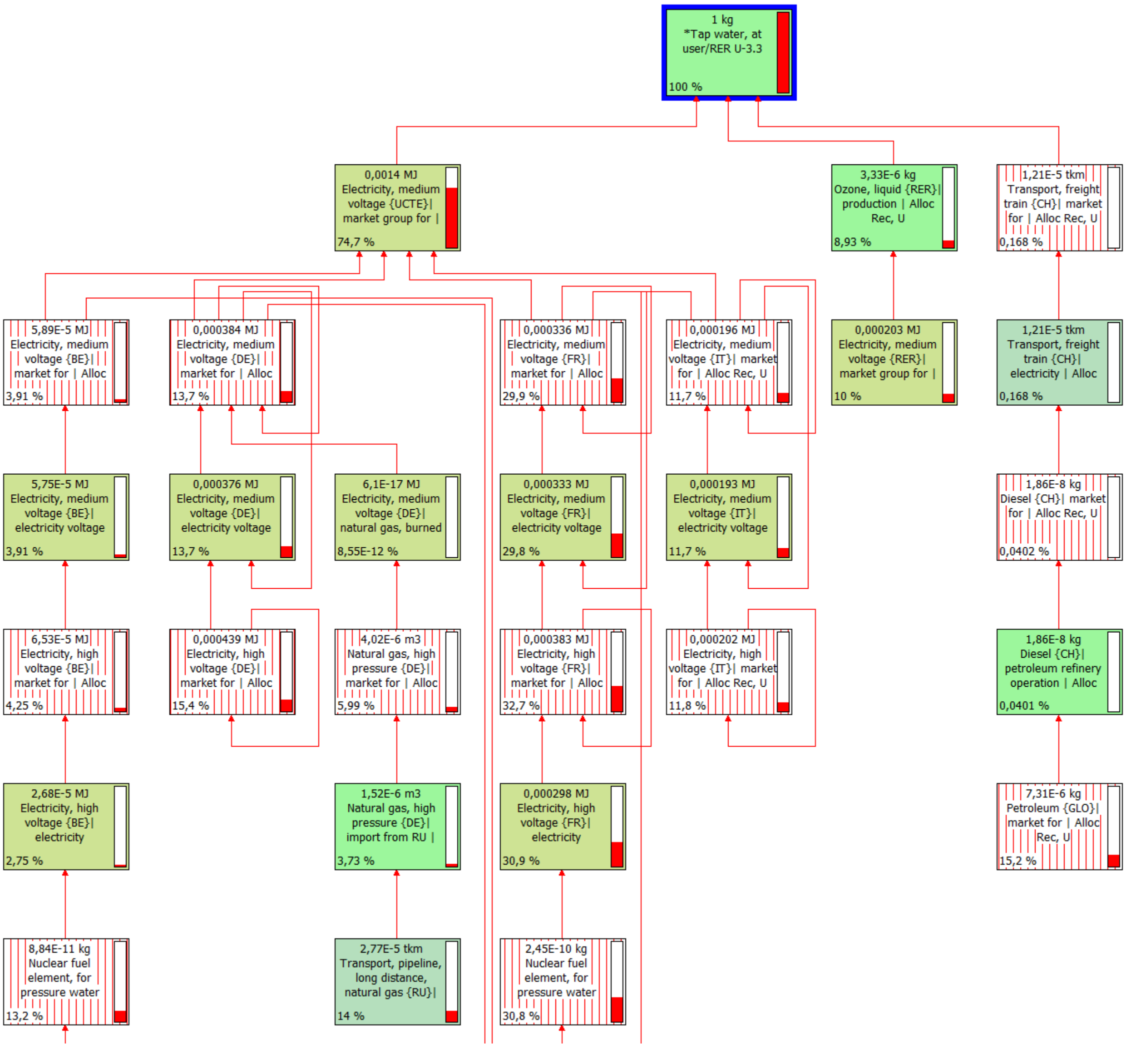


Figure G.18.: *ODP of Tap Water v3.3 - Network*

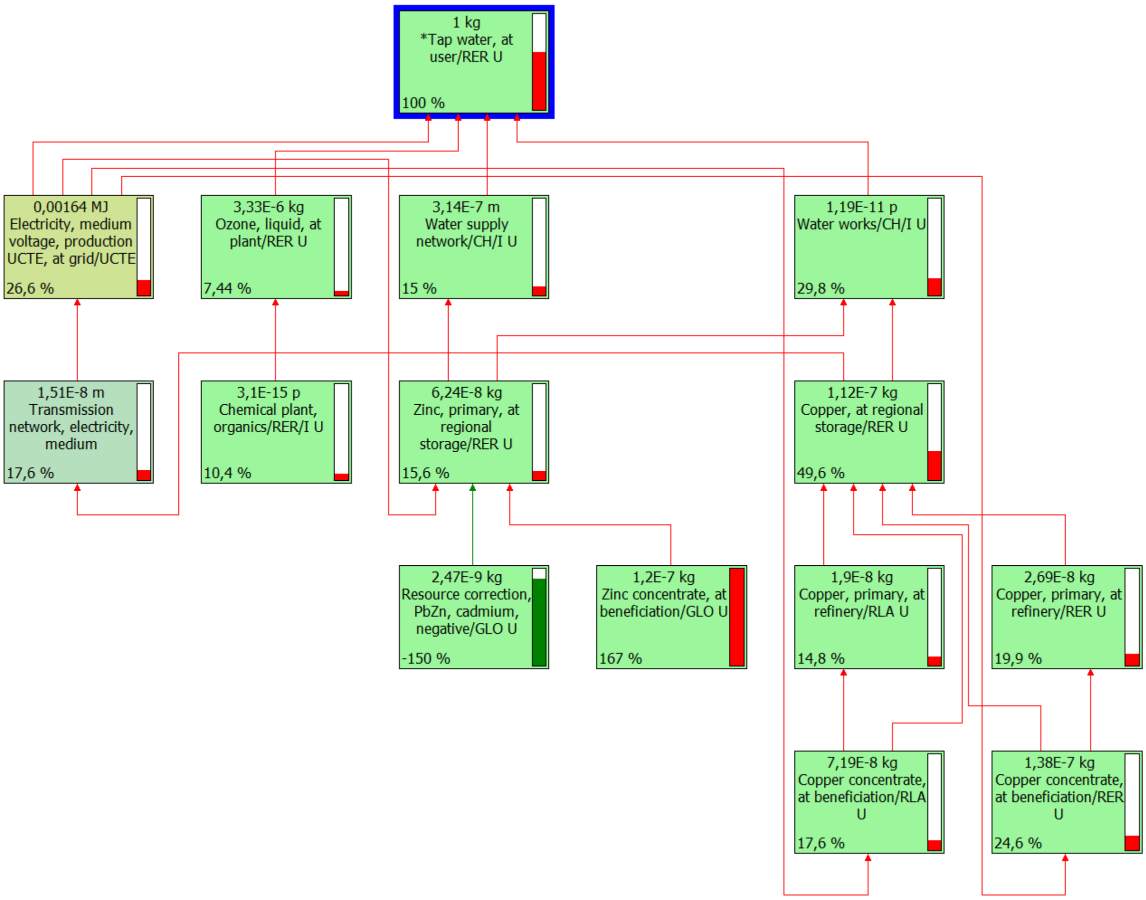


Figure G.19.: *ADP of Tap Water v2.2 - Network*

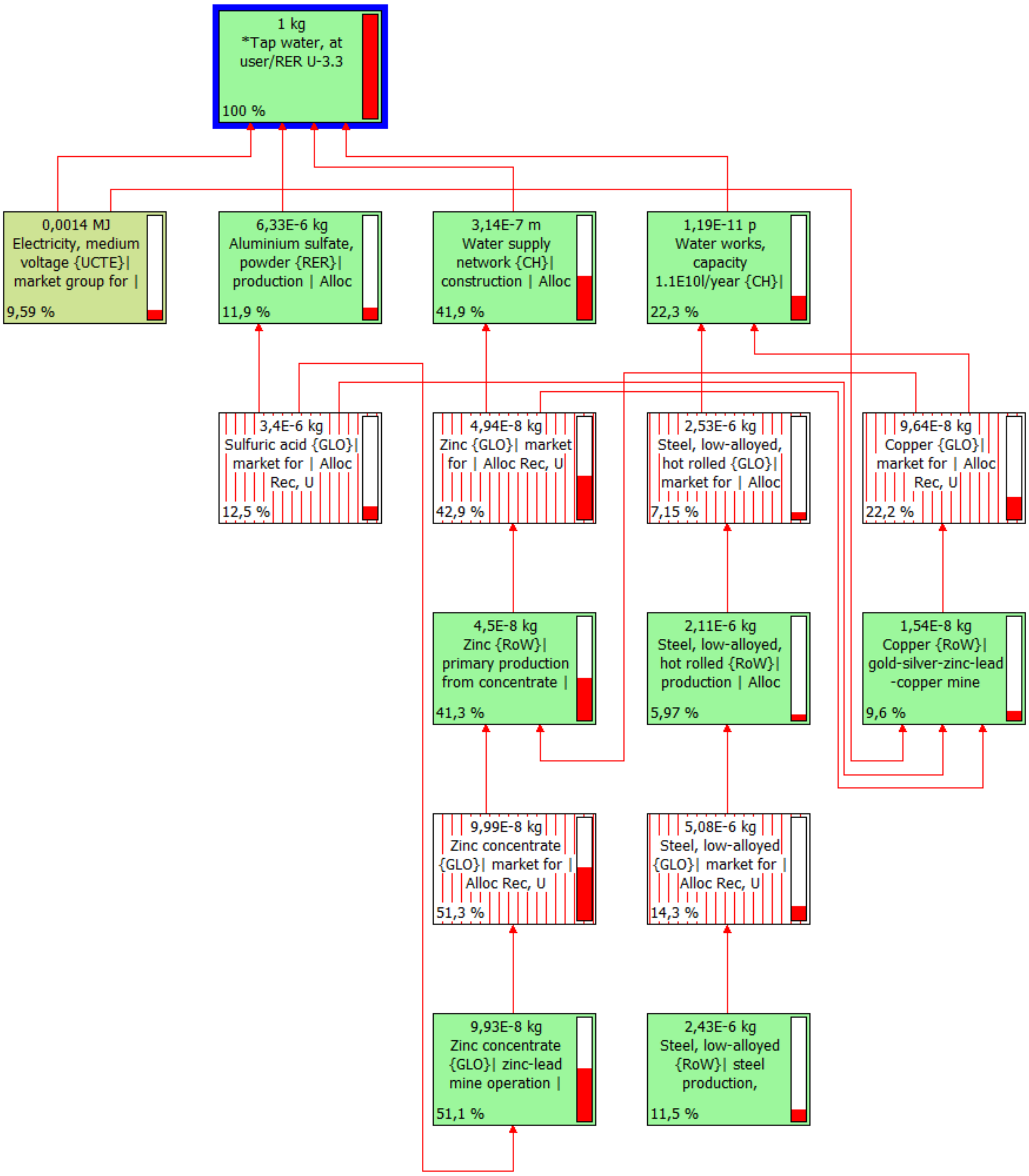


Figure G.20.: *ADP of Tap Water v3.3 - Network*

H. Appendix 8: Contribution Networks - ODP and POCP of Mix Designs NRef1, NRef4 and N1 in EcoInvent v2.2 and v3.3

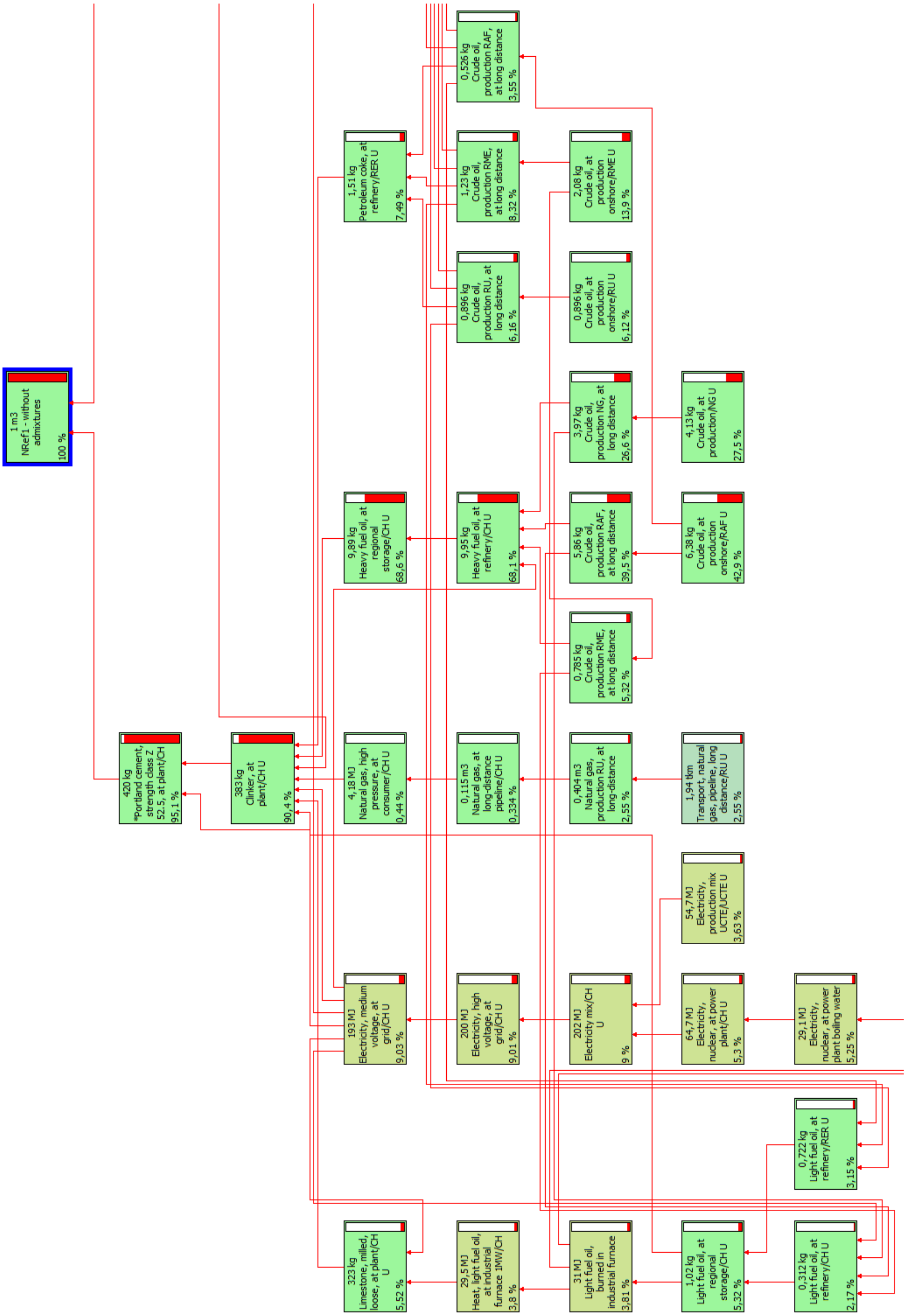


Figure H.1.: *ODP of NRef1 v2.2 - Network*

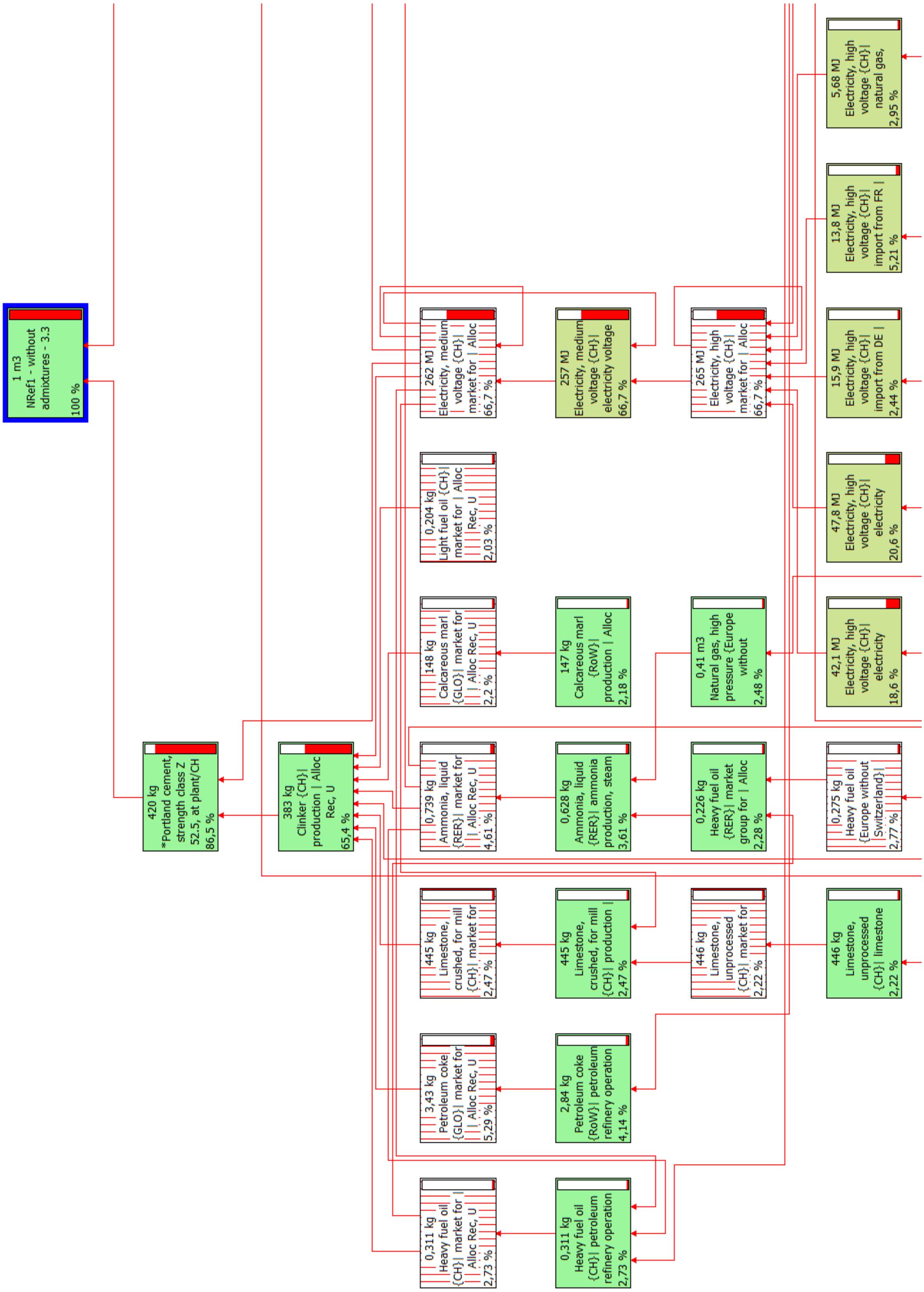


Figure H.2.: *ODP of NRef1 v3.3 - Network*

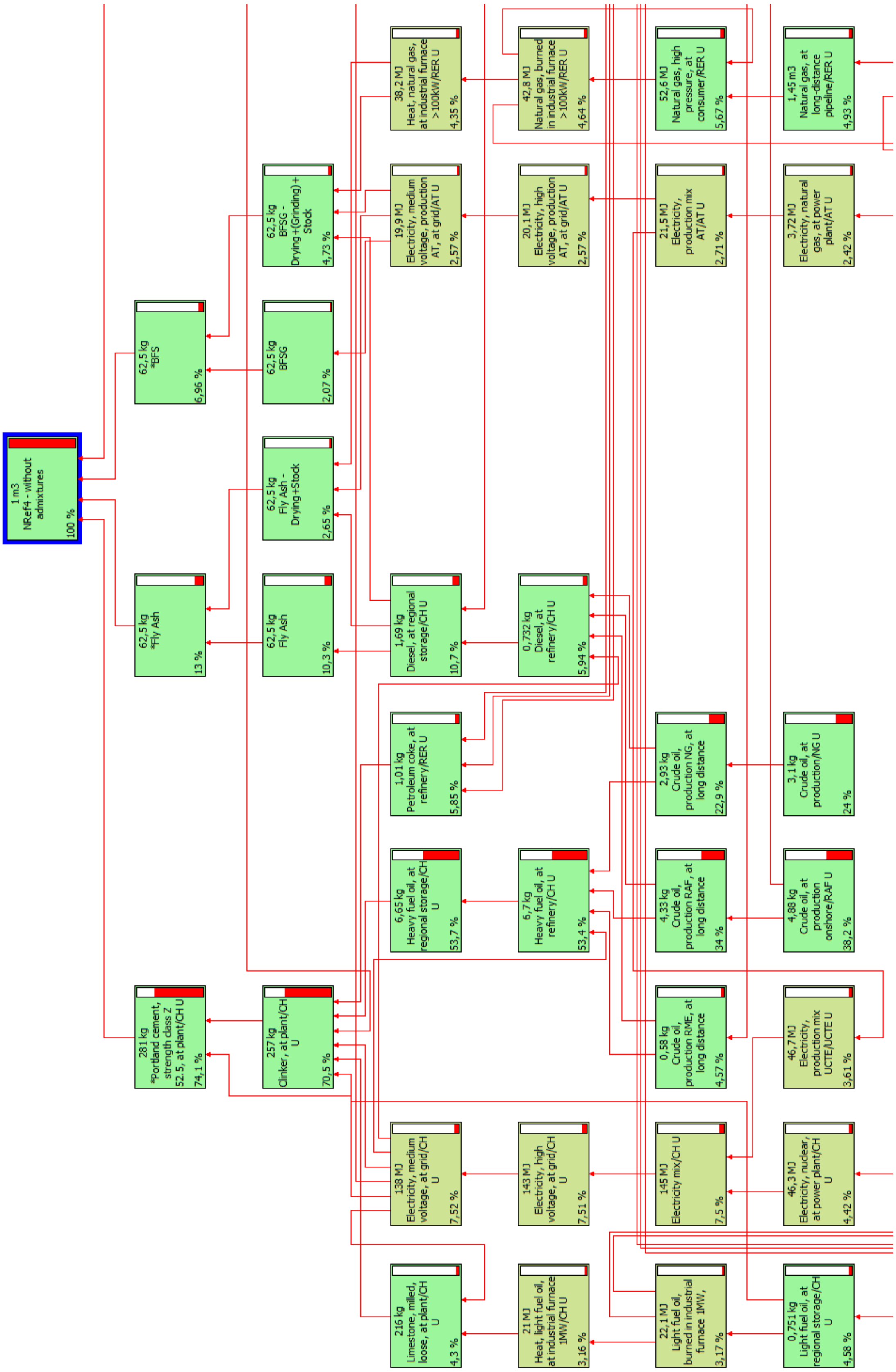


Figure H.3.: *ODP of NRef4 v2.2 - Network*

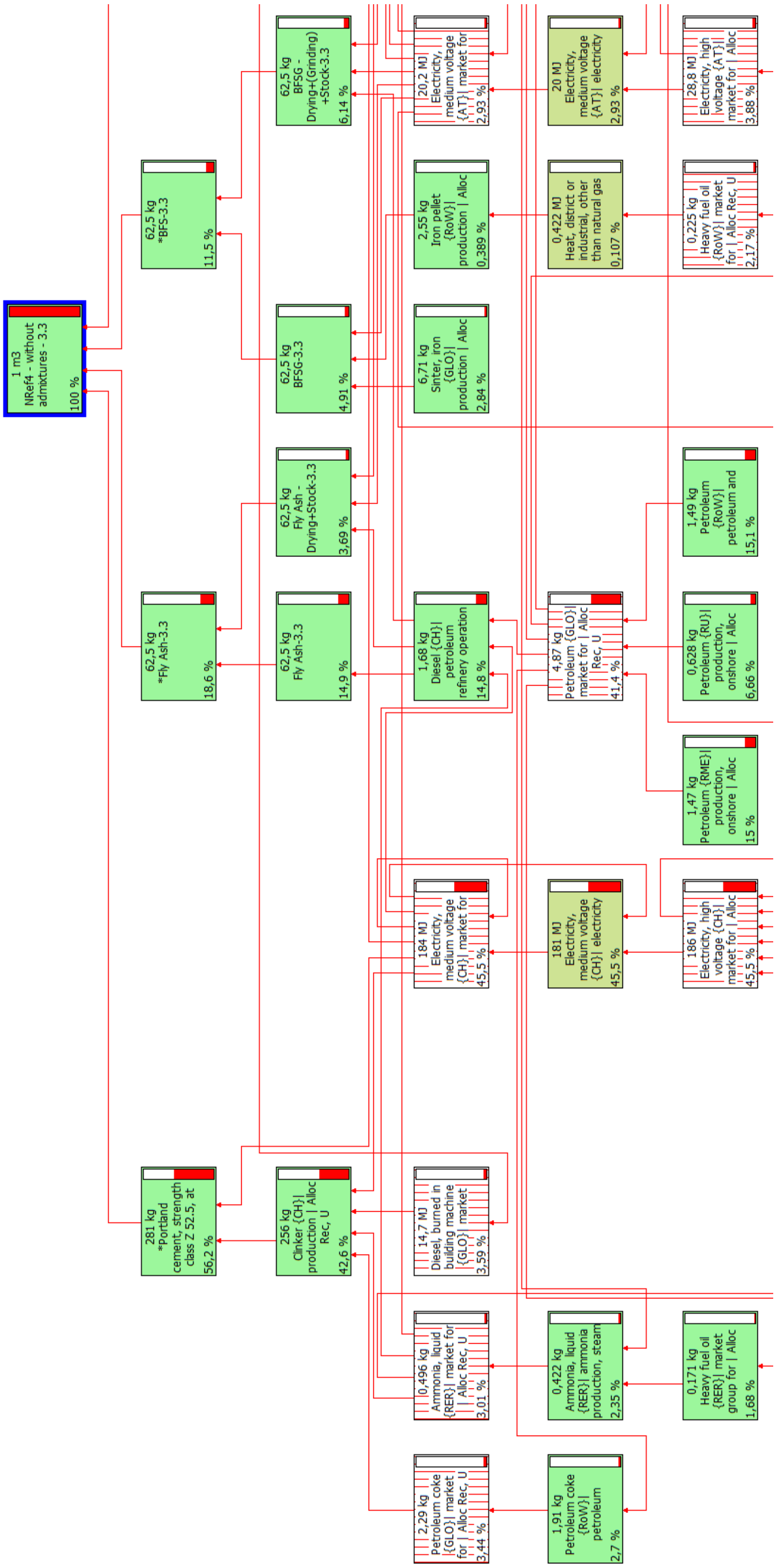


Figure H.4.: *ODP of NRef4 v3.3 - Network*

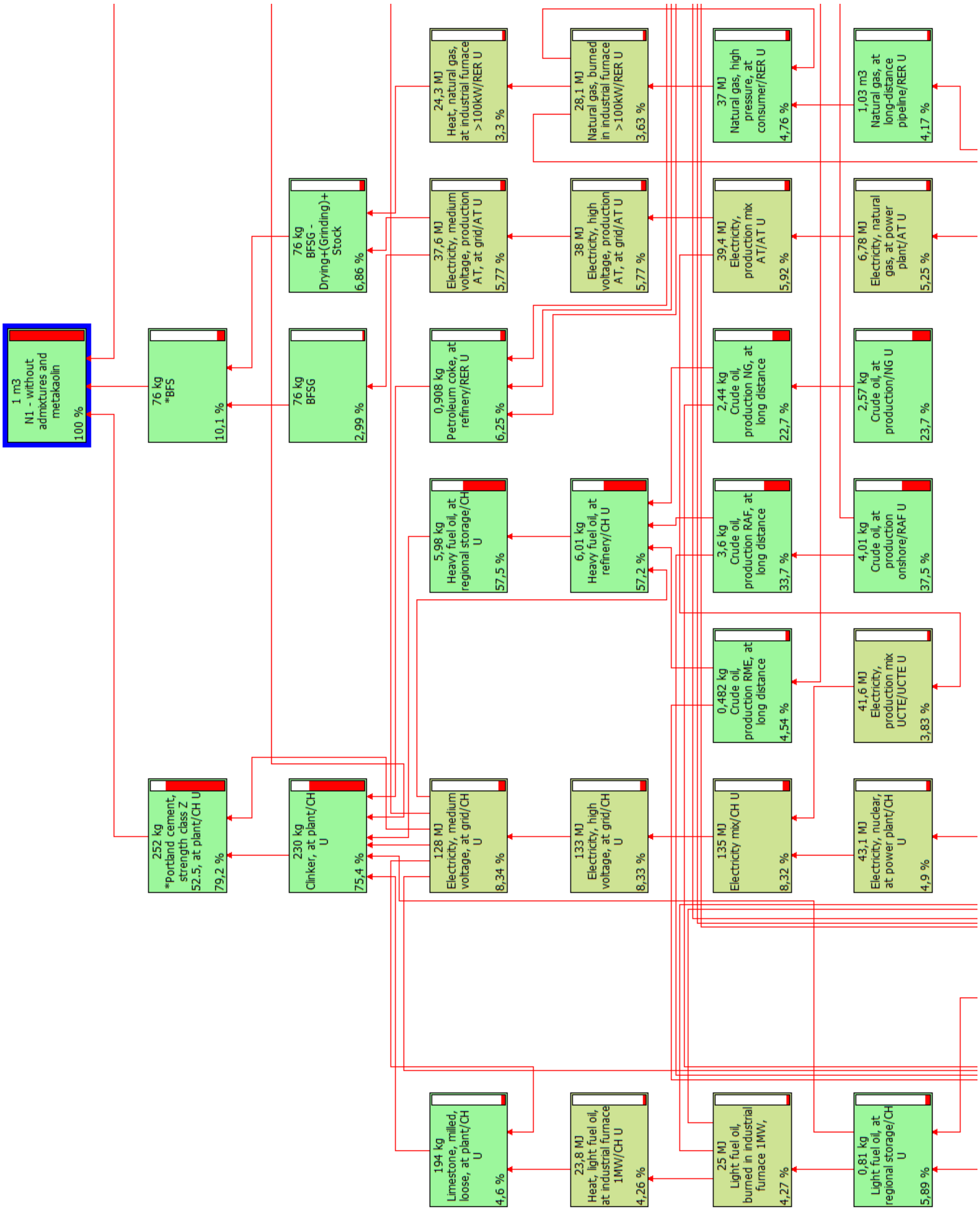


Figure H.5.: *ODP of N1 v2.2 - Network*

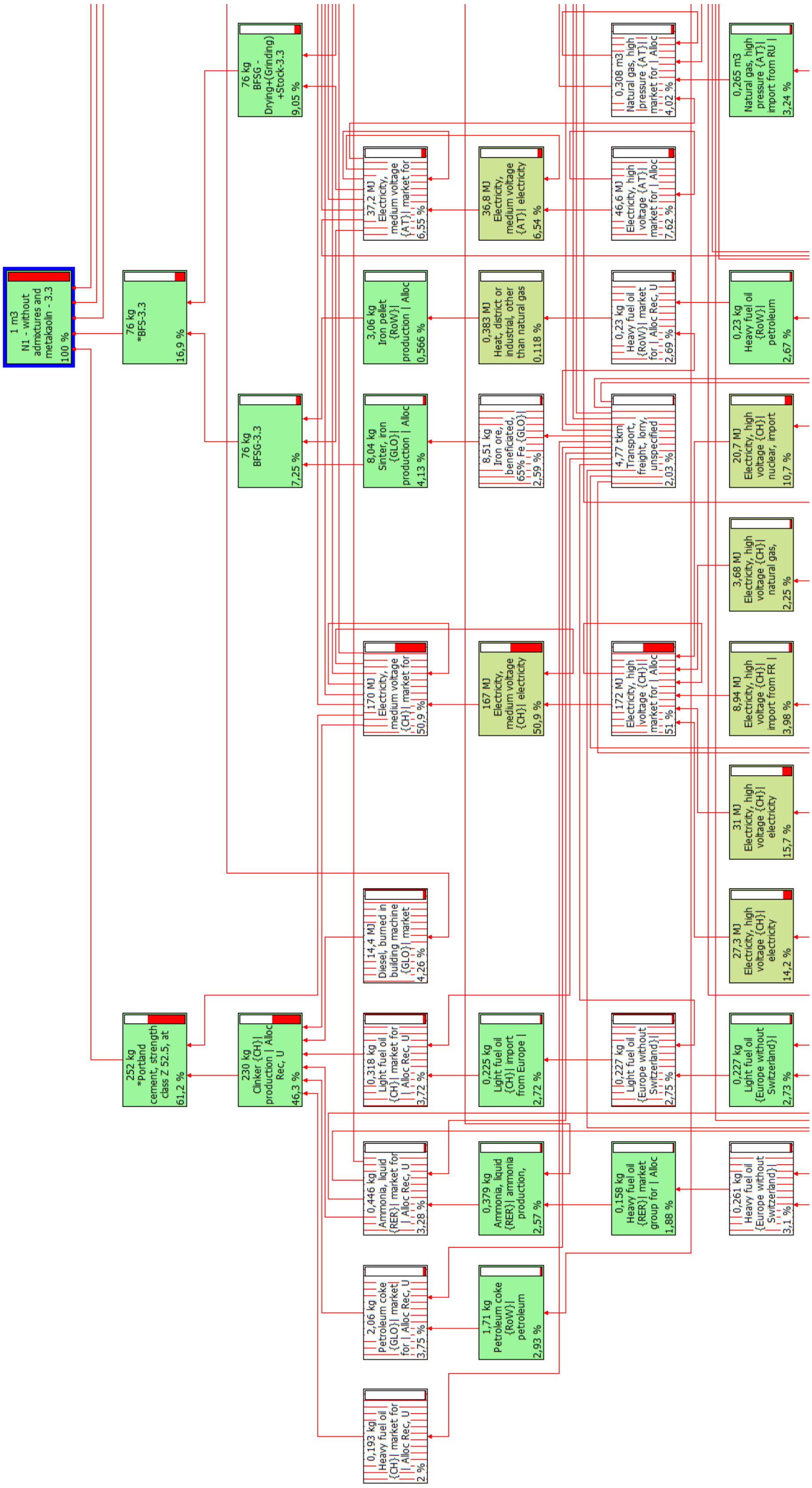


Figure H.6.: *ODP of N1 v3.3 - Network*

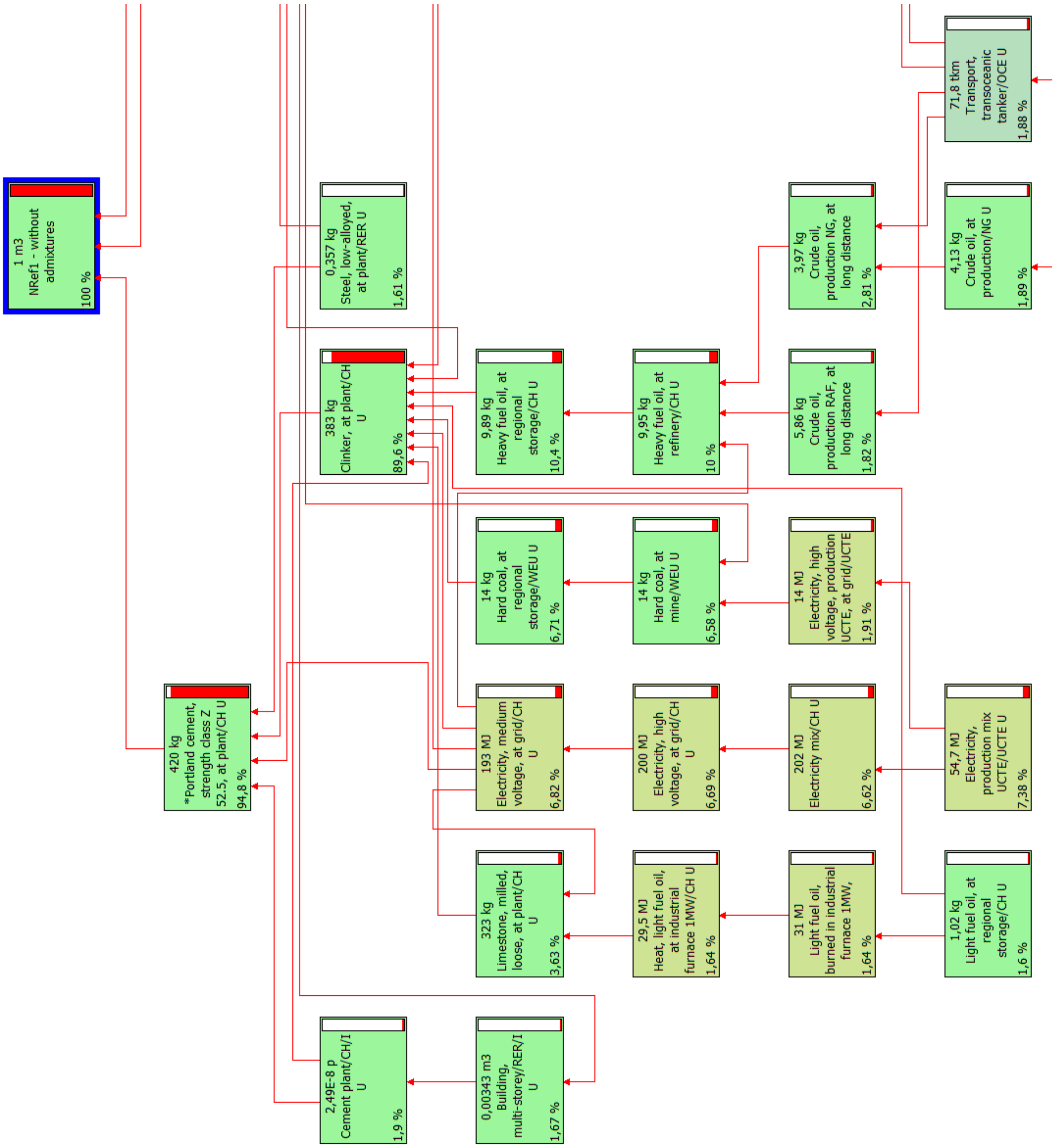


Figure H.7.: *POCP of NRef1 v2.2 - Network*

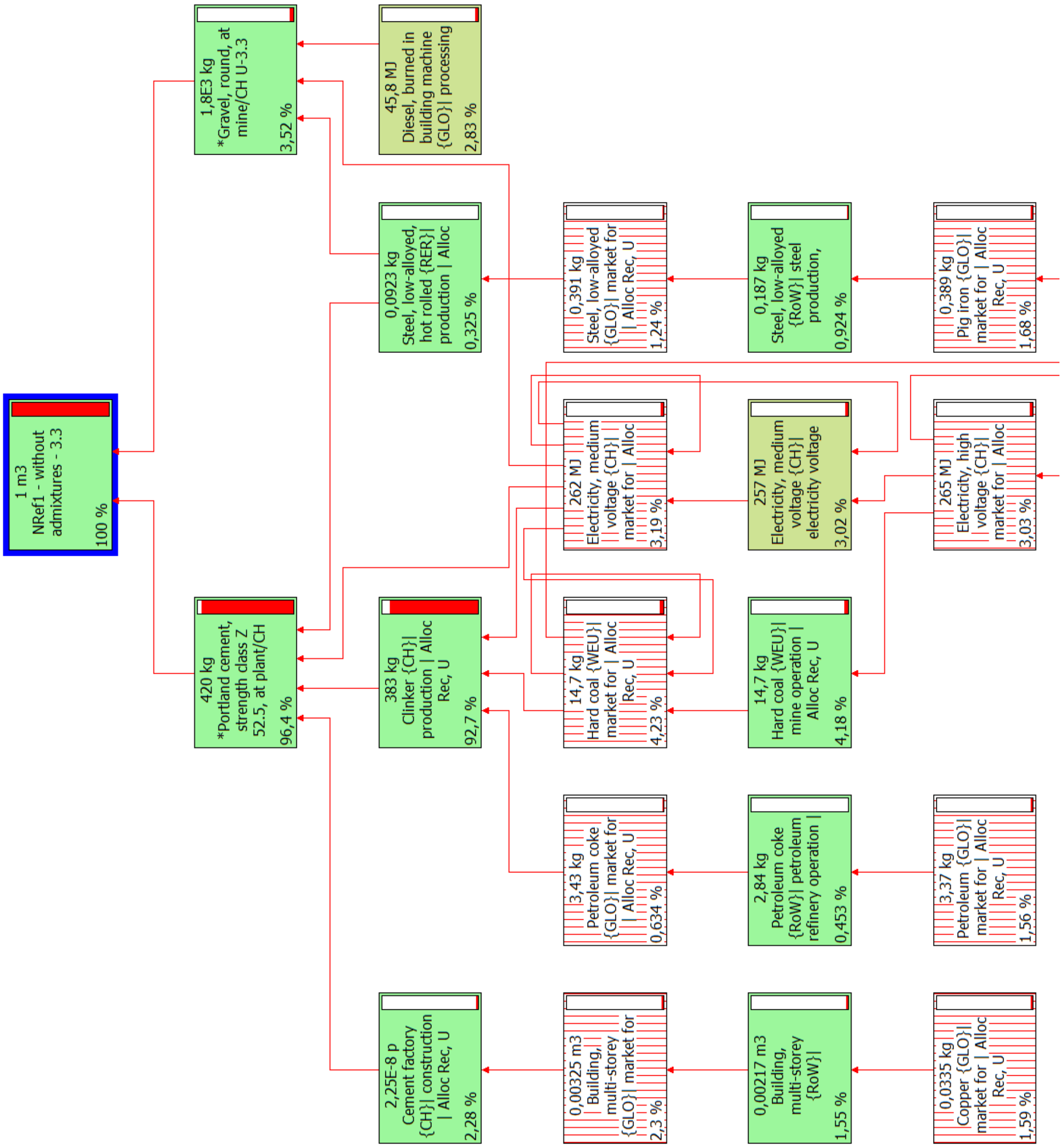


Figure H.8.: *POCP of NRef1 v3.3 - Network*

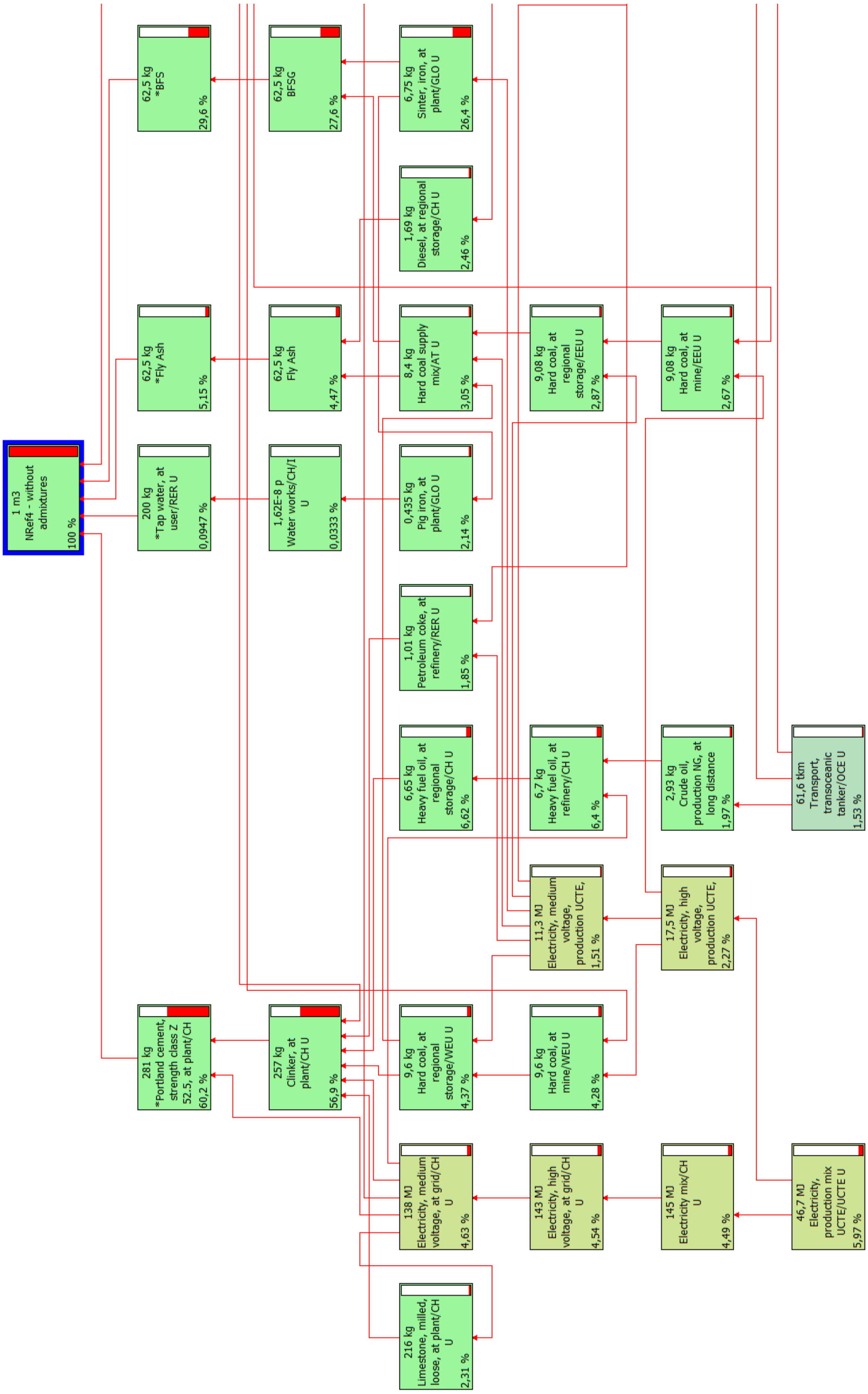


Figure H.9.: *POCP of NRef4 v2.2 - Network*

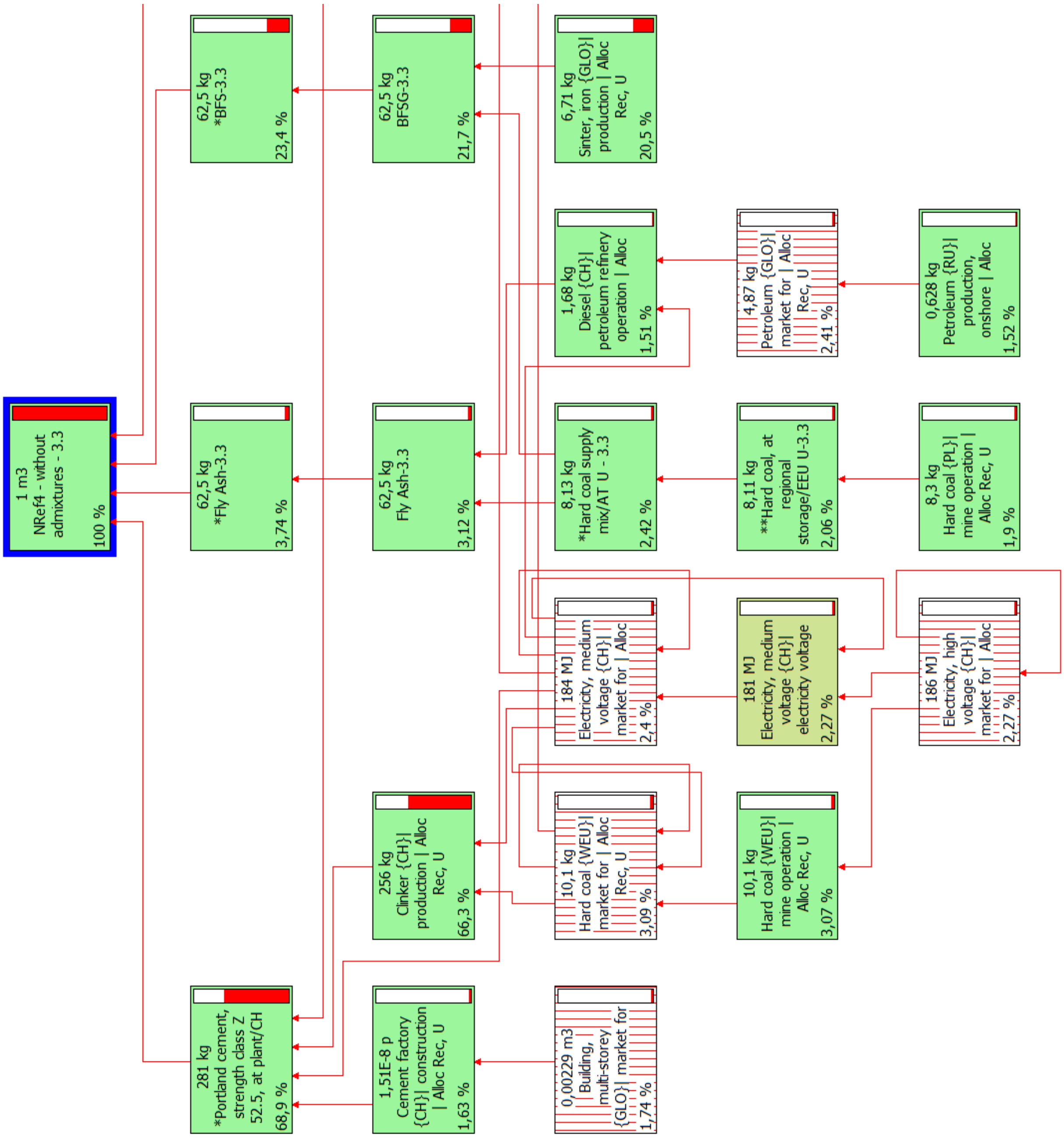


Figure H.10.: *POCP of NRef4 v3.3 - Network*

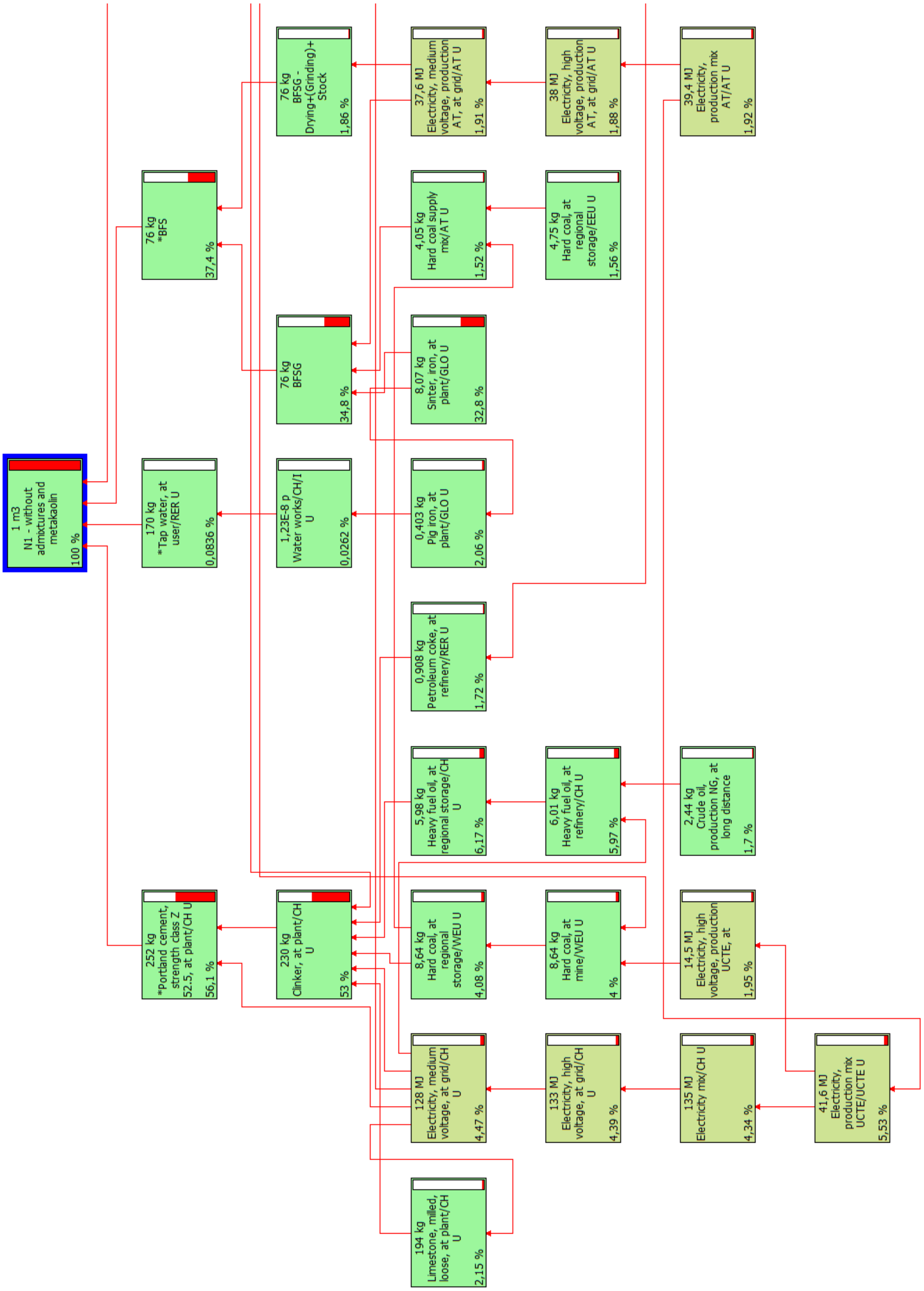


Figure H.11.: *POCP of N1 v2.2 - Network*

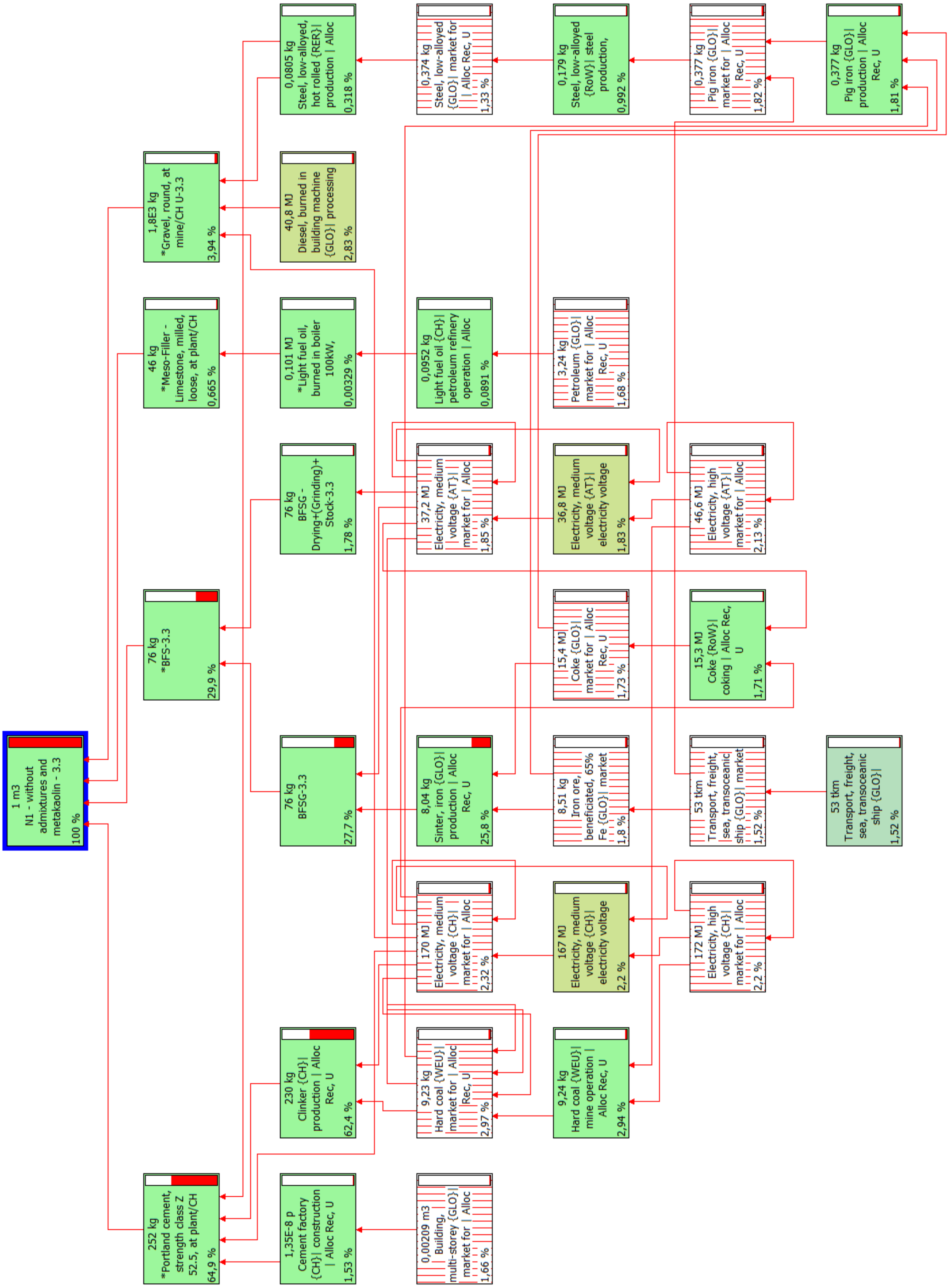


Figure H.12.: *POCP of N1 v3.3 - Network*