Environmental Impact Assessment of a School Building in Iceland Using LCA

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60 ECTS thesis submitted in partial fulfillment of a
Magister Scientiarum degree in Civil Engineering

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Abstract

Buildings play a key role in our lives and society as a complex system. Iceland provides an interesting case since the energy demand in the whole country is mostly supplied by geothermal and hydroelectric resources.

Life cycle assessment, or LCA, has become an accepted tool to performing sustainability assessment of various systems including buildings. Therefore it was decided to apply it to develop a framework that enables us to make estimates of the environmental impacts of the materials used in the structure and envelope of the Vættaskóli-Engi building in Reykjavik, Iceland, during four modules of raw material extraction (A1), transportation to manufacturing site (A2), manufacturing of construction materials (A3) and transportation to the construction site (A4), as defined in the standard EN 15804. The environmental impacts covered in this study include global warming potential (GWP), Ozone depletion potential (ODP), Human Toxicity (HT), Acidification (AP) and Eutrophication (EP). It should be emphasized that, the construction work, use stage and end of life were excluded from this analysis.

The overall environmental impacts of the Vættaskóli-Engi building from modules A1-A4 in terms of GWP, ODP, HT, AP and EP are estimated to be 1490 ton CO_2 eq, 0.0305 kg CFC 11 eq, 0.262 CTUh, 5.5 kmol of H+ eq, 13 kmol of N eq, respectively; while per one square meter impacts are equal to 298 kgCO_2/sqm, 6.11E-06 kg CFC 11 eq/sqm, 5.22E-05 CTUh/sqm, 1.10 Mole of H+ eq/sqm and 2.56 Mole of N eq/sqm. As expected concrete, aluminum windows and reinforcing steel represent 70%-85% of total environmental impacts. Based on the developed model in GaBi, it was found that 1 kg of stone wool produced in Iceland emits between 59-67% less CO_2 compared to the similar processes in UK and Germany.

The results of this analysis confirms the suitability of using life cycle analysis approach to assess the environmental impacts of construction materials. The outcomes enabled us to make comparisons with similar studies in other countries and identify the specific opportunities to improve the sustainability of buildings in Iceland.

Útdráttur

Byggingar gegna lykilhlutverki í lífi okkar og þjóðfélaginu í heild.Byggingar á Íslandi eru áhugavert tilvik þar sem orkunotkun tengd rekstribygginga er nánast alfarið fengin með umhverfisvænum orkukostum;jarðvarma og vatnsaflsvirkjunum. Vistferilsgreining er orðið viðurkennt verkfæri í mati á sjálfbærnimati ýmissa kerfa, þ.á.m. bygginga. Í verkefninu var því ákveðiðað nota aðferðafræðina til að meta umhverfisáhrif efna ogbyggingarhluta í hjúpfleti Vættaskóla-Engis, skólahúss í Grafarvogi.Greiningin nær til fjögurra stiga í ferlinu (skilgreind í staðlinum EN 15804); hráefnisöflunar (A1), flutninga hráefnis til framleiðslustaðar (A2), framleiðslu byggingarefna (A3) og loks flutninga til byggingarstaðar (A4). Það skal bent á að áhrif frá byggingarstarfsemi, rekstri ogförgun eru ekki innifalin í greiningunni. Eftirtalin umhverfisáhrif erumetin; hnattræn hlýnun (GWP), ozon eyðing (ODP), efna- og líffræðilegáhrif á mannkyn (HT), súrnun (AP) og ofauðgun (EP).

Efnisnotkun í skólabyggingunni, metin sem heildaráhrif GWP, ODP, HT, AP ogEP, reiknast jafngilda 1490 tonnum CO_2 ígilda, 0.0305 kg CFC 11 ígilda,0.262 CTUh, 5.5 kmol H+ ígilda og 13 kmol N ígilda. Reiknað á fermetragólfflatar þá eru þessi áhrif eftirtalin; 298 kg CO_2 ígildi, 6.11E-06 kg CFC 11 ígildi, 5.22E-05 kg CTUh, 1.10 mole H+ ígildi og loks 2.56 mole Nígildi. Eins og vænta mátti þá vegur steypa mikið í heildinni, en tilsamans vega steypa, járnbending og álgluggar á bilinu 70-85% afofannefndum heildaráhrifum.

Greiningin sýnir ennfremur að umhverfisáhrifíslenskrar steinullar eru 59-67% lægri heldur en uppgefin áhrif vegnaframleiðslu steinullar í Bretlandi og Þýskalandi. Niðurstöður þessarar greiningar sýna svo ekki verður um villst kostivistferilsgreininga í mati á umhverfisáhrifum byggingarefna. Útkoman gerir okkur kleyft að gera samanburð við hliðstæðar greiningar erlendisog greina nánar hvaða möguleikar eru á að gera byggingar á Íslandi ennumhverfisvænni

I dedicate this thesis to my family and my husband, Reza
for their constant support and unconditional love.

I love you all dearly.

Table of Contents

List of Figures

List of Tables

Abbreviations

AP Acidification Potential

DE Germany

EU Europe

EP Eutrophication Potential

GaBi Ganzheitliche Bilanzierung Integrated Assessment

GHG Greenhouse gas

GWP Global Warming Potential

HT Human Toxicity

IS Iceland

LCA Life-Cycle Assessment

LCI Life-Cycle Inventory

ODP Ozone Depletion Potential

UK United Kingdom

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My greatest appreciation goes to my parents for supporting me spiritually throughout my life. From the bottom of my heart, I believe that no matter what happens, parents will always be there. I can’t ever appreciate them enough for all sacrifices they went through for me.

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1 Introduction

Buildings play a key role in our lives and society as a complex system. While, construction is not an environmentally friendly process by nature, the impact is expected to increase due to the demand for new construction. Therefore, it is becoming more important to analyze engineering designs and find ways to reduce humankind's environmental burden.

Sustainable development was defined in the Brundtland Report 1987 as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". With the publication of the Brundtland Report in 1987 and the Rio Declaration in 1992, sustainable development has become a well-known global paradigm. While the building industry generates 5% to 15% of the global GDP, construction waste is one of the heaviest and most voluminous waste streams generated and it accounts for approximately 25% - 30% of all waste generated in the EU (IEA, 2013). The construction waste consists of numerous materials, including concrete, gypsum, wood, glass, metals and plastic, many of which could be recycled for significantly higher extent than they currently are (Fischer and Werge, 2009). Therefore, it is important to quantify the performance of buildings in order to link their potential environmental impacts as well as their influence to sustainable development. To apply the sustainability concept to the construction sector, quantitative methods are needed that provide a holistic view of the building over the total span of design, construction and use.

According to the report by Intergovernmental Panel on Climate Change (IPCC 2012), total anthropogenic greenhouse gas (GHG) emissions have continued to increase over 1970 to 2010 with larger absolute increases between 2000 and 2010, despite a growing number of climate change mitigation policies. Anthropogenic GHG emissions in 2010 have reached 49±4.5 $GtCO_2$ eq/yr, and the atmospheric concentration has exceeded 400 ppm. Buildings and activities in buildings are responsible for a significant share of GHG emissions, but they are also the key to mitigation strategies. GHG emissions from the building sector have more than doubled since 1970 and reached 9.18 $GtCO_2eq$ in 2010, representing 25% of total emissions without the Agriculture, Forestry, and Land Use (AFOLU) sector; and 19% of all global 2010 GHG emissions (including electricity-related) (IEA, 2012; JRC/PBL, 2013; see Annex II.8).

Mitigating climate change through operational energy reduction in existing buildings is of highest priority for policy-makers in Europe, considering the focus of the European Performance Building Directive (EPBD) 2010/31/EU, and the Energy Efficiency Directive (2012/27/EU), which resulted in considerable efforts towards better insulation, more efficient HVAC systems and more use of sustainable energy. The main reason for this approach is the result of many years of research which shows that operational energy consumption is the most energy-consuming phase in a building's life cycle (Blanchard and Reppe 1998, Scheuer et. al., 2003, Wang 2007 and Ramesh et. al., 2012). However, the continued tightening of the building regulations' requirements for operational efficiency will reduce the environmental impacts from building's operation; hence, the significance of embodied impacts will increase relative to the total. In addition, improving operational energy performance may involve the use of materials, components, and energy systems that increase the environmental impacts from materials (Tingley and Davinson, 2011, Georgiadou, 2014). Recent evidence actually depicts that it might not be so much the increasing consumption which drives the global emissions growth, but the required capital investments to accommodate the rural-urban movement, that is, the construction materials (Minx et al. (2011), which currently are neglected in the majority of assessment schemes and mitigation policies.

Iceland is a Nordic island country located in the North Atlantic Ocean. It has a population of around 330,000 and an area of 103,000 km^2. Natural conditions are difficult, with limited option for production of local materials, and therefore, imports are very important. Domestic building materials are essentially only various types of fill, stone wool and cement until 2012, and significant amount of construction materials including styrofoam insulation, insulating glass and glulam are imported for further processes.

Hydroelectric energy remains adequate for local use in Iceland, in addition to which, geothermal energy is in large surplus, so the vast majority of energy used in buildings is environmentally friendly. Thus, Iceland's position is unique, and in order to reduce the building's life cycle environmental impacts, it‘s necessary to examine the environmental impacts of building materials. The life cycle assessment of advanced building materials and systems is principal to significantly improving overall environmental building performance (Marteinsson, 2002).

There are a few studies that have focused on the embodied energy, and associated embodied emissions. A study of the energy use of Swedish low-energy buildings found that the initial energy embodied in a one family home accounted for more than 45% of the total energy need over a 50 years life span (Thormark, 2002). Rawlinson and Weight (2007) estimate that in the UK the embodied energy in complex commercial buildings may be equivalent to 30 times annual operational energy use. At the same time Sturgis and Roberts (2010) suggest that the embodied emission accounts for 45% of the whole life-cycle carbon of its structure.

Several studies have also assessed other environmental impacts such as ODP (Ozone depletion potential), AP (Acidification potential), EP (Eutrophication potential) and POCP (photochemical ozone creation potential). For example, Belengini, et al, (2010) developed a detailed LCA over several impact categories including GWP, ODP, AP, EP and POCP for a house in Morozzo in Northern Italy. Their analysis has highlighted that, when addressing energy-saving and sustainability performances of low-energy buildings, the role and significance of all life cycle phases and subsystems must be carefully considered. In 2012, Passer et al, have analyzed the influence of five residential buildings in Austria on seven environmental indicators (AP, EP, GWP, ODP, POCP, CED_{nr} (cumulative energy demand-non-renewable), CEDr (cumulative energy demand-renewable)). This analysis shows that although the building operation dominates the overall indicator results in most environmental categories, the ratio between construction products and operation may vary strongly (e.g., 48/52 % for building 1 to 62/38 % for building 4 on indicator AP and 42/58 % for building 1 to 54/468 % for building 4 on indicator POCP).

Despite the importance of all environmental impacts, GHGs and climate change are still the most widely studied impact related to buildings and the one receiving the vast majority of the attention. McKinsey & Company's greenhouse gas abatement cost curve (figure 1) provides a quantitative basis to compare the effectiveness of actions in delivering emissions reductions and their cost, relative to the business-as-usual projection. It provides a global mapping of opportunities to reduce the emissions of GHGs across regions and sectors. McKinsey covered different sectors such as power generation, manufacturing industry (with a focus on steel and cement), transportation, residential and commercial buildings.

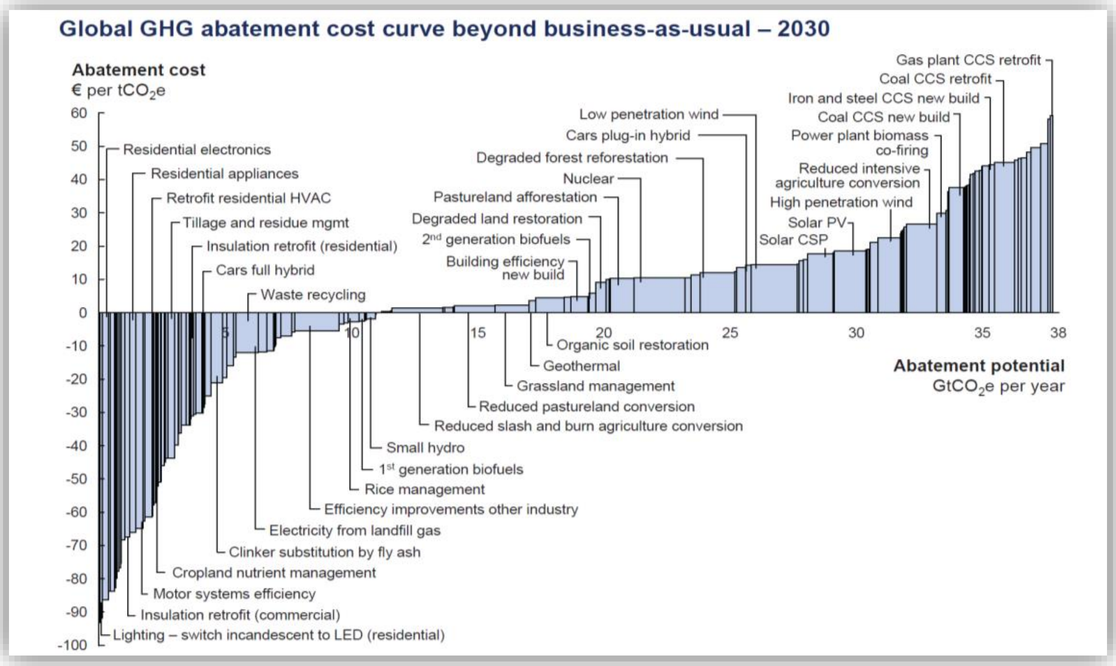

Figure 1: Global GHG abatement cost curve beyond business-as-usual-2030

Figure 1 shows estimates of the annual abatement cost in dollar per ton of avoided GHG emissions, as well as the abatement potential of these approaches in gigatons of emissions. Their analysis offers some noteworthy insights. It would be technically possible, to capture 26.7 gigatons of abatement by addressing only measures costing no more than 40 euros a ton. At the low end of the curve are, for the most part, measures in building sector that improve energy efficiency. For example, improving the insulation of new buildings would lower demand for energy to heat them and thus reduce emissions. Unfortunately up to now similar studies don't exist for other impacts caused by buildings and building materials. More recently, a similar analysis was conducted for Iceland by Davíðsdóttir and Agnarsson, (2010).

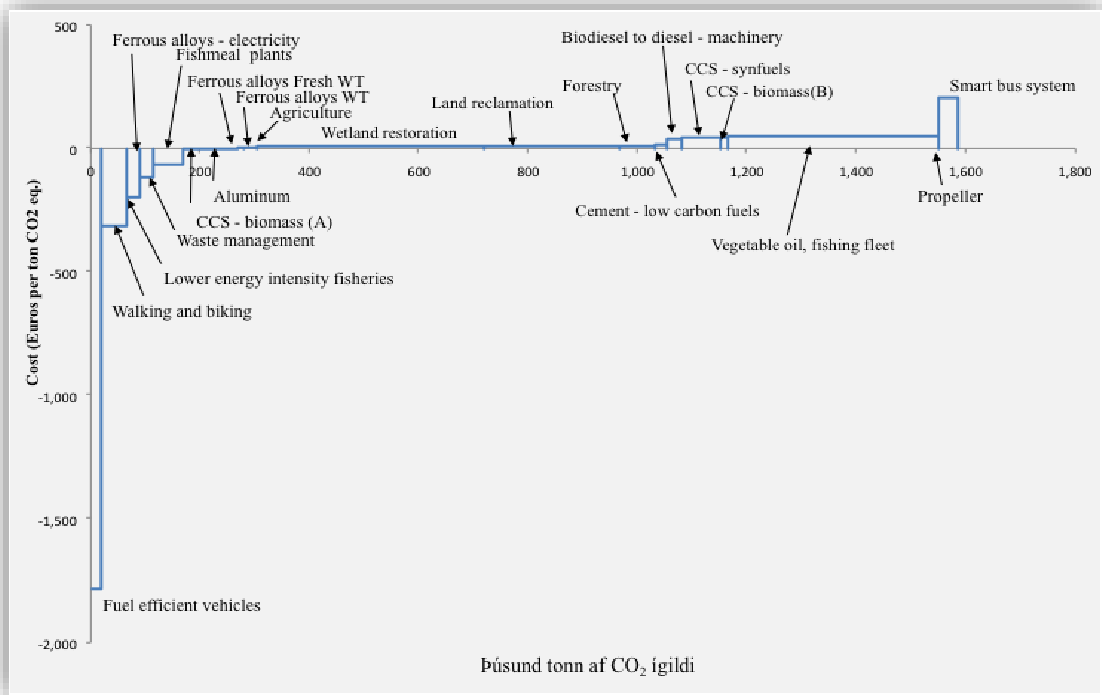

Figure 2: GHG mitigation supply curves for Iceland

Figure 2 illustrates two important features of the Icelandic mitigation cost curve, which as expected closely align with the specific features of the Icelandic emissions profile. First, mitigation at a net benefit can significantly contribute to lower GHG emissions of up to 4%. Second, it is obvious that improvement of energy efficiency in buildings available in most other countries is not cost-effective in Iceland due to the low price of heating and electricity in buildings (Davíðsdóttir and Agnarsson, 2010).

With the progress in reducing the GHG intensity of energy supply systems around the world, it's becoming more and more critical to focus on embodied emissions. As it was mentioned before, unlike many other countries, Iceland has abundant renewable energy sources, including geothermal and hydropower which are used to satisfy the energy demand in buildings (heating, cooking and lighting). Therefore, the fraction of embodied emissions is significantly higher compared to other locations with non-renewable energy supply systems.

Methods for the assessment of the environmental performance of buildings have been developed since the early 1990s. The International Standardization Organization (ISO) prepared the first standards in 1951, intended to address specific issues and aspects of sustainability relevant to building and civil engineering of construction works. These standards are founded on the Life Cycle Assessment methodology (LCA) in ISO 14040 (International Organization for Standardization 2006a).

LCA has become an accepted tool that quantifies and assesses the emissions, resources consumed, and impacts on health and the environment that can be attributed to different goods or services over their entire life cycle. It seeks to quantify all physical exchanges with the environment, whether these are inputs in the form of natural resources, land use and energy, or outputs in the form of emissions to air, water and soil.

1.1 Research Problem and questions

According to recent studies, the building sector is considered to have the most feasible potential worldwide for reducing the GHG emissions in the short term i.e. the time frame of the near future climate mitigation (IPCC, 2007).

Evaluation of buildings in Iceland has certain characteristics. First of all, the GHG emissions during the use phase are low, mainly because of using hydro and geothermal resources for space heating and power generation. Nonetheless, there are still some communities which use oil for heating instead of renewable energy resources (e.g. Vestmann islands). Therefore, the importance of the embodied emissions increases compared to other regions. Secondly, most of the materials for the buildings envelope (such as steel, glulam and Aluminum windows) are not produced in Iceland, which increases the need for a comprehensive evaluation to understand where the emissions are released.

1.1.1 Objectives

The aim of the study is to analyze the environmental impacts of materials used in the structure and envelope of the Vættaskóli-Engi building in terms of global warming potential (GWP), Ozone depletion potential (ODP), Human Toxicity (HT), Acidification (AP) and Eutrophication (EP). These impact categories are selected to represent major environmental impacts.

In addition, the emissions from transportation to construction site will be estimated. Considering the importance of GWP impact, most of the discussions in this study are focused on this category.

1.1.2 Primary Research Questions

To capture the potential for reducing the impact of a school building construction, the following questions need to be answered:

- What are the overall environmental impacts of construction materials used in the structure and envelope of the Vættaskóli-Engi building in Reykjavik, Iceland in terms of GWP, ODP, HT, AP and EP impacts?
- Which materials are the main sources of environmental impacts?
- What is the share of transportation in each impact category?

2 Background

The main target of this research is to assess the environmental impacts of construction materials used in the school building in Reykjavik, Iceland. Therefore, a review on environmental assessment approaches is conducted. Three environmental assessment approaches including Checklists, Matrices and the Battelle environmental evaluation system are described in section 2.1. Then, section 2.2 defines the general framework of LCA and common parameters. Then, LCA tools are classified and briefly discussed. Consequently, based on two comprehensive review papers by Cabeza et al, (2014) and Sharma, et al., (2011), several applications of LCA for residential and non-residential buildings are reviewed.

2.1 Environmental assessment approaches

Environmental Impact Assessment (EIA) is a process, which when properly followed permits potential impacts of developments on the natural environment to be recognized, assessed and, where possible, mitigated. The key purposes of EIA methods are to identify the core environmental issues and aspects, assess the environmental performance of the suggested scheme against the substantial aspects, detect significant positive and negative impacts, evaluate the overall environmental impact of the scheme to enable comparison between alternative plans and facilitate a comprehensive approach with the project stakeholders (FAO, 1996). In this chapter, three methods available for EIA analysis are briefly discussed: Checklists, Matrices and the Battelle environmental evaluation system (Sorensen and Moss, 1973; Warner and Preston, 1973). LCA approach is discussed in chapter 2.2.

2.1.1 Checklists

Checklists are known to be the simplest method for the evaluation of any project impacts on the various components of the environment. Checklists are inclusive lists of environmental effects and impact indicators intended to motivate the analyst to think broadly about possible consequences of anticipated actions. They are mainly for organizing information or ensuring that no potential impact is ignored (Aziz, 2005). There are several major motives for using checklists (Carter, 1996):

- They are useful in summarizing information to make it reachable to specialists from other fields, or to decision makers who may have a limited amount of technical knowledge;
- Scaling checklists provide a preliminary level of examination; where the listed impacts are ranked in order of magnitude or severity
- Weighting is a mechanism for integrating information about ecosystem functions, where numerous environmental parameters are weighted (using expert judgement), and an index is then calculated to serve as a measure for comparing project alternatives.

Westman (1985) listed some of the problems with checklists when used as an impact assessment method:

- They are too general or inadequate;
- They do not demonstrate interactions between effects;
- The number of categories to be reviewed can be enormous, thus distracting from the most significant impacts;
- The identification of effects is qualitative and subjective.

2.1.2 Matrices

Matrices method detect interactions between various project actions and environmental parameters and components. They include a list of project activities with a checklist of environmental components that might be affected by these actions. A matrix of potential interactions is produced by combining these two lists (placing one on the vertical axis and the other on the horizontal axis). One of the earliest matrix methods was developed by Leopold et al. (1971). In a Leopold matrix and its variants, the columns of the matrix correspond to project actions (for example, flow alteration) while the rows represent environmental conditions (for example, water temperature). The impact associated with the action columns and the environmental condition row is described in terms of its amount and importance.

Most matrices were built for specific applications, although the Leopold Matrix itself is quite general. Matrices can be tailor-made to suit the requirements of any project that is to be evaluated. They should rather cover both the construction and the operation phases of the project, because sometimes, the former causes larger impacts than the latter. Simple matrices are useful (Baskar and Baskar, 2005):

- In early EIA processes for scoping the evaluation;
- For recognizing areas that require further research;
- For identifying interactions between project activities and specific environmental components.

However, according to Aziz, (2005), matrices have three main drawbacks:

- They tend to overly simplify impact pathways
- They do not explicitly represent spatial or temporal considerations,

2.1.3 The Battelle Environmental Evaluation System

The Battelle Environmental Evaluation System (EES) is an evaluation system which tries to conduct environmental impact analysis developed at Battelle Columbus Laboratories by an interdisciplinary research team under contract with the U.S. Bureau of Reclamation (Dee et al., 1972; Dee et al., 1973). It is based on a hierarchical assessment of environmental quality indicators.

The system is based on a classification containing of four levels: categories, components, parameters, and measurements. Each category is divided into several components, each component into numerous parameters, and each parameter into one or more measurements. The EES identifies a total of four categories, eighteen components and seventy-eight parameters.

EES assessment of the environmental impacts of each projects is based on commensurate "environmental impact units" (EIU). Two EIU scores are estimated, one 'with' and another 'without' the proposed project. The case ‘without’ the proposed project accounts for the environmental impacts in the business as usual condition. The difference between the two scores is a measure of the environmental impact. The scores are based on the magnitude and significance of specific impacts. Major features of the EES are:

- Hierarchical classification system;
- Commensurate unit of measure (EIU);
- Flagging of environmentally sensitive areas.

2.2 Life-cycle Assessment – General method

The LCA approach to quantify environmental burden is formalized by the International Organization for Standardization (ISO) 14040 series. LCA is defined as a method which allows the development of objective criteria and procedures for the assessment of the environmental impacts of products (e.g., emission), based on the total life cycle of the product (from cradle to grave). According to ISO 14040, LCA is defined as the “compilation and evaluation of the inputs and outputs and their potential environmental impacts of a product system during its lifetime.” Thus, LCA is a tool for the analysis of the environmental burden of products at all stages in their life cycle – from the extraction of resources, through the production of materials, product parts and the product itself, and the use of the product to the management after it is discarded, either by reuse, recycling or final disposal (in effect, therefore, ‘from the cradle to the grave’). Notable documents in this series are ISO 14040:2006 – Principles and Framework and ISO 14044:2006 – Requirements and Guidelines (ISO 2006a; ISO 2006b), which together shape fundamental concepts relevant to developing and conducting an LCA study. The ISO standards break the LCA framework into four stages: goal and scope definition, inventory analysis, impact assessment and interpretation. Figure 3 depicts these stages, their relationship and potential applications.

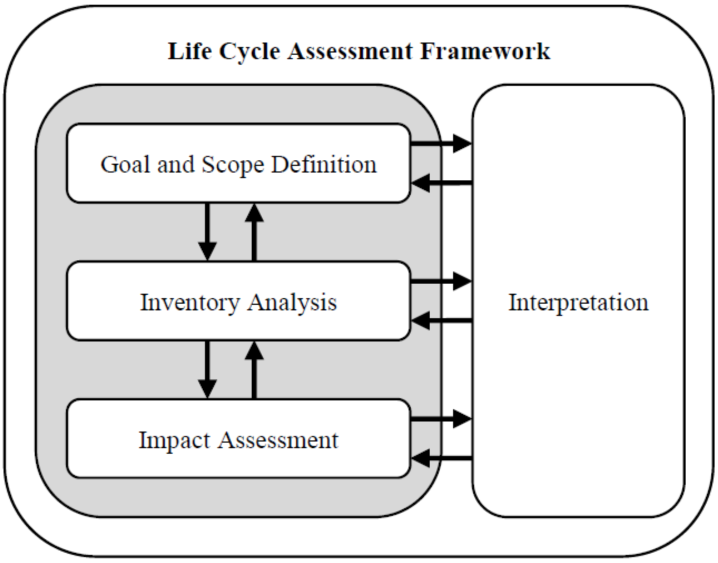

Figure 3: Stages of a life cycle assessment

The standard ISO2006a defines the activities to be included in each of the stages as follows;

2.2.1 Goal and Scope

It defines the plan for conducting an LCA. The goal states the intended application, the reasons for conducting a study, the anticipated audience, and the dissemination of the final product. The scope offers the approach to meet the specified goals, defining the functional unit(s), system boundaries, impact assessment methodology, and other relevant parameters (ISO, 2006a).

2.2.2 Inventory analysis

The ISO (2006a) lay out a general framework for identifying and quantifying the inputs and outputs of each process that falls within the scope. This is the key organizational step in the LCA process, where the data and process relationships are recognized. Within the inventory analysis, the life cycle is broken down into phases (e.g., pre-use, use, end-of-life), which are further organized into processes (e.g., materials flows, transportation distances). On the lowest level, these processes comprise data on inputs (i.e., material and energy consumption) and outputs (i.e., products, emissions and wastes). The life cycle inventory then sums up all inputs and all outputs that cross the defined system boundary. In an ideal case, the inventory contains only elementary flows (flows taken from or released into the environment without extra transformation) such as resources or emissions. Inventory analysis outcomes can then be summed over all processes to determine the total emissions over the life cycle.

2.2.3 Impact assessment

The Life Cycle Impact Assessment (LCIA) identifies and evaluates the amount and significance of the potential environmental impacts arising from the LCI. According to ISO 14044 (2006), LCIA proceeds through two mandatory and two optional steps:

1. Selection of impact categories and classification, where the categories of environmental impacts, which are of relevance to the study, are defined by their impact pathway and impact indicator, and the elementary flows from the inventory are assigned to the impact categories according to the substances‘ ability to contribute to different environmental problems. (Mandatory step according to ISO).
2. Characterization, where the impact from each emission is modelled quantitatively according to the underlying environmental mechanism. The impact is expressed as an impact score in a unit common to all contributions within the impact category (e.g. kg CO2-equivalents for greenhouse gases contributing to the impact category climate change) by applying characterization factors (Mandatory step according to ISO).
3. Normalization, where the different characterized impact scores are related to a common reference, in order to facilitate comparisons across impact categories. (Optional step according to ISO).
4. Weighting, where a ranking and/or weighting is performed of the different environmental impact categories reflecting the relative importance of the impacts considered in the study (Optional step according to ISO).

2.2.3.1 Impact assessment methods

The first impact assessment methodologies for Life Cycle Assessment, can be traced back to before 1992 (EC-JRC, 2010):

- The EPS (Environmental Priority Strategies) methodology based on endpoint modelling expressing results in monetary values,
- Swiss Ecoscarcity (or Ecopoints) based on the distance to target principle,
- the CML 1992 (Dutch guidelines) methodology based on midpoint modelling. These three methodologies formed the basis for three main schools that were further developed, and also today there are many LCA practitioners that belong to one of the three schools of thought.

These three methodologies formed the basis for three main schools that were further developed, and also today there are many LCA practitioners that belong to one of the three schools of thought.

EC-JRC, (2010) published a review on overall principles, the consistency across impact categories, and innovative‖ aspects across LCIA methods. In this section, the focus is on a brief review on the most popular methods.

- The CML 2002 LCA Handbook (Guinée et al., 2002) is a follow up of the CML 1992 LCA Guide & Backgrounds (Heijungs et al., 1992). It aims to provide best practice for midpoint indicators, operationalising the ISO14040 series of Standards. It includes recommended methods for normalization but no recommended methods for weighting.
- Eco-indicator 99 was developed with the aim to simplify the interpretation and weighting of results. One of the intended applications was the calculation of single-point eco-indicator scores that can be used by designers in day to day

decision making, but it is also used as a general purpose impact assessment method in LCA (Goedkoop and Spriensma, 2000).

- ReCiPe is a follow up of Eco-indicator 99 and CML 2002 methods. It integrates and harmonises midpoint and endpoint approach in a consistent framework. Although initially integration of the methods was intended, all impact categories have been redeveloped and updated (except ionising radiation). The method is not published as a single document yet, but most impact categories have been described in peer reviewed magazines (De Schryver et al., 2009).

2.2.3.2 Impact categories

There are many categories, but the number of impact categories are typically chosen based on the goal of the study. The following section describes the impact categories included in this study and the unit that is used for the estimation of each impact, based on the report on GaBi Database and Modelling Principles by Baitz et al. (2011).

Global Warming Potential (GWP)

The mechanism of the greenhouse effect can be observed on a small scale, as well as global scale. As shown in the left section of figure 4, the naturally occurring greenhouse gases - water vapor, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) - normally trap some of the sun's heat, keeping the planet from freezing. However, due to human activities, such as the burning of fossil fuels, the greenhouse gas levels have increased, leading to an enhanced greenhouse effect. The result is global warming and unprecedented rates of climate change. An analysis of the greenhouse effect should consider the possible long term global effects (Baitz, et al, 2011).

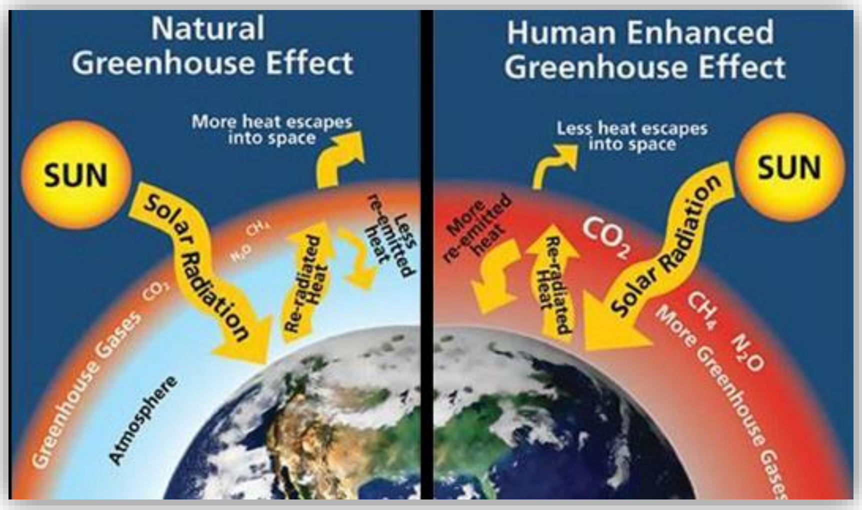

Figure 4: The global warming driven by naturally occurring GHGs (left) and human activities, such as the burning of fossil fuels (right) .

As stated in Baitz, et al, (2011), the GWP value is calculated in carbon dioxide equivalents (CO_2-Eq.). The most common basis for evaluation is GWP_{100} , meaning the averaged contribution of a material to the greenhouse effect over one hundred years. The lower the CO_2-equivalent result is, the lower is the potential influence on global warming and the related impacts on the environment.

Ozone Depletion Potential (ODP)

Ozone is created in the stratosphere by the disassociation of oxygen atoms that are exposed to short-wave UV-light. This leads to the formation of the so-called ozone layer in the stratosphere (15-50 km high). In spite of its minimal concentration, the ozone layer is essential for life on earth. Ozone absorbs the short-wave UV-radiation and releases it in longer wavelengths. As a result, only a small part of the UV-radiation reaches the earth.

The substances which have a depleting effect on the ozone can essentially be divided into two groups; the chlorofluorocarbons (CFCs) and the nitrogen oxides (NO_X). Figure 5 depicts the procedure of ozone depletion (Kreissig and Kummel, 1999).

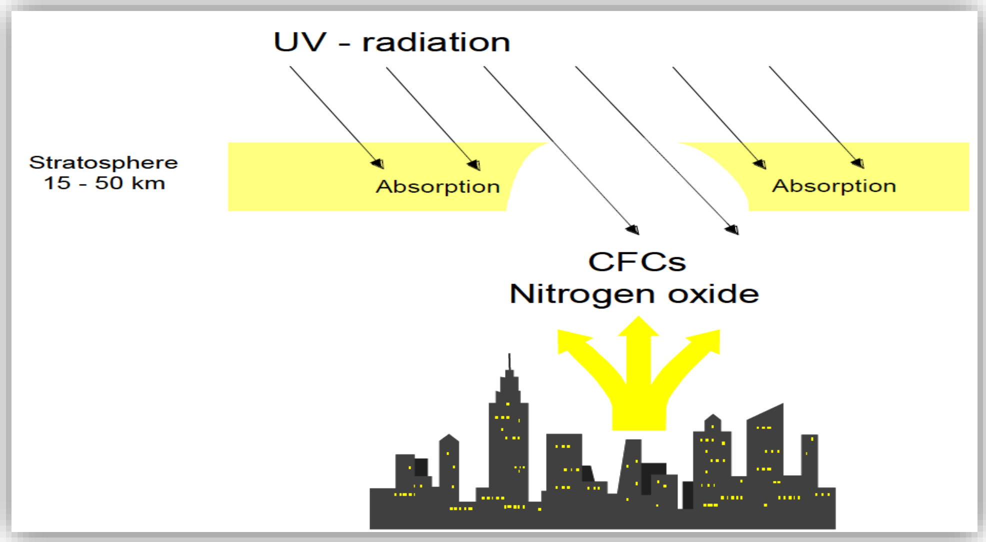

Figure 5: The procedure of ozone depletion

One effect of ozone depletion is the warming of the earth's surface. The sensitivity of humans, animals and plants to UV-B and UV-A radiation is of particular importance. Possible effects are changes in growth or a decrease in harvest crops (disruption of photosynthesis), indications of tumors (skin cancer and eye diseases) and a decrease of sea plankton, which would strongly affect the food chain.

According to WMO (2011), standard ODP reflects change in stratospheric ozone column in the steady state due to the amount of emission of that substance relative to CFC-11 (similar equivalency principle to GWP).

Human Toxicity (HT)

Toxicity is the ability of a substance to produce an unwanted effect when the chemical has reached a sufficient concentration at a certain site in the body. Once a toxic substance has contacted the body it may have either immediate or long term effects.

USEtox calculates characterization factors for human toxicity and fresh-water eco-toxicity via three steps: environmental fate, exposure and effects (Rosenbaum et, al., 2008). The human exposure model quantifies the increase in amount of a compound transferred into the human population based on the concentration increase in the different media. Based on Rosenbaum et, al., (2008), the characterization factor for human toxicity (human toxicity potential) is expressed in comparative toxic units (CTU_h), providing the estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases per kilogram), assuming equal weighting between cancer and non-cancer due to a lack of more precise insights into this issue.

Acidification Potential (AP)

The acidification of soils occurs predominantly through the transformation of air pollutants into acids, while ocean acidification is occurring because too much carbon dioxide is being released into the atmosphere. This leads to a decrease in the pH-value of rainwater and fog from 5.6 to 4 and below. Sulphur dioxide and nitrogen oxide and their respective acids (H_2SO_4 und HNO_3) produce relevant contributions.

According to Gruiz, et al, (2014), acidification has direct and indirect damaging effects, such as nutrients being washed out of soils, water or an increased solubility of metals into soils. Meanwhile, buildings and building materials can also be damaged. Examples include metals and natural stones which are corroded or disintegrated at an increased rate. Many programmes and projects are now investigating the impacts of ocean acidification on marine biodiversity and its wider implications, with strong international linkages (Aze et al. 2014). The United Nations General Assembly has urged States to study ocean acidification, minimize its impacts and tackle its causes. Many United Nations bodies are focusing attention on these issues (Guinée et al., 2002). Figure 6 displays the primary impact pathways of acidification (Kreissig and Kummel, 1999).

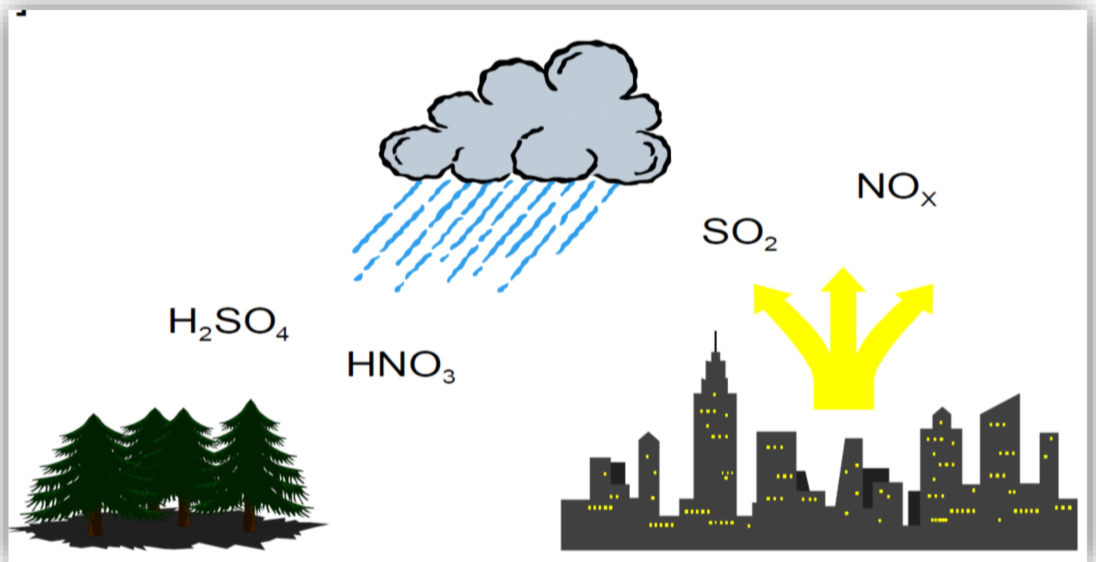

Figure 6: Primary impact pathways of acidification

The acidification potential is estimated in sulphur dioxide equivalents (SO_2-Eq.) (Seppälä, et al. 2006). The acidification potential is described as the ability of certain substances to build and release H+ ions (Baitz, et al, 2011).

Eutrophication Potential (EP)

Eutrophication is the enrichment of nutrients in a certain place. Eutrophication can be aquatic or terrestrial. Air pollutants, wastewater and fertilization in agriculture all contribute to eutrophication.

The result in water is an accelerated algae growth, which in turn, prevents sunlight from reaching the lower depths. This leads to a decrease in photosynthesis and less oxygen production. Oxygen is also needed for the decomposition of dead algae. Both effects cause a decreased oxygen concentration in the water, which can eventually lead to fish dying and to anaerobic decomposition (decomposition without the presence of oxygen). Hydrogen sulphide and methane are produced. This can lead to the destruction of the eco-system, among other consequences.

Nitrate also ends up in drinking water. Nitrate at low levels is harmless from a toxicological point of view. Nitrite, however, is a reaction product of nitrate and toxic to humans. The causes of eutrophication are displayed in Figure 7 (Kreissig and Kummel, 1999). According to Baitz, et al, (2011), the eutrophication potential is calculated in phosphate equivalents (PO_4-Eq.). As with acidification potential, it is important to remember that the effects of eutrophication potential differ regionally.

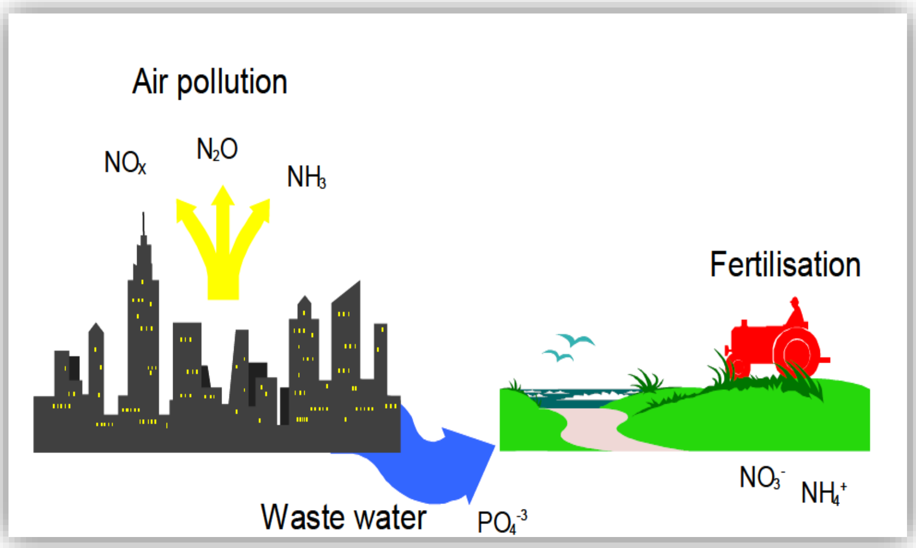

Figure 7: The sources of Eutrophication

All emissions of N and P to air, water and soil and of organic matter to water are aggregated into a single measure, as this allows both terrestrial and aquatic eutrophication to be assessed. The characterization factors in PO_4-equivalents, NO_3-equivalents and O_2- equivalents are all interchangeable, and PO_4-equivalents are used (Guinée et al., 2002).

2.2.4 Interpretation

It synthesizes the results from the inventory analysis and/or impact assessment stages in order to draw defensible conclusions. This stage permits the LCA practitioner to make suggestions to decision-makers in the context of assessment uncertainties and assumptions.

2.3 LCA Tools and assessment frameworks

A variety of software tools and databases provide standardized assessment models and inventory data at multiple scales (Singh, et. al., 2011, Haapio and Viitaniemi, 2008). The scales range from industry-wide and sector-wide data down to product- and even brand-specific data. Trusty and Horst (2005) categorized LCA related tools into three-tiered levels:

(1) Level-1 product Level-1 product comparison tools such as Ganzheitliche Bilanzierung Integrated Assessment (GaBi); SimaPro; BEES; National Renewable Energy Laboratory′s (NREL) U.S. Life-Cycle Inventory (LCI) Database; and Life Cycle Explorer.

(2) Level-2 whole-building decision support tools like Athena Eco-Calculator; Envest 2; and LCA in Sustainable Architecture.

(3) Level-3 whole-building assessment systems and frameworks, such as Athena Impact Estimator; BRE environmental assessment method; and the LEED rating system.

Haapio and Viitaniemi (2008) summarized the environmental assessment tools developed for the building sector focusing on European and North American ones (Table 1). Most of the building environmental assessment tools have been developed by research institutes.

Table 1: Building environment assessment tools

Tool	Developer
ATHENA™ Experimental Impact Estimator	ATHENA Sustainable Material Institute, Canada
BEAT 2002	Danish Building Research Institute (SBI), Denmark
BeCost (previously known as LCA-house)	VTT, Finland
BEES 4.0	U.S. National Institute of Standards and Technology (NIST), USA
BREEAM	Building Research Establishment (BRE), UK
EcoEffect	Royal Institute of Technology (KTH), Sweden
EcoProfile	Norwegian Building Research Institute (NBI); Norway
Eco-Quantum	IVAM, The Netherlands
Envest 2	Building Research Establishment (BRE), UK
Environmental Status Model (Miljöstatus)	Association of the Environmental Status of Buildings, Sweden
EQUER	École de Mines de Paris, Centre d′Énergétique et Procédés, France
ESCALE	CTSB and the University of Savoie, France
EXIOBASE	The Institute of Environmental Sciences (CML), Universiteit Leiden
GaBi	University of Stuttgart, Germany
LEED®	U.S. Green Building Council, USA
LEGEP® (previously known as Legoe)	University of Karlsruhe, Germany
PAPOOSE	TRIBU, France
SimaPro	PRé Consultants, The Netherlands
TEAM™	Ecobilan, France

Source: Haapio and Viitaniemi (2008)

In the following section, the most widely used LCA tools are briefly introduced.

- GaBi is a process-based model, established at the University of Stuttgart, Germany, that allows for life-cycle assessments that are ISO 14040-compliant. It uses an integrated products database developed through industry reviews and technical literature. Economic cost integration is built into GaBi; however, use-phase impacts do not appear to be addressed thoroughly by this software package.
- SimaPro also have information on common building materials. Developed by PRe consultants, this software is product design orientated. SimaPro is a professional LCA software tool. Complex products with complex life cycles are easily compared and analyzed. The inventory databases and the impact assessment methods can be edited and expanded without limitation. The ability to trace the origin of any result makes SimaPro unique. It is one of the most widely used LCA tool. Three versions of SimaPro are available, depending on the kind of analysis one intends to conduct (Bayer, et al. 2010). It enable conducting hybrid LCAs by combining process data and input–output data. The SimaPro data libraries include input–output data for a number of countries, including the United States, Japan, and Denmark.

- BEES is a building material specification tool used in the United States. It provides an integrated economic and environmental assessment package for a variety of building materials. Users apply functional weights to both economic and environmental shares of the analysis, as well as to a variety of damage classes. These weighting schemes, in turn, affect the performance score provided by the software. For the construction industry, BEES includes two desirable characteristics - the inclusion of integrated economic analysis, and an indoor air quality damage category. Lack of transparency may be considered as a limitation of BEES. A survey of BEES users identifies that builders, designers, and government entities find LCA tools that require less expert input easier to use, while 82% of respondents value transparency in an LCA tool (Hofstetter, 2002).
- The Athena EcoCalculator considers whole-building assemblies, recognizing that changes in specifying one building material may have greater consequences for other associated materials. The EcoCalculator also addresses two additional limitations of other LCA tools: availability of life cycle inventory data and the establishment of reference values against which to compare building performance. LCI data availability was addressed by the creation of a North American database within the application. The database was developed by a public–private partnership, and regional and national case studies have been established to provide reference values (Trusty and Horst, 2005).
- Envest 2 was developed as a building life-cycle design tool that permits an analyst to study environmental and financial trade-offs and impacts during the building design process. Designers start by entering data related to building height, window area, and choices of exterior assemblies such as walls and roof materials. The software then selects those components with the optimal overall environmental and economic impacts to allow the analyst to make trade-offs during the design stage. The model explicitly includes data from the building′s use phase, including repair, maintenance, and replacement.
- LISA is a freely available streamlined LCA decision support tool for construction developed in Australia. The LISA website lists a number of case studies of building LCAs using the software (Billiton Technology BHP, 2012).
- ECO-BAT is another software tool available for conducting LCAs of buildings that has LCI information on over 100 generic construction materials, drawn from the ecoinvent database, and on various energy sources for Europe (HEIG-VD, 2012). Users can define their buildings by picking construction elements (walls, windows), choosing materials composition, and defining an energy mix profile for heating, cooling, ventilation, etc.
- Carnegie Mellon University′s Economic Input–Output based LCA (EIO-LCA), an online tool, although not designed specifically for the construction industry, however, it has been used for life-cycle assessments of buildings and construction processes by estimating environmental impacts from various inputs from their corresponding industry sector averages (Ochoa Franco, 2004, O′Brien, et. al., 2006, Sharrard, et al, 2008). As another example of IO tools,

EXIOBASE is a global, detailed Multi-regional Input–Output database developed at the Institute of Environmental Sciences (CML), Universiteit Leiden. The advantage of this method is that IO-Models allow for high sectoral detail, while using a future projection of this model alleviates the historic character associated with IO-Model analysis (Tukker et al. 2013).

2.4 Previous LCA studies of buildings

Buildings can be categorized according to their usage i.e. residential and non-residential buildings. Residential buildings can further be divided into single-family houses and multi-family houses, and non-residential buildings are those which are used for collective use purposes, such as public buildings, transport services, tourism and sports, office, industrial, agricultural, commercial services, and stores (Sharma, et al., 2011). The literature review benefited greatly from two recent studies on the applications of LCA for buildings (Cabeza et al, 2014 and Sharma, et al., 2011).

The majority of building LCAs have looked at the full life cycle of residential and non-residential buildings. As the focus of this study is on the environmental impacts from materials used in the school building in Reykjavik, Iceland, it was decided to focus mostly on non-residential buildings. So, the result of only one LCA for a residential building in Sweden was presented, mainly because of the use of quite similar materials and also because it covers the same impact categories as used in this study. Regarding the non-residential buildings, the main reason behind selecting the literature was that the results of impacts from building materials were available. Then, the estimated impacts are used in subchapter 4.4 to validate the result of the current study. Besides, considering the use of similar building materials in the Nordic countries, it was decided to focus more on those studies.

Based on the described approach to select the literature to review, the findings from the life cycle analysis of one residential and eight non-residential buildings are reviewed.

LCA of residential buildings

Adalberth et al. (2001) performed LCA on four multi-family buildings built in 1996 at Sweden. The functional unit was considered as usable floor area (m^2) and the lifetime of building was assumed to be 50 years. The main aim was to study different phases of life-cycle of all four buildings and to find out which phase has the highest environmental impact. The environmental impact was assessed with an LCA tool developed at Danish Building Research Institute (Peterson, 1997). The assessed environmental impacts are GWP, AP, EP and HT. Different phases of a building covered were manufacturing, transport, erection, occupation, renovation, demolition and removal phase. The occupation phase alone accounted for about 70–90% of total environmental impact caused by a building, so it is important to choose such constructions and installations options which have less environmental impact during its occupation phase. The second dominant phase is the manufacturing of building and installation materials. This phase constitutes approx. 10–20 % of the life cycle. As can be seen in figure 8, the total global warming potential is approximately 1.5 ton CO_2 eq/(m^2.50 years), while the effect of manufacturing and transportation equals to around 150-250 kg CO_2-eq. The total acidification is approx. 8–10 kg SO_2 equivalents/(m².50 years). Also the eutrophication is approx. 4–5 kg NO_3 equivalents/(m².50 years) and the photochemical ozone creation is approx. 0.3 kg C_2H_4 equivalents/(m².50 years) for each building.

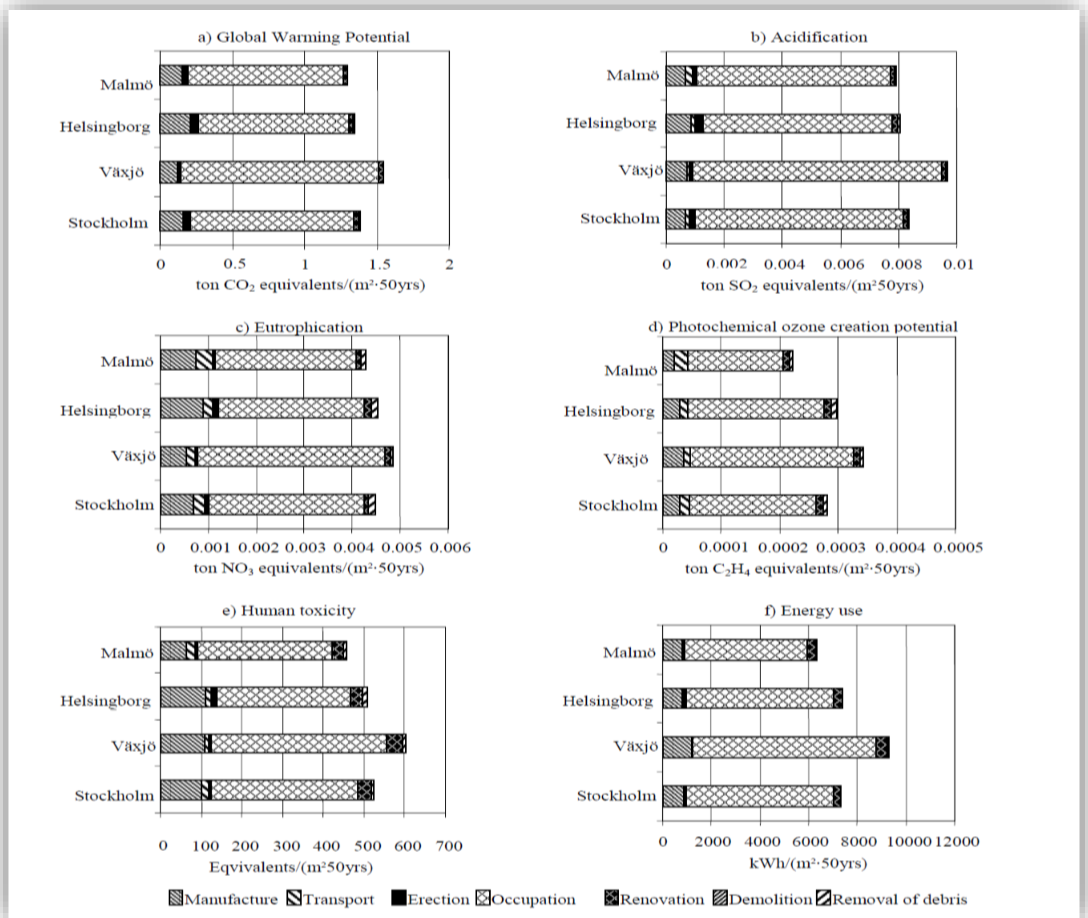

Figure 8: Environmental impacts of four multi-family buildings in Sweden during their life cycle (Adalberth et al. 2001)

Total environmental impacts from two phases of manufacture and transport are listed in the table 2, for four multi-family buildings in Sweden.

Table 2: Total environmental impacts of four multi-family buildings in Sweden during the manufacturing and transport

	GWP (ton CO_2 eq./m^2)	**AP (ton SO_2 eq./m^2)**	**EP (ton NO_3 eq./m^2)**	**HT (Equivalents/m^2)**
Malmö	1.25E-01	9.30E-04	1.06E-03	8.40E+01
Helsingborg	2.00E-01	1.06E-03	1.06E-03	1.24E+02
Växjö	1.00E-01	8.00E-04	7.30E-04	1.16E+02
Stockholm	1.50E-01	8.00E-04	9.00E-04	1.16E+02

LCA of non-residential buildings

Junnila et al, (2003) analyzed the significant environmental aspects of a new high-end office building with a life span of over 50 years, which is located at Southern Finland. The building has 15,600 m^2 of gross floor area, and a volume of 61,700 m^3. The building consists of three five-story office towers. The structural frame is made of cast-in-place concrete. The life cycle of the building was divided into five main phases; building materials manufacturing, construction processes, use of the building, maintenance, and demolition. Transportation of materials was included in each life-cycle phase. The building materials phase included all of the transportation to the wholesaler's warehouse. The construction phase included the transportation from the warehouse to the site. The environmental impacts covered in that study include global warming, acidification, summer smog, Eutrophication and the results on impact categories from building materials manufacturing are equal to 308 $kgCO_2eq/sqm$, 1.22 kg SO_2eq/sqm, 0.48 kg H_2C_4 eq/sqm, 0.12 kg PO_4 eq/sqm, respectively.

Junnila et al, (2006) tried to choose a U.S. office, so that the location and size match as closely as possible the climatic conditions in the European case study. The five-story building has 4,400 m^2 of gross floor area, and a volume of 16,400 m3. The structural frame is a steel-reinforced concrete beam-and-column system with shear walls at the core. The exterior envelope of the building consists of an aluminum curtain wall. The overall mass of the building materials used in construction is 1,290 kg/m^2 and in maintenance 70 kg/m^2. According to their assessment, total CO_2 emissions from the building materials in Finland and United States are estimated to be 295 and 450 $kgCO_2/sqm$, respectively.

Kofoworola et al, (2008) operated an LCA for an office building in Thailand. The building is a 38 storey building in the central business district of Bangkok and its service life was estimated to be 50 years. The functional unit for this study was considered as 60,000 m^2 gross floor area of building. This study included whole life cycle consisting material production, consumption, construction, occupation, maintenance, demolition and disposal. Inventory data was simulated in an LCA model and environmental impacts for each phase were computed. Three impact categories were considered; GWP, AP and photo-oxidant potential. Total GWP impacts from the material production is estimated to be 417 $kgCO_2/sqm$. As expected, they observed that the life cycle environmental impacts of commercial buildings are dominated by the operation stage; 52% of total global warming, 66% of total acidification and 71% of total photo-oxidant formation potential.

Robertson et al, (2012) compared the environmental impacts associated with alternative designs for a typical North American mid-rise office building (Discovery Place-Building 12). Discovery Place is a 14,233 m^2 office building, which was constructed in 2009 in Burnaby, British Columbia, Canada. The building is five-story with three levels of underground parking and its reinforced concrete structural frame. The system boundary of the comparative LCA study was cradle-to-gate, considering a 50-year building lifetime horizon. The environmental burdens associated with each building product were considered from raw materials acquisition, through the manufacture/processing stages, accounting for the production and use of fuels, electricity, and heat, as well as taking into account transportation/distribution impacts at all points along the product supply chain. Two scenarios were considered; a traditional cast-in-place reinforced concrete frame and a laminated timber hybrid design, which utilized engineered wood products (cross-laminated timber (CLT) and glulam). The GWP impacts from cradle-to-gate for these two scenarios are estimated to be 420 and 126 $kgCO_2$/sqm, respectively.

Thiel et al. (2013) have analyzed the environmental impacts of the materials used in the new Center for Sustainable Landscapes (CSL) building is a 2262 square meter office, built in Pittsburgh, PA, USA, with the purpose to reach the high green standards of the Living Building Challenge v1.3, LEED Platinum, and SITES certification for landscapes. The CSL has 3 stories with cast-in-place concrete and steel framing for the structure and aluminum/glass curtain wall and wood cladding for the envelope while the roof is a combination of a green roof, paver patio, and thermoplastic polyolefin white roof (Phipps). They studied the total GWP impacts of the materials used in CSL in two cases: one with Photovoltaic (PV) and Geothermal Wells (GW) and one without PV and GW. The impacts are estimated to be 1131 and 893 ton CO_2 equivalent, which is equal to 500 and 395 $kgCO_2$/sqm, respectively.

Biswas et al. (2014) assessed the environmental performance of new Building 216 “Engineering Pavilion Complex” at Curtin University in Western Australian in terms of carbon footprint and embodied energy consumption. The Building 216 has 4020 m^2 of gross floor area. The carbon footprint, including GHG emissions from the mining, construction and usage stages of the new building was 14229 tons CO_2 eq. The ‘usage stage’ produced a carbon footprint of 12145 tons CO_2 eq, representing about 85% of the total life cycle GHG emissions. This is approximately seven times more carbon intensive than the ‘supply of construction materials stage’ (1778 tons CO_2 eq and 13% of total emissions), and 40 times more carbon intensive than the ‘construction stage’ (2% of total emissions) of the new building. The GHG emissions from supply of construction materials stage is estimated to be 442 $kgCO_2$/sqm. Table 3 listed the properties of buildings and materials, as well as the GWP impacts from materials for reviewed literature.

Table 3: Properties of buildings and material and GWP impact for reviewed literature

	Junnila'03	Junnila'06	Junnila'06	Kowoforola'08	Robertson'12	Thiel '13	Biswas'14
Building Purpose	High-tech organizations	Typical Office Space	Office/Laboratory Space	Typical Office Space	Office Building	Multi-use Education/Office	Building 216 at Curtin University
Building Certification/Efficiency	37% reduced heating energy from baseline	NR	6%higher heating energy from baseline	NR	NR	Living Building Challenge	NR
Location	Finland	Midwest, USA	Finland	Thailand	Canada	Pennsylvania, USA	Perth, Australia
Life Expectancy	50 Years	50 Years	50 Years	50 Years	50 Years	50 Years	50 Years
Total Gross Floor Area	15600 m^2	4400 m^2	4400 m^2	60000 m^2	14233 m^2	2262 m^2	4020 m^2
Total Volume	61,700 m^3	16,400 m^3	17,300 m^3	9,120,000 m^3	NR	18,800 m^3	NR
Floors	5	5	4	38	3	3	NR
Structure	Cast-in-place concrete	Steel-reinforces concrete beam-column system with shear wall	Steel-reinforced concrete mean-column system	Cast-in-place concrete	Cast-in-place reinforced concrete	Cast-in-place concrete and steel frame	Steel Reinforced concrete
Envelope	Brick/curtain wall combination	Aluminum curtain walls	NR	Brick/Curtain wall combination	Steel Stud Framing, curtain walls	Aluminum/ glass curtain wall and wood cladding	Brick, Timber cladding Window and door frame / glass
GWP of the materials production ($KgCO_2/m^2$)	310	450	295	417	420	500	442

NR = Not Reported

3 Research Design

The Vættaskóli-Engi school building located in Reykjavik, Iceland was decided on as a case study for this project. Iceland is characterized with abundant resources of renewable energy (and water), which is the main reason why there has been relatively limited attention to regulation of the energy consumptions in buildings compared to the other Nordic or European countries. The situation with low consumer prices is a general issue in Iceland, where efficiency measures regarding water, heat and electricity often suffers from lack of feasibility due to very low prices.

In a survey done by Sand et al (2012), only a few regulatory initiatives with relevance for sustainable building materials in Iceland have been found. For example, the objective for the disposal of construction materials is to reuse 60% of the waste by 2015, which should increase to 75% in 2020.

On one hand, it can be claimed that there has not been a large political or legislative focus on issues which are traditionally related to sustainable buildings. One the other hand it can also be argued that Iceland have some of the most sustainable buildings, as the operation of the buildings (heat, electricity and water) is based on almost 100% renewable resources. This means that there is a relatively low level of interest for energy efficiency. Recently, there seem to be a move toward a more broad focus on sustainability aspects of buildings in Iceland. Hence it has been decided that new public buildings should be certified using BREEAM or similar schemes (Sand, et. al 2012).

3.1 Description of Case study

The Vættaskóli-Engi school building is located in Vallengi 14,112 Reykjavík, Iceland. The construction of the building began in 1996 and was commissioned in 1997. It has a gross floor area of 5000 square meters separated into two areas by a hallway in the middle in a longitudinal direction. The building has laboratories, kitchen, hallway, classrooms, offices, and gym. The drawings for ground and first floors and for windows are in appendices A1-A5.

In the following sections, based on the map description, building elements including roofs, walls and floor slabs are discussed. Besides, the detailed characteristics of the materials used in each element are presented.

3.1.1 Building elements

Roofs

The Vættaskóli-Engi has two types of roofs: a low-slope roof system and a pitched roof system. The low-slope system is made of wet insulation roofing "upside down". It has a main structure of reinforced concrete that is cast-on-site. The pitched roofing system in hallway is covered with corrugated steel cladding and supported by a glulam.

Roof type 1: Insulated pitched roof with glulam frame

The main support of the roof type 1 is made up of 50x350 mm "glulam" timber beams spaced at four meters apart in a transversal on length direction of roof. In between the main supports are 50x200 mm wood purlins spaced 0.60 m in the center with 200 mm thick stone wool insulation. The density of stone wool equal 80 kg/m^3. The roof covering is made up of corrugated steel cladding fastened to a 33x70mm and 12x70mm timber frame. The ceiling finish is corrugated steel cladding. Refer to Figure 9 for section drawing details.

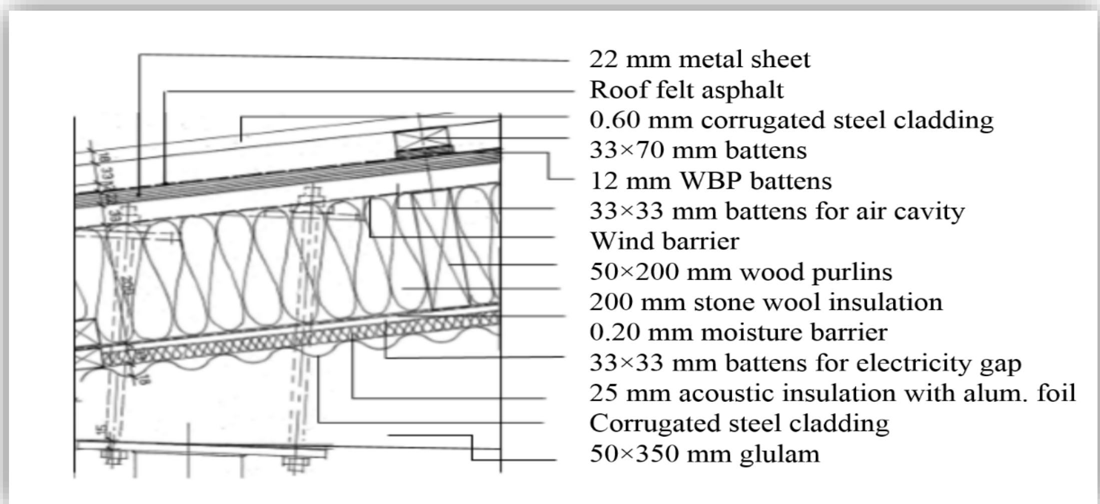

Figure 9: Insulated pitched roof with glulam frame

Roof type 2: Wet insulation

A reinforced concrete flat roof cast on site, 16 cm thick with a concrete quality of S-25 MPa as shown on Figure 10. This type of low slope roof is called "Wet Insulation or up-side down" roof type. On top of the slab is a concrete screed with slope to drain of 2.5%, covered with 2 layers of bituminous membrane. A 150 mm XPS insulation, density 32 kg/m3, are laid above the membrane. A top the insulation is a felt soil cover loosely laid and covered with sand and concrete tile about 5 cm in thickness. The interior concrete ceiling is polished and coated with 1.0 cm thick plaster and applied with crackle paste to smooth the surface. The final finish was painted with one coat of primer and two coats of paint.

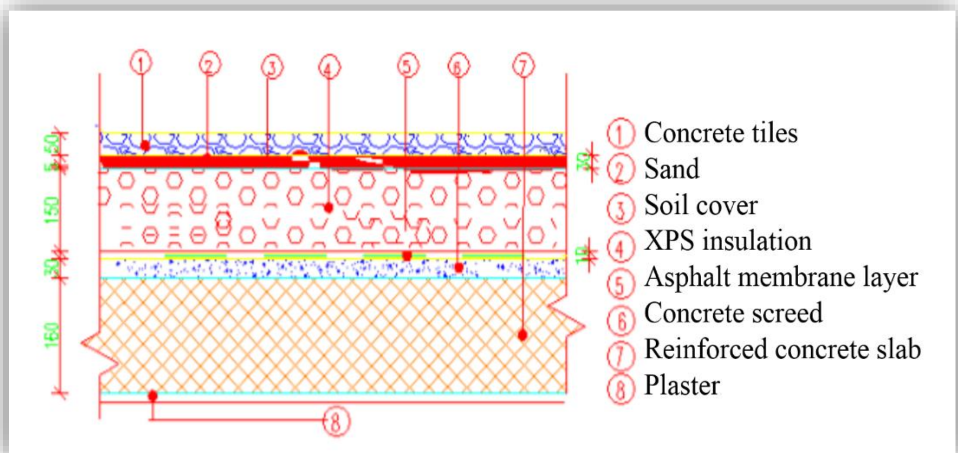

Figure 10: Upside down (wet insulation) roof system

Walls

The Vættaskóli-Engi has two types of exterior walls and two types of interior walls: Cast-in-place reinforced concrete wall which is insulated outside with stone wool and cladded with corrugated steel, Stucco wall which is a reinforced concrete wall insulated outside with stone wool insulation and exterior covering with plaster cement) are two types of exterior walls. Gypsum wall insulated with stone wool between four gypsum plasterboard and concrete wall are two types of interior walls .The detailed description of existing walls is discussed below.

Wall type 1: **Cast-in-place reinforced concrete**

Wall is 200 mm thick, reinforced concrete, cast on site with a concrete quality of S-25 MPa. The wall is insulated on the outside with 2x50 mm stone wool, density 80 kg/m3, in a 50x100 mm wood frame. Outside the frame is a12x50 mm plywood strip screwed into the frame. They form an air gap between wind barrier and corrugated steel cladding horizontally. The corrugated steel sheet fastened with 4.8x50 mm hot galvanized. . The inside wall finish is with spackling compound, primed and painted with two coats of oil paint (Figure 11).

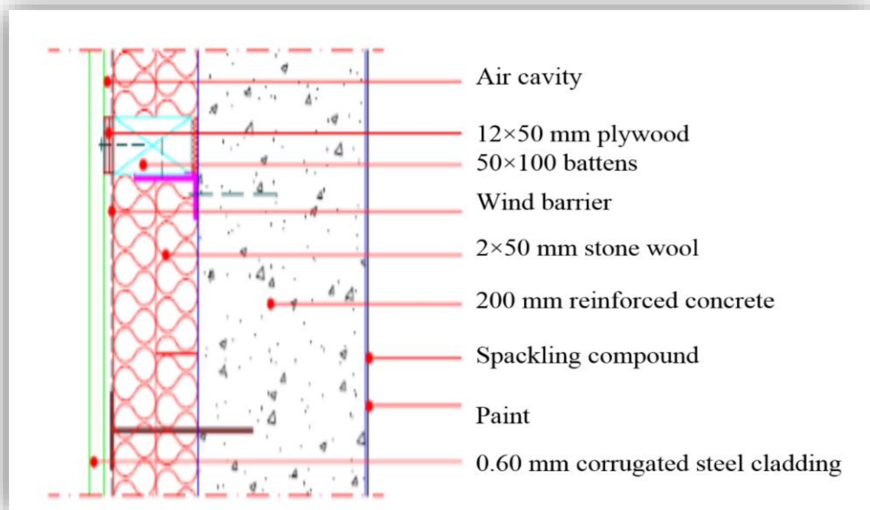

Figure 11: Cast-in-place reinforced concrete wall insulated outside and cladded with corrugated steel

Wall type 2: stucco (Plaster)

A 200 mm thick reinforced concrete cast-in-place, S-25 MPa concrete quality. The system is insulated outside with 100 mm stone wool insulation, density 80 kg/m^3. The exterior covering is made up of plaster cement, smooth finish with net attached. The interior finish is with spackling paste. The wall is primed and with two coats of paint on both surfaces (Figure 12).

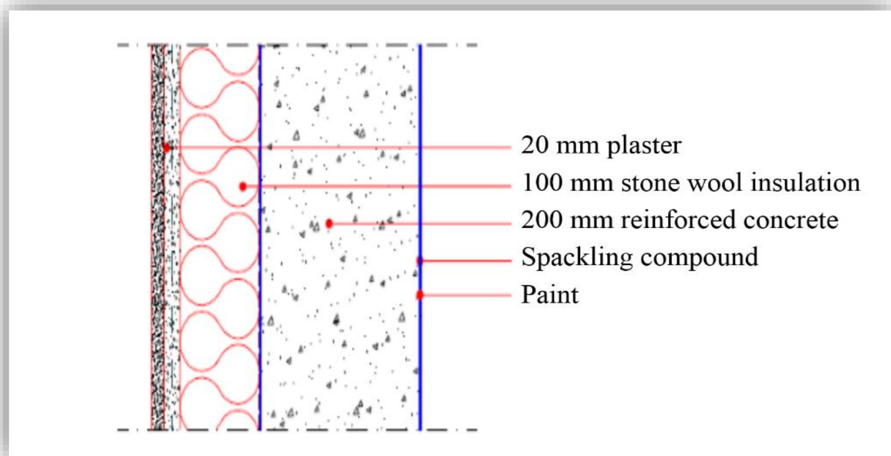

Figure 12: Reinforced concrete wall insulated outside with stone wool insulation

Wall type 3: Gypsum wall

The gypsum wall which is interior wall has double gypsum plasterboard with 50 mm stone wool, density 80 kg/m3, between the gypsum plasterboard (Figure 13).

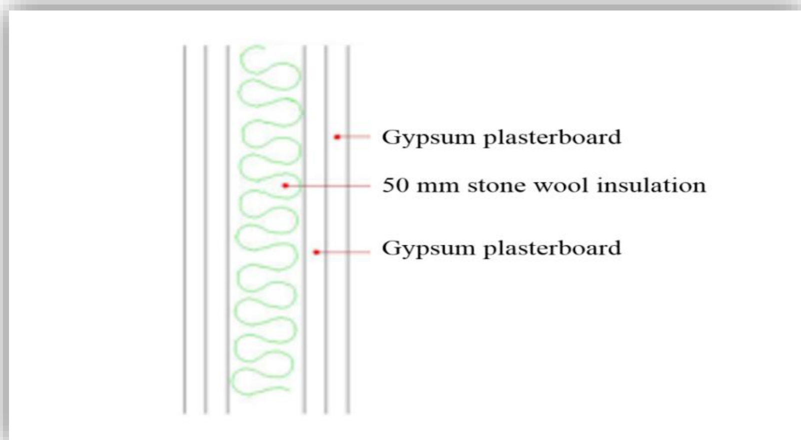

Figure 13: Gypsum wall

Floor slabs

Concrete slabs are common structural elements of modern buildings. In the Vættaskóli-Engi, horizontal slabs of steel reinforced concrete are used to construct floors and ceilings, and their thickness varies between 50-100 millimeters.

3.2 LCA structure

The most widely used assessment tool for an integrated assessment of all environmental impacts from cradle to grave of a given project is the environmental Life Cycle Assessment, or LCA (Guinée et al., 2002). While the LCA methodology in general was described in chapter 2, this section describes the methodology used in this study.

3.2.1 Goal and scope definition

The main goal of this study is to analyze the environmental impacts of materials used (including the manufacturing and transportation) in the structure and envelope of the Vættaskóli-Engi building in Reykjavik, Iceland. To account for major environmental concerns, a set of five impact categories are evaluated: global warming potential (GWP), Ozone depletion potential (ODP), Human Toxicity (HT), Acidification (AP) and Eutrophication (EP).

The official modeling guideline suggested by the European Commission is the International Reference Life Cycle Data System (ILCD), therefore these impact categories are assessed using the ILCD method, which is fully described in the Life Cycle Assessment handbook (Curran, 2012) and International Reference Life Cycle Data System (ILCD) handbook (EC-JRC, 2011).

3.2.2 System boundaries

Figure 14 illustrates the whole life cycle stages defined in the standard EN 15804 and the green line shows the system boundary of this study which includes four modules of A1-A4: raw material extraction (A1), transportation to manufacturing site (A2), manufacturing of construction materials (A3) and transportation to the construction site (A4). Based on the earlier discussion, the focus of this work is on the embodied emissions which have higher impacts compared to operation phase, due to use of sustainable energy. Therefore, the materials used in the structure and envelope of the school building (foundation, beams and columns, floor slabs, exterior and interior walls, roofs, windows and paint) are assessed. It should be noted that, surface materials, fixture, fittings, filling material, electric and heating systems and plumbing were excluded from this analysis. Due to lack of information, the impacts from the construction work (A5), use stage (B1-B7) and end of life (C1-C4) were omitted from this analysis.

	Life cycle stages	Product			Construction		Use stage							End-of-life				Benefits and loads beyond the system boundary
							Related to the building fabric					Related to the building operation						
	Modules	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
		Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Demolition	Transport	Waste processing	Disposal	Reuse / Recovery / Recycling potential
					Scenarios													
Type of EPD	Cradle to Gate[1]	M	M	M														
	Cradle to Gate with option(s)[2,4]	M	M	M	O	O	O	O	O	O	O	O	O	O	O	O	O	O
	Cradle to Grave[3,4]	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	O

Key: M mandatory; O optional

Notes:
[1] for a declared unit
[2] for a declared unit or functional unit
[3] for a functional unit
[4] Reference Service Life to be included only if all scenarios are included

Figure 14: Life cycle stages according to the standard EN 15804

3.2.3 Functional unit

Based on the literature review, it was decided to select two functional units for this analysis which are defined as:

- Entire Vættaskóli-Engi school building.
- One square meter gross floor area of the Vættaskóli-Engi school building.

3.2.4 Inventory Data

Currently, around 95% of all buildings in Iceland are constructed in reinforced concrete. Cement was locally produced until 2012, whilst gravel and sand are found in abundance in Iceland. Besides, insulation is locally produced using imported raw materials. Other building materials including lumber, reinforcing steel, metal claddings, structural steel, and electrical and plumbing materials are imported from different European countries, China, Canada and USA.

The life-cycle inventory data for the analysis is taken from various sources, including the map description. Table 4 presents a list of building materials (used in foundation, beams and columns, floor slabs, exterior and interior walls, roofs, windows and paint), with the details on the consumed amount and where the materials are produced.

Table 4: Inventory data for building materials used in the Vættaskóli-Engi school based on the map description

Building Materials	Quantities	Unit	Density (kg/m³)	country
Reinforcing steel	175000.0	Kg		Lithuania
Reinforcing mat	17197.8	kg		Lithuania
Concrete	2505.0	m³	2278	Iceland
Glued laminated timber	15.42	m³	515	Norway
Corrugated steel cladding	1.7	m³	7850	Finland
insulation, stone wool	12.3	m³	100	Iceland
insulation, hard pressed stone wool	306.8	m³	80	Iceland
insulation lightweight stone wool	234.4	m³	32	Iceland
Polyethylene High density	0.1	m³	950	Germany
Gypsum plaster board	8908.0	m²	800	Denmark
Aluminum window	670.1	m²	2700	Germany
Expanded Polystyrene	210.0	m³	25	Germany
Extruded polystyrene	400.5	m³	32	Germany
Underroof membrane	2670.0	m²		Germany
Plywood board	13.4	m³	575	Finland
Built up asphalt	3845.0	m²		Denmark
Concrete roofing tile	131.8	m³	2100	Iceland
Plaster	148.6	m³	2000	Iceland
Paint	2.1	m³	1350	Norway

The total weight of building materials, for the scope[1] of this study per gross floor area of Vættaskóli-Engi building is around 1.3 ton/m^2. As expected, concrete represents 85% of total weight of building.

In this study, GaBi was used to estimate the environmental impacts from construction materials. In this software, the impact factors are estimated based on models that are developed according to ILCD recommendations. Two models are developed in GaBi 6.0 for the production of concrete and stone wool in Iceland. For the rest of construction materials, the impact factors are obtained from GaBi's databases, except for aluminum windows, reinforcing steel and alkyd paint that the information from the database of SimaPro was used. Both of these databases are compliant to ILCD recommendations.

Concrete

Concrete is probably the best-known building material where strength and durability features are concerned. The quality of concrete is to a great extent dependent on the permeability of the material, which is again dependent on quality of ballast material and cement, proportioning of the concrete (the particle size distribution, content of binder and water/cement ratio), the hydration and compaction of the finished concrete (Marteinsson, 2013).

Concrete is an artificial conglomerate consisting of a mixture of a binder, water and aggregates (sand and gravel) which, depending on the need, can be integrated with additives, in order to modify its physicochemical and mechanical properties. Nowadays, cement is the binder mainly used for the production of concrete even if, in the past, lime was sometimes used. Cement, when mixed with water, hydrates and hardens, giving to the mixture (concrete) hardness values as high as that for rocks (Habert et al. 2012). According to Habert et al. (2012), the building materials sector is one of the largest CO_2-emitting and resources consuming industrial sector in the world. Concrete is the single most world-widely used building material mainly because of its strength and durability, among other benefits.

Considering the conditions of concrete production process in Iceland, it was decided not to utilize GaBi concrete options and develop a module in GaBi with the collected data for Iceland. Table 5 presents the inventory data for concrete production in Iceland.

Sementverksmidjan, owned by Islenskt Sement since 2003, is the only cement producer in Iceland. It operates a single integrated plant at Akranes but the production of cement stopped in February of 2012. Local geology limits the availability of land-based raw materials, while sea shells are dredged around 17km to be used. However, producing clinker from these raw materials is expensive, even though waste oil and organic solvents are used to reduce fuel costs (Baldursson and Johannesson, 2004).

The school was built in 1997, and cement was produced in Iceland during that time. Besides, there are local resources for gravel and sand in Iceland. The transportation distance for cement was 40 km, and for sand and gravel was 30 km.

[1] which excludes filling materials in foundation

Table 5: Inventory data for 1 kg concrete production in Iceland

Flow	Amount	Unit	Embodied Energy[2] (MJ/kg)
Cement (CEM I 32.5)	0.1334	Kg	3.4
Sand	0.3781	Kg	0.0379
Gravel	0.4092	Kg	0.0422
Concrete admixtures-plasticizer	0.0013	Kg	30
Water	0.0780	Kg	-
Electricity	8.90E-06	MJ	-

Figure 15 illustrates the developed model in GaBi 6.0 for 1 kg of concrete produced in Iceland. This model captures the impact from three modules of raw material extraction, transportation to manufacturing site, and manufacturing of construction materials. The environmental impacts of the cement were estimated based on the information available in GaBi database.

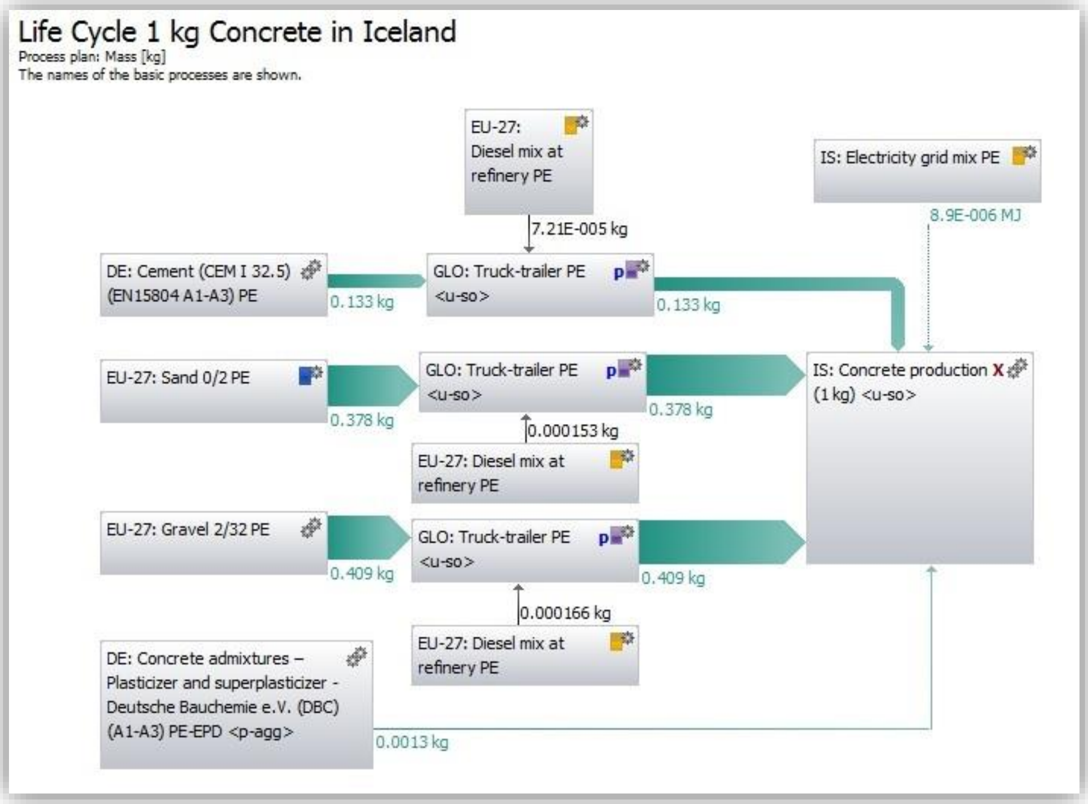

Figure 15: Model for1 kg Concrete produced in Iceland - GaBi 6.0

Stone wool

The Icelandic mineral fiber (rock fiber) insulation factory is situated at Sauðárkrókur on the northern coast of Iceland. The factory started production in 1985 and it is capable of producing 10000 tons of high-class insulation per year.

[2] The embodied energy data was obtained from Marteinson, (2002)

The raw material is mainly local basalt sand and crushed sea shells, including proportionally small amount of dust binding oil and other ingredients. In fact, the main constituent of sea shell sand is calcium carbonate ($CaCO_3$) and the reaction of producing quicklime (CaO) from calcium carbonate is as follows:

$$CaCO_3 + heat \rightarrow CaO + CO_2$$

Therefore, in addition to the emissions attributed to the energy consumption of the lime production process, the chemical reaction also leads to the production of CO_2. The molecular weight ratio of CO_2 to CaO in the raw material mineral calcite ($CaCO_3$) is 0.785, assuming 100% decarbonation of limestone (Ecofys, 2009). However, in reality, lime contains a small fraction of limestone, meaning that actual process emissions are lower. Based on EuLA, (2012), in 2010, the average CO_2 intensities for the production of 1 kg quicklime was 0.75 Kg CO_2 eq. Considering the fact that the electricity used for the required heating for this reaction emits very-low emissions in Iceland, so the total GWP impact per 1 kg of quicklime is 0.75 Kg CO_2 eq. In the developed model for stone wool production in Iceland, it was decided to choose “quicklime” instead of sea shell sand.

Manufacture of stone wool is carried out on a single 1.8m wide line using electric melting. The products are in roll, slab and loose wool form, together with rolls of foil faced duct wrap. Foil and paper faced products can be manufactured using a heated drum, and tissue facings can be applied on both sides of the insulation. The density range is Rolls: 20kg/m³ – 100kg/m³. Slabs: 20kg/m³ – 200kg/m³. The thickness has an extensive range from 20 to 200mm. Stone wool slabs are enclosed in polythene bags, or can be supplied on pallets (Steinull HF, Iceland). The inventory data presented in table 6, for the production of 1 kg of stone wool in Iceland was obtained from Úlfarsson (2011).

Table 6: Inventory data for 1 kg stone wool production in Iceland

Flow	Quantity	Amount	Unit
Electricity [Electric power]	Energy	7.92	MJ
Gravel (2/32) [Minerals]	Mass	0.82	Kg
Sea shell sand	Mass	0.22	Kg
Olivine [Nonrenewable resources]	Mass	0.10	Kg
Aluminum oxide (alumina) [Inorganic intermediate products]	Mass	0.05	Kg
Phenol (hydroxyl benzene) [Organic intermediate products]	Mass	0.05	Kg
Three-Layer panels [Parts from renewable materials]	Mass	0.04	Kg
Plastic profile [Plastics]	Mass	0.015	Kg
Urea formaldehyde resin in- situ foam [Plastics]	Mass	0.008	Kg
Ammonia [Inorganic intermediate products]	Mass	0.007	Kg

The transportation data (shipping distance and land transfer) for the material used for stone wool production is given in table 7.

Table 7: Transport raw material to Iceland for stone wool production

Components	Country	shipping [km]	Land Transfer [km]
Gravel (2/32) [Minerals]	Iceland (Sauðárkrókur)		12
Sea shell sand	Iceland (Faxaflói to Sauðárkrókur)		670
Olivine	Norway to Sauðárkrókur	1710	
Aluminum oxide (alumina)	Australia to Straumsvík and Straumsvík to Sauðárkrókur	22460	500
Phenol (hydroxyl benzene) [Organic intermediate	Europe to Reykjavik and Reykjavik to Sauðárkrókur	2400	500
Three-Layer panels [Parts from renewable materials]	Finland to Reykjavik and Reykjavik to Sauðárkrókur	3460	500
Plastic profile [Plastics]	Latvia to Reykjavik and Reykjavik to Sauðárkrókur	3310	500
Urea formaldehyde resin in-situ foam [Plastics]	Europe to Reykjavik and Reykjavik to Sauðárkrókur	2400	500
Ammonia	Europe to Reykjavik and Reykjavik to Sauðárkrókur	2400	500

Figure 16 illustrates the developed model in GaBi 6.0 for 1 kg of stone wool produced in Iceland. The scope of this model includes raw material extraction, transportation to manufacturing site, and manufacturing of construction materials.

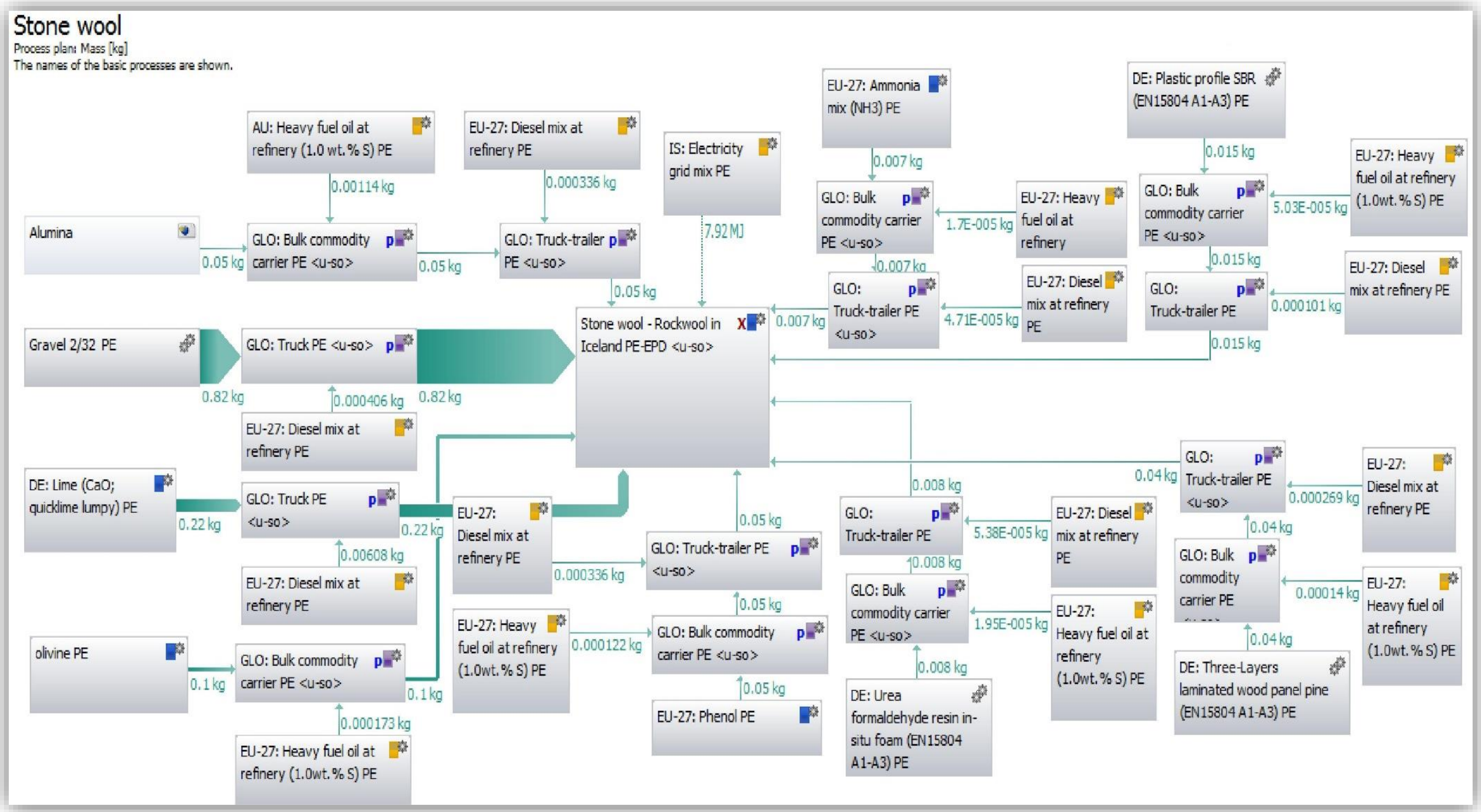

Figure 16: Model of 1 kg stone wool produced in Iceland - GaBi 6.0

Steel rebar (Reinforcing steel)

Steels can be made either from raw materials (e.g. iron ore, coal and limestone) or by recycling steel scrap. The two main process routes are the Blast furnace/basic Oxygen Furnace (BOF) route and the Electric Arc Furnace (EAF) route.

The BOF route is primary ore-based which generally uses up to 35% scrap input (Fruehan, 1998). The steelmaking stage of this route is carried out using the basic oxygen furnace. The EAF route is predominantly a 100% scrap-based steelmaking process. Both routes continuously cast products that feed into hot and cold rolling processes. In principle, all products can be produced via both process routes. For example, steel sections that are often produced from the EAF process are produced in both the EAF and BOF routes at Tata Steel.

Rebar is a steel reinforcing bar rolled on a hot rolling mill; can be further processed. This product is used to strengthen concrete in highway and building construction also as primary product for the wire rod process. Steel production involves several processing stages including ironmaking, primary and secondary steelmaking, casting and hot rolling. These are followed by some of the following fabrication processes: cold rolling, annealing, tempering, coating and/or heat treatment (World Steel Association, 2011). Because there was no value in GaBi database on the impacts of reinforcing steel, the impact factors reported in SimaPro were applied in this study.

Aluminum windows

The Vættaskóli-Engi has one type of window which is Double glazed aluminum window, comprising two panels of normal glass with 4mm thickness, with an air cavity of 6 mm for Openable windows and 12 mm for fixed windows. The material of structural frame is Aluminum. Total window area in the Vættaskóli-Engi school building is 670 m^2 and in this analysis the impacts are estimated based on the reference window which has 1 sqm area.

Because there was no value in GaBi database on the impacts of double glazed aluminum windows, the impact factors reported in SimaPro were applied in this study. It includes the impacts from aluminum frame as well as the glass.

Glued laminated timber

Glued laminated timber – glulam – is obtained by bonding together a series of laminations whose grain is essentially parallel. Glulam members are larger and longer than those obtained simply by sawing a normal log. Fundamentally this is rectangular in section, but additional operations lead to a variety of other cross sections and component shapes. For example, tapered profiles create pitched and shaped beams, portals and arches. Many types of curve are also fabricated, requiring thinner laminations bent on formers with bonding, clamping and curing arrangements. Uniquely this facilitates even three dimensional curves (Glued Laminated Timber Association, 2010).

The data were taken from GaBi database. Glue laminated timber is made up of a minimum of 3 glued boards up to 33mm thick known as lamellae. The lamella are glued with the fibers parallel to one another so that larger beams can be produced.

Gypsum plaster board

The data were taken from GaBi database. The process shows the average plasterboard production of Germany, France and Great Britain representative for the EU-27 region.

The gypsum used for plasterboard production is originated either from mined gypsum, gypsum gained from flue-gas desulphurization in coal power plants, so called FGD gypsum, other synthetic gypsum or recycled gypsum. Mined gypsum is mainly gained from open cast mining. To assess the impacts of the production of FGD gypsum from coal power plants the electricity consumption for the dehydration and purification of the gypsum slurry is considered, i.e. not the complete electricity consumption of the FGD as well as no lime consumption is considered for the FGD gypsum production. The reason therefore is the fact that the desulphurization is done for legal or environmental reasons but not to produce gypsum. Energy consumption for the recycling process of gypsum products as well as waste flow treatment is considered.

Expanded polystyrene (EPS)

The production of expanded polystyrene (EPS) takes place with the following steps:

1. Frothing of the polystyrengranulate
2. Treatment in a block foaming machine in dimensions for various products
3. Post-foaming
4. Cutting and piling.

For fire safety, Hexabromcyclododecan (HBCD) might be added to the EPS-foam. (The specific weight 25 kg/m³ and 75 mm thickness). The data on global warming potential from expanded polystyrene was taken from GaBi database. However, it should be noted that heating energy came from geothermal and so the collected data from GaBi overestimate the impact.

Extruded polystyrene (XPS)

Polystyrene extruder foam (extruded polystyrol rigid foam XPS) is fabricated in a continuous extrusion process: polystyrene granulate is melted in an extruder and pentane is added as a foaming agent. The foam is then formed into the respective plastic construction part. The produced foam is homogenous and closed-cell and is offered in the form of plates. (The specific weight 32 kg/m³ and 125 mm thickness). The data on global warming potential from extruded polystyrol was taken from GaBi database.

Polyethylene High Density (PEHD)

The basis for the production of polyethylene is crude oil. There are a few process types for polymerizing ethylene to polyethylene. Polyethylene is polymerized from ethylene, which is extracted by cracking naphtha or gas oil in a steam-cracker. PEHD is produced in a low-pressure process which are classified, according to the phase in which the reaction occurs into solution process, suspension process and gas phase process. Because of its high market share, the gas phase process in a fluidized bed reactor is chosen as reference process for the production of polyethylene.

- The specific weight of Polyethylene High density: 950 kg/m³
- The thickness: 0.2 mm

The data on global warming potential from polyethylene was taken from GaBi database.

4 Results of Impact Assessment

This chapter presents the results of impact assessment of construction materials used in the Vættaskóli-Engi school building during four modules of A1-A4 as defined in the standard EN 15804 in terms of global warming potential (GWP), Ozone depletion potential (ODP), Human Toxicity (HT), Acidification (AP) and Eutrophication (EP).

The results on overall environmental impacts are presented in section 4.1. Considering the domestic production of concrete and stone wool in Iceland, the results of their environmental impacts are presented in section 4.1.1 and 4.1.2, respectively. The significance of emissions from transportation needed from source country to Iceland and from seaport to the construction site (stage A4) was estimated in section 4.2. The results of GWP impacts per one square meter from building elements (two types of roof and three types of wall) are presented in section 4.3. The overall estimated GWP impact per one sqm of gross floor area is validated by a comparison with literature in section 4.4. Finally, section 4.5 provides an overall discussion on results.

4.1 Overall environmental impacts

The overall environmental impacts of construction materials used for the structure of Vættaskóli-Engi school building (including the transportation), on GWP, ODP, HT, AP and EP are 1490 ton CO2 eq, 0.0305 kg CFC 11 eq, 0.262 CTUh, 5.5 kmol of H+ equivalent, 13 kmol of N eq, respectively. Table 8 shows the overall environmental impacts per one square meter of gross floor area by impact categories.

Table 8: The results of environmental impacts per one sqm of school building by impact categories

Impacts categories	Total impacts per one sqm	Unit
Global warming potential (GWP)	2.98E+02	$kgCO_2$-eq/sqm
Ozone depletion potential (ODP)	6.11E-06	kg CFC 11 eq/sqm
Human Toxicity (HT)	5.24E-05	CTUh /sqm
Acidification (AP)	1.10	Mole of H+ eq /sqm
Eutrophication (EP)	2.56	Mole of N eq/sqm

The contributions of construction materials to environmental impacts are compared. Figure 17 presents the significance of construction materials in environmental impacts including GWP, ODP, HT, AP and EP.

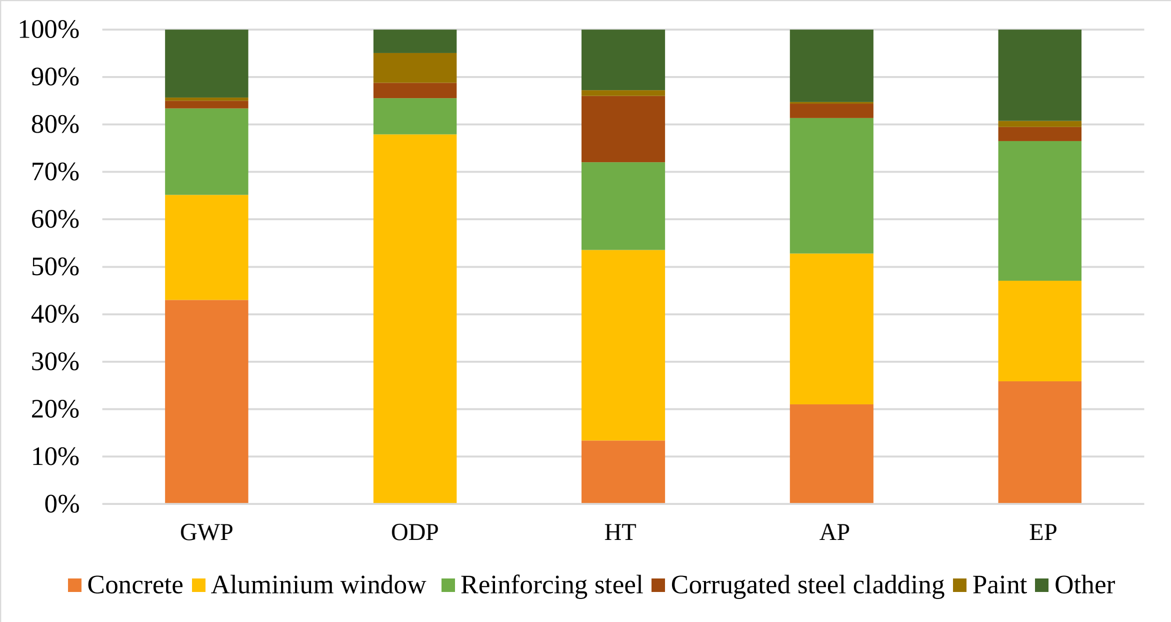

Figure 17: Environmental impacts by construction materials used in Vættaskóli-Engi building[3]

Because concrete, aluminum windows and reinforcing steel represent in total between 70%-85% of total environmental impacts, reducing their usage would have high-yield results for the building's overall environmental impacts.

As expected, concrete, aluminum windows and reinforcing steel and represent 43%, 22% and 17% of total GWP impact from school building, respectively. It should be noted that the main component of concrete is cement, and it represents over 95% of total CO_2 emission from concrete. Regarding the ODP impact, the impact of concrete is too low. In section 5.2, the uncertainty analysis was performed regarding the ODP impacts from concrete. Aluminum windows are the major contributor to HT and AP impacts accounting for 40% and 32% of total HT and AP impacts, respectively. Reinforcing steel and concrete are found to be the main sources of eutrophication by 27% and 26%.

The detailed information for overall environmental impact assessment of construction materials including transportation is given in appendix B1.

4.1.1 Concrete

To validate the results from the developed model for concrete, a comparison was done with the values in GaBi database for 1 kg of concrete produced in Germany and China. The main source of differences in terms of environmental impacts is expected to be the emission intensity of electricity generation in each country. However, because the electricity consumption is not significant in the concrete production process, the differences in impacts across different countries is anticipated to be minor. The estimated impact for concrete produced in Iceland was the same as the one in Germany and only 2% lower than the one in China.

[3] The group of "Other" includes plywood board, underroof memberane, glulam, stone wool, PEHD, plaster, EPS and XPS.

According to figure 17, concrete is the main contributor for GWP impact, therefore it was decided to focus on the materials that are used to produce it. Table 9 presents the results of the developed model on GWP, ODP, HT, AP and EP impacts. The scope of model includes A1-A3 modules. Therefore, the impacts reported for transportation in table 9, refer to transportation to the concrete factory (A2) and the impacts from transportation from the factory to the construction site (A4) is given in table 11.

Table 9: Total impacts from material and energy consumed for the production of 1 kg of concrete in Iceland

	Quantity	**Unit**	**GWP (kg CO_2 eq.)**	**ODP (kg CFC 11 eq.)**	**HT (Mole of H+ eq.)**	**AP (CTUh)**	**EP (Mole of N eq.)**
Cement (CEM I 32.5)	0.1334	Kg	1.08E-01	1.03E-12	4.84E-09	1.76E-04	4.65E-04
Sand	0.3781	Kg	9.73E-04	5.10E-14	4.22E-10	6.14E-06	2.60E-05
Gravel	0.4092	Kg	9.46E-04	2.93E-13	4.53E-10	7.87E-06	2.88E-05
Concrete admixtures-plasticizer	0.0013	Kg	2.37E-03	3.61E-13	4.48E-11	3.67E-06	7.76E-07
Diesel	4.60E-04	L	1.95E-04	5.99E-15	3.61E-10	1.66E-06	4.22E-06
Electricity	8.90E-06	MJ	4.90E-08	5.56E-20	4.50E-16	1.69E-11	5.95E-11
Transportation (Truck)	100	Km	5.16E-04	0.00E+00	3.88E-16	7.66E-06	4.92E-05
Total			1.13E-01	1.74E-12	6.12E-09	2.03E-04	5.74E-04

4.1.2 Stone wool

The total environmental impacts for each impact categories for producing 1 kg of stone wool are presented in table 10. The scope of model includes A1-A3 modules. Therefore, the impacts reported for transportation in table 10, refer to transportation to the stone wool factory and the impacts from transportation from the factory to the construction site (A4) is given in table 11.

Table 10: Total impacts by material and energy consumption for 1 kg of stone wool produced in Iceland

Components	Quantity	Unit	GWP (Kg CO_2 eq.)	ODP (Kg CFC 11 eq.)	HT (Mole of H+ eq.)	AP (CTUh)	EP (Mole of N eq.)
Gravel (2/32)	0.82	Kg	1.90E-03	5.88E-13	9.09E-10	1.58E-05	5.76E-05
Sea shell sand	0.22	Kg	1.65E-01	1.04E-12	1.35E-08	4.99E-05	1.88E-04
Olivine	0.1	Kg	1.17E-03	6.14E-14	5.07E-10	7.38E-06	3.13E-05
Alumina	0.05	Kg	4.40E-04	4.98E-14	1.79E-11	2.30E-06	4.30E-06
Phenol	0.05	Kg	8.91E-02	6.60E-12	4.16E-09	2.61E-04	5.70E-04
Three-Layer panels laminated wood	0.04	Kg	4.92E-03	9.51E-14	9.19E-09	8.67E-05	3.39E-04
Plastic	0.015	Kg	5.75E-02	2.69E-12	1.58E-08	1.07E-04	2.82E-04
Urea formaldehyde resin in- situ foam	0.008	Kg	2.54E-02	9.68E-13	3.82E-09	1.10E-04	4.35E-04
Ammonia	0.007	Kg	1.93E-02	1.05E-12	6.19E-11	9.81E-06	2.75E-05
Electricity	7.92	MJ	4.36E-02	4.95E-14	4.01E-10	1.51E-05	5.30E-05
Transportation (Bulk and Truck)		Km	3.31E-02	1.13E-13	7.08E-09	4.59E-04	2.09E-03
Total			4.33E-01	1.33E-11	5.34E-08	1.05E-03	3.45E-03

To validate our analysis, the estimated GWP impact of 1 kg of stone wool was compared in figure 18, with the findings of UK (Hammond & Jones 2008), Average EU (Steinull) and Germany (GaBi 6.0 database).

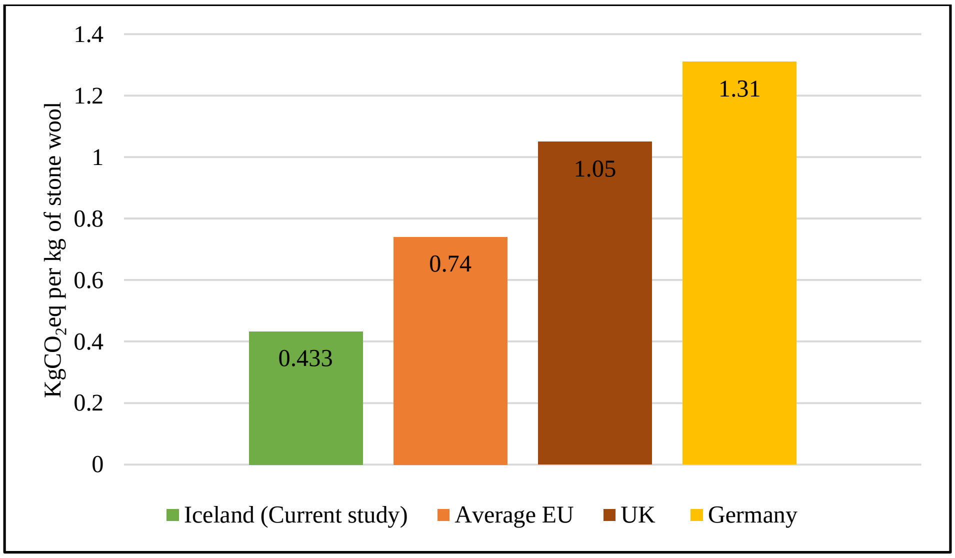

Figure 18: Comparison of GWP impact per 1 kg of stone wool

According to figure 18, the GWP impact of stone wool produced in Iceland (0.433 kg.CO_2 kg-eq) is much lower compared to the other studies. This differences is due to the significant consumption of electricity in the stone wool production process in Iceland. Considering the low CO_2-emitting electricity generation in Iceland, the production of 1 kg of stone wool in Iceland emits 60% less compared to the similar process in Germany and UK.

4.2 Transportation

In this section, the focus is on environmental impacts from transportation needed from source country to Iceland and from seaport to the construction site (A4). Table 11 presents the transportation distances (shipping and land) for the construction materials used in Vættaskóli-Engi school building.

Table 11: Transportation of construction materials to Vættaskóli-Engi

Components	Quantities	Unit	Country	Port	shipping [km]	land distance [km]
Reinforcing steel	175000	Kg	Lithuania	Tallinn	3310	547
Reinforcing mat	17197.81	kg	Lithuania	Tallinn	3310	547
Concrete	2505	m³	Iceland			6
Glued laminated timber	15.42	m³	Norway	Fredrikstad	2910	62
Corrugated steel cladding	1.692	m³	Finland	Kotka	3460	162
Stone wool	12.3	m³	Iceland			280
Hard pressed, stone wool	306.75	m³	Iceland			280
lightweight, stone wool	234.35	m³	Iceland			280
Polyethylene High density	0.115	m³	Germany	Hamburg	2450	362
Gypsum plaster board	8908	m²	Denmark	Aarhus	2300	262
Aluminum window	670.09	m²	Germany	Hamburg	2450	362
Expanded Polystyrene	210	m³	Germany	Hamburg	2450	362
Extruded polystyrene	400.5	m³	Germany	Hamburg	2450	362
Underroof membrane	2670	m²	Germany	Hamburg	2450	362
Plywood board	13.39	m³	Finland	Kotka	3460	162
Asphalt	3845	m²	Denmark	Aarhus	2300	262
Concrete roofing tile	131.75	m³	Iceland			6
plaster	148.55	m³	Iceland			40
Paint	2.08	m³	Norway	Fredrikstad	2910	62

Different emission factors were found for truck and containership in literature (table 12).

Table 12: Emission factors for truck and containership

	Carbon emission (kg CO_2 eq/ton*km)	Reference
Truck- (32 ton) diesel	0.0330	Ashby 2009
Ship- ocean shipping	0.0150	
Truck diesel driven, Euro 3, cargo, up to 7.5t gross weight	0.1400	GaBi 6
Truck-trailer, diesel driven, Euro 3, cargo, 34 - 40t gross weight	0.0474	
Container ship, heavy fuel oil driven, cargo, 27500 dwt payload capacity	0.0143	
Containership	0.0327	Breiðfjörð 2011

According to Breiðfjörð 2011 study, the GWP impact from containerships is 0.0327 kg CO_2 eq/ton.km, while the value for GWP impact from container ship in GaBi 6.0 is 0.0143 kg CO_2 eq/ton.km. It means that the GHG emissions are almost double. One important reason for higher emission factor for Iceland compared to international shipping might be heavy wind, small cargo and the difficulty of shipping route to Iceland.

Therefore, it was decided to choose the emission factor of 0.0327 kg CO_2 eq/ton.km for containership, according to the specific calculation for Iceland by Breiðfjörð (2011). The emission factor for Truck-trailer was found 0.0474 kg CO_2 eq/ton.km according to GaBi 6 database. Table 13 summarizes the emission factors of truck and containership for five impact categories.

Table 13: Environmental impacts assessment for truck and containership

	GWP (kgCO₂/ton*km)	**ODP (kg CFC 11 eq./ton*km)**	**HT (CTUh/ton*km)**	**AP (Mole of H+ eq./ton*km)**	**EP (Mole of N eq./ton*km)**
Truck-trailer, diesel driven, Euro 3, cargo, 34 - 40t gross weight	4.74E-02	2.06E-13	1.24E-08	4.45E-04	2.38E-03
Container ship, based on the 70% efficiency of containers	3.27E-02	1.32E-13	6.58E-10	1.23E-03	3.27E-03

The overall environmental impacts from transportation of construction materials to construction site (A4) on GWP, ODP, HT, AP and EP are 45 ton CO_2 eq, 1.8E-07 kg CFC 11 eq, 3.31E-03 CTUh, 1413 Mole of H+ eq, 4019 Mole of N eq. Figure 19 illustrates the contributions of materials and transportation (A4) across impact categories.

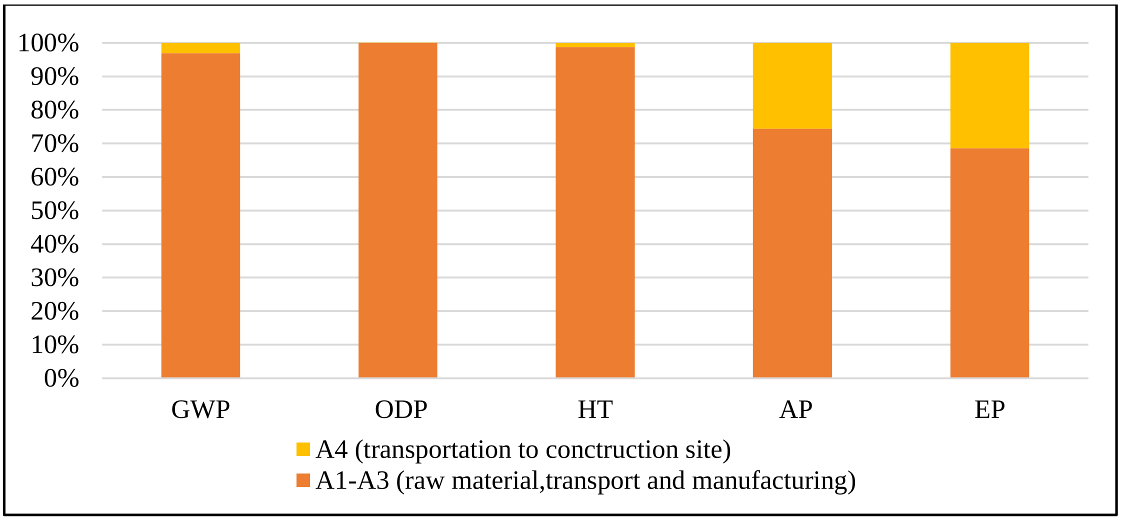

Figure 19: The contributions of materials and transportation in each impact category [4]

[4] Modules A1-A4 are defined in the standard EN 15804. A1-A3 cover raw material extraction, transportation to manufacturing site and manufacturing of construction materials and A4 include transportation to the construction site.

According to figure 19, the share of transportation varies significantly across five impact categories. Transportation represent 25.6% and 31.4% of total acidification and eutrophication impacts, respectively, while the impacts of transportation on other impact categories are insignificant (less than 5%).

Table in appendix B3 provides detailed information about the environmental impacts associated with transportation from manufacturing site to Vættaskóli-Engi school (A4 stage).

4.3 Building elements

In this section, the impacts of each building element (two types of roof and three types of wall) is estimated using the impact factors from GaBi and SimaPro databases. However, it should be noted that the results of this estimation shall not be interpreted as a suggestion for changing the material composition of each element, mainly because there are many factors that should be considered such as technical feasibility and cost. Techno-economic evaluation of alternative materials is out of the scope of this study. Due to the importance of global warming potential impact, the results on GWP impacts per one square meter of building elements are analyzed (tables 14-18).

In the following section, the GWP impacts from the materials used for the construction of building elements are studied[5]. The functional unit of the results in table 14 is one square meter of roof type 1. According to table 14, the main contributors to GWP impact from insulated pitched roof with glulam frame are corrugated steel (52%) and plywood (24%).

Table 14: GWP impacts from Roof Type 1- Insulated pitched roof with glulam frame[6]

Components	Density (kg/m^3)	Embodied GWP ($kg\ CO_2\ eq/m^2$)	GWP from Transportation ($kg\ CO_2\ eq/m^2$)	Total GWP
Glulam	515	6.51	1.09	7.60
Stone wool (200 mm)	80	2.56	0.04	2.60
Roof felt asphalt		0.37	0.05	0.42
corrugated steel (0.6 mm)	7850	22.28	1.57	23.85
Plywood	575	9.22	1.83	11.05
			$kg\ CO_2$ eq/sqm	45.51

The GWP impacts from the materials used for the construction of roof type 2 are reported[7] in table 15 and the functional unit is one square meter of roof type 2. According to table 15, the main contributors to GWP impact from roof type 2 are concrete plus concrete tiles (70%) and XPS (14%).

[5] It includes the embodied emissions and transportation
[6] The impacts of sound insulation with aluminium foil and construction plastic are not included.
[7] It includes the embodied emissions and transportation, while the fasteners are excluded.

Table 15: GWP impact from Roof type 2- upside down (wet insulation)[8]

Components	**Density (kg/m³)**	**Embodied GWP (kg CO_2 eq/m²)**	**GWP from transportation (kg CO_2 eq/m²)**	**Total GWP**
Steel reinforcement	7850	6.17	0.46	6.63
Concrete, S250	2248	40.64	0.10	40.75
Concrete screed	1900	10.37	0.10	10.48
XPS, 150 mm	32	13.01	0.32	13.33
Sand, 30mm thickness	1602	0.12	0.068	0.19
Concrete tiles	2100	24.15	0.03	24.18
Painting	1350	0.96	0.02	0.98
Plaster, 10 mm	2000	4.18	0.04	4.22
Asphalt membrane layer		1.93	0.06	1.99
			kg CO_2 eq/sqm	102.74

The GWP impacts from the material and transportation phase for the material used for the construction of wall type 1 are reported in table 16 and the functional unit is one square meter of wall type 1. To analyze the GWP impact from type 1 wall, the impacts from battens and fasteners are not included. According to table 16, the main contributors to GWP impact from wall type 1 are concrete (72%), corrugated steel (12%) and steel reinforcement (9%).

Table 16: GWP impacts from wall type 1- Cast in place reinforced concrete wall insulation outside and corrugated cladding steel[9]

Components	**Density (kg/m³)**	**Embodied GWP (kg CO_2 eq/m²)**	**GWP from transportation (kg CO_2 eq/m²)**	**Total GWP**
Stone wool (100 mm)	80	3.46	0.11	3.57
Concrete (200 mm)	2248	50.80	0.13	50.93
Steel reinforcement	7850	6.17	0.46	6.63
Interior paint	1350	0.96	0.02	0.98
corrugated steel (0.6 mm)	7850	8.10	0.37	8.47
			kg CO_2 eq/sqm	70.59

The GWP impacts from materials used in wall type 2 are listed[10] in table 17 and the functional unit is one square meter of wall type 2. According to table 17, the main contributors to GWP impact from wall type 2 are concrete (72%) and plaster (12%).

[8] The impacts of fasteners, slab formworks and supports, drainage layer and soil cover are not included
[9] The impacts of fasteners and battens are not included.
[10] It includes the embodied emissions and transportation

Table 17: GWP impacts from wall type 2- Reinforced concrete wall insulated outside with stone wool insulation sheets[11]

Components	Density (kg/m³)	Embodied GWP (kg CO_2 eq/m²)	GWP from transportation (kg CO_2 eq/m²)	Total GWP
Plaster (20 mm)	1600	6.82	0.08	6.90
Stone wool (100 mm)	80	3.46	0.11	3.57
Concrete (200 mm)	2248	50.80	0.13	50.93
Steel reinforcement	7850	6.17	0.46	6.63
Interior paint	1350	0.96	0.02	0.98
			kg CO_2 eq/sqm	70.56

The GWP impacts from materials used in interior wall "type 3" are reported[12] in table 18 and the functional unit is one square meter of wall type 3. According to table 18, the main contributor to GWP impact from wall type 3 is plasterboard (88%).

Table 18: GWP impact from wall Type 3- Gypsum wall

Components	Density (kg/m³)	Embodied GWP (kg CO_2 eq/m²)	GWP from transportation (kg CO_2 eq/m²)	Total GWP
Double Gypsum plasterboard	800	4.26	1.18	5.44
Stone wool (50 mm)	32	0.69	0.02	0.71
			kg CO_2 eq/sqm	6.15

4.4 Validation of GWP impact assessment

In order to validate the analysis, it was decided to compare the estimated GWP impact per one square meter of gross floor area from A1-A3 modules with previous studies (figure 20). In fact, it is challenging to compare one LCA study to another, mainly because of inherent boundary issues with LCA studies. Therefore, before discussing the comparative results, it's necessary to argue the system boundaries and functional units of previous studies.

In the LCA study by Thiel et al. (2013), the functional unit was the entire CSL building. The system boundary covered material extraction, product processing and manufacturing, while transportation of the building materials to the construction site, construction waste, and materials used for construction itself were excluded. Besides, Thiel et al. (2013) did not include landscaping elements: interior finishes such as carpet tiling and paints. On the other hand, they assessed the GWP impacts from the production of the photovoltaic (PV) panels[13] and the geothermal heat wells.

The life-cycle phases covered in Junnila et al, (2003) and in Junnila et al, (2006) are identical, which included materials manufacturing, construction, use, maintenance, and end of life. Each life-cycle phase accounted for the transportation of materials. Transportation

[11] The impacts from fasteners and sparkling compound are not included.
[12] It includes the embodied emissions and transportation
[13] The PV panels do not include the mounting and monitoring systems and the associated materials with those PV system parts.

to the wholesaler's warehouse was included in the building materials phase. Junnila et al, (2003) assessed the impacts from the substructure, foundation, structural frame, external envelope, roof, internal complementary elements (e.g., doors, partition walls, suspended ceilings and railings), internal surfaces, elevators, mechanical services, and electrical services. The categories not included in the study were the construction site (e.g., fence and lighting) and internal equipment (e.g., refrigerators in the building's lunch areas).

Kofoworola et al, (2008) defined the functional unit as 60,000 m^2 gross floor area of building and the entire life cycle of the office building are included[14], whereas transportation for each stage was also covered. Only the major construction components such as concrete, structural steel, reinforcing steel, and bricks that are used in the structure and envelope of the selected building are assessed, while the potential of renewable energy use (on-site electricity generation with photovoltaic or solar hot water), indoor air quality issues (off-gassing from paints and flooring, and cleaning materials) during the use phase, water consumption and water effluents, and, future technological breakthroughs were excluded.

The boundary of the quantitative analysis performed by Robertson et al, (2012) was cradle-to-construction site gate and encompassed foundation, the structural support system and the building enclosure. The environmental burdens associated with each building product were considered from raw materials acquisition, through the manufacture/processing stages, accounting for the production and use of fuels, electricity, and heat, as well as taking into account transportation/distribution impacts at all points along the product supply chain.

Biswas et al. (2014) employed a 'mining to use' approach, which was limited to three stages: the supply of construction materials, the construction stage and finally the usage stage. The 'supply of construction materials' stage covered mining, processing, and production of construction materials (e.g., concrete, steel, glass) along with transportation to the construction site. The 'construction stage' consisted of construction process, including fencing, site-clearing, excavation and filling, installation of a tower crane, concrete pouring, pre-casting, shuttering and mortar preparation. The 'usage stage' included end use appliances within the building, including lighting, computing, office and kitchen equipment, air conditioning, lifts, fans and heating.

Based on this thorough review on the system boundaries and functional units of previous studies, it was observed that the system boundary of the current study is limited compared to the literature. However, it was decided to make a comparison between the estimated GWP impacts from Vættaskóli-Engi school building and other building LCAs (figure 20). It should be noted that the impacts from materials required for temporary construction or maintenance are not included in this comparison. The results are shown in kg-CO_2eq per one m^2 area of each building, not by the lifespan of the materials. The aggregate GWP impacts were available for Robertson (2012) and Biswas (2014).

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[14] Manufacturing of building materials, construction, operation, maintenance, and demolition

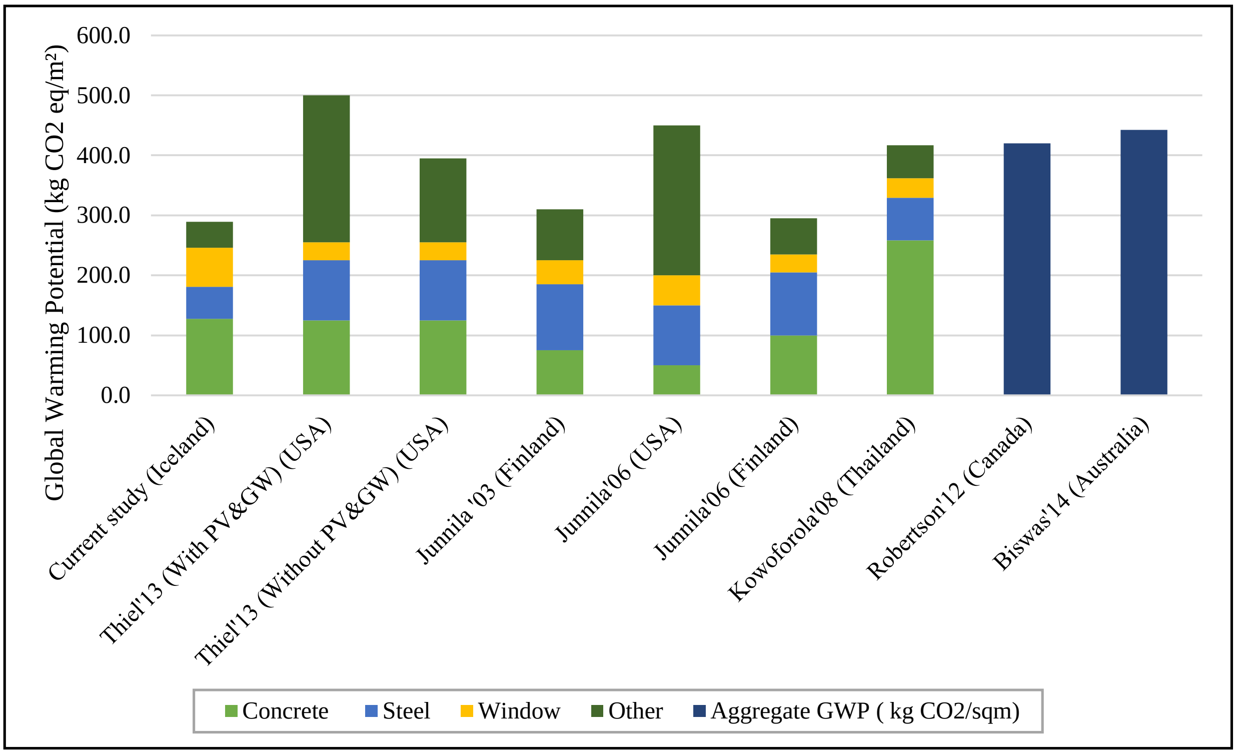

Figure 20: GWP impacts per square meter of Vættaskóli-Engi school building compared with similar LCA studies.
(PV = Photovoltaic & Inverters; GW = Geothermal Wells)

Considering figure 20, the estimated GWP per one square meter of Vættaskóli-Engi school building is comparable to other case studies. Comparing the GWP impacts from "Other" materials group across LCA studies, it can be seen that the scope of this work is limited compared to the other case studies. In all cases, concrete and steel accounted for significant share of total GWP, ranging from 11% to 62% for concrete and 17% to 36% for steel.

Based on the Theil et al (2013), it can be seen that including PV panels and geothermal wells has increased the GWP impact per sqm by 25%. Their results show that PV panels and inverters account for approximately 16% of the total GWP, while the geothermal wells account for 5% of the total GWP for the CSL building.

4.5 Discussion

The aim of this study was to estimate the total environmental impacts from construction materials used in the Vættaskóli-Engi school building during four modules of A1-A4 as defined in the standard EN 15804. The impact categories include global warming, ozone depletion potential, human toxicity, acidification and eutrophication. In this section, the results are briefly discussed.

The total GWP impact of A1-A3 is 1445 ton CO_2eq which is equal 289 KgCO_2eq/sqm, which is comparable to previous studies according to figure 20. Because concrete, aluminum windows and reinforcing steel represent in total between 70%-85% of all impact categories, it’s necessary to study the alternative options to reduce their impacts.

The main component of concrete is cement, and it represents over 95% of total CO_2 emission from concrete. As a results, the Cement Sustainability Initiative (OECD/IEA and World Business Council for Sustainable Development, 2009) suggests three pathways to reduce the environmental impacts of the concrete industry by promoting efficient technologies for new and existing production plants, increasing awareness of alternative fuels and encouraging clinker substitution. Fly ash, Blast furnace slag and silica fumes are three well known examples of cement replacement materials that are in use today that, like Ordinary Portland Cement (OPC). These are by-products of coal combustion, iron smelting and electric arc furnace production of elemental silicon or ferro silicon alloys, respectively (Imbabi, et al. 2013). Alkali-activated cements (AACs) are also competitive with OPC in performance and cost, and their production emits 95% less CO_2 than OPC (if the NaOH and KOH required are assumed to be carbon free) (Bondar, 2007). Besides, research is underway to develop a magnesium based cement that absorbs more CO_2 than it produces during the manufacturing process (Biello, 2008).

In fact, the use of low-carbon cements and concretes as an alternative to current materials looks promising. Mainly because they are useable and perform well both short term and long term; there is sufficient information validating the capabilities of the product so that they meet engineering standards for specific functions, ranging from the making of cavity blocks to ready mix for in situ casting of foundations. Besides, there is sufficient raw material that can be transported in bulk to processing plants (Hendriks et al., 1999).

According to Fischedick et al, (2014), in addition to CO_2 emissions resulting from electrode and reductant use, the production of aluminum result in the emission of high-global warming potential GHGs, for example PFC[15]. To reduce the environmental impacts, the reaction can be minimized by controlling the process to prevent a drop in alumina concentrations, which triggers the process. Increasing the recycling rate is expected to be beneficial as well.

Regarding the steel, the coal and coke consumed in conventional iron-making is emissions intensive and where economic and practicable, switching to gas-based direct reduced iron (DRI) and oil and natural gas injection has been done. However, DRI production currently occurs at smaller scale than large blast furnaces (Cullen et al., 2012), and any emissions benefit depends on the emissions associated with increased electricity use for the required

[15] Perfluorocarbons

electric arc furnace (EAF) process. Charcoal, another coke substitute, is currently used for iron-making, notably in Brazil (Taibi et al. 2011; Henriques Jr. et al., 2010). Other substitutions include use of ferro-coke as a reductant (Takeda et al., 2011) and the use of biomass and waste plastics to displace coal (IEA, 2009).

Considering the domestic production of stone wool in Iceland, the results of this study confirms a great potential of 60% in reducing the GWP impacts from stone wool, when produced in Iceland, due to the low CO_2-emitting electricity generation in Iceland.

This analysis shows that the share of transportation (stage A4 of life cycle) varies significantly across five impact categories and it represents 25.6% and 31.4% of acidification and eutrophication impacts, respectively, while the impacts of transportation on the other impact categories are insignificant (less than 5%).

To assess the environmental benefits of domestic production of construction materials, the significance of impacts from transportation and electricity are crucial. It’s expected that the transportation would be somewhat reduced especially if the raw materials are available, but whenever electricity plays a major role, the impact reduction from Icelandic production might be significantly higher.

5 Aspects concerning sensitivity and uncertainty

The results of a LCA study can be affected by several uncertainty sources, mainly due to the methodological choices, the initial assumptions, i.e. allocation rules, system boundaries, impact assessment methods, and the quality of the available data (Cellura et. al., 2011).

There is another key motivation to analyze the sensitivity of the impacts assessment, which is the capability of LCA tool to support decision-makers. For that purpose, the information is needed on the robustness of the results. In the sensitivity analysis, the influence of variations in process data, model choices are deliberately introduced in order to determine the robustness of the results with regard to these variations (EC-JRC, 2011).

In this chapter, a general argument about the credibility of life cycle analysis and a classification of various sources of uncertainties are given in section 5.1. Section 5.2 provides insights on the key sources of uncertainties identified in this study are presented. Finally, considering the limitation of this work and the identified uncertainty in the assessment results, section 5.3 defined the potential for future developments of this work and similar life cycle analysis.

5.1 Classification of uncertainty sources

Dealing with uncertainty has become a key challenge for integrated assessments (see e.g. Van der Sluijs et al, 2005; Ascough et al., 2008). For most studies, a complete LCA is unaffordable as long as it is not integrated with other tools such as quantity surveying or energy simulation (Kohler and Moffatt, 2003). Huijbregts (1998) classified the types of uncertainties as follows:

- Parameter uncertainty, due to inaccurate, incomplete, or missing values of data needed in the inventory analysis or in the impact analysis.
- Models uncertainty, which depends on the model characteristics, but often due to the adoption of linear models to describe the relationships among environmental phenomena and of aggregate data regarding spatial and temporal features.
- Uncertainty due to unavoidable methodological choices in LCA, such as allocation methods, functional unit, system boundaries, cut-off rules, data collection methods.
- Spatial variability across location and temporal variability over a short and long time scales in the Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA) parameters.
- Variability between sources in LCI (e.g. variation in comparable technical processes) and between objects of the assessment in LCIA (e.g. human characteristics).

5.2 Insights from uncertainty Analysis

Based on the five classes of uncertainties identified by Huijbregts (1998) in section 5.1, in this section, the outcome of uncertainty analysis due to uncertainty in parameters, in system boundary, software selection, developed model, chosen methodology and variability between sources are presented.

The life-cycle inventory data for this analysis is collected from various sources, including the map description, building plans, published literature and LCI databases. Despite all efforts to prepare a very precise and comprehensive data inventory, it is important to note that there is inherent uncertainty and variability in these numbers and the environmental impacts are predominantly actually assessed based on average or even case values (Heinonen et al. 2016). For example, there is limited information about the energy consumption and emissions from production process of the imported elements and materials. Therefore, the assessment of imported materials was performed based on the information from GaBi database except for reinforcing steel, alkyd paint, and aluminum window frame, that the impact factors from SimaPro were used. This issue was argued by Zabalza et al. (2011), who strongly suggest extending, adjusting and harmonizing the inventory databases to take differences in construction in different countries into consideration.

According to the ISO 14040, ISO 14041, and ISO/TR 14049 standards, a system boundary is determined by an iterative process in which an initial system boundary is chosen, and then further refinements are made by including new unit processes that are shown to be significant by sensitivity analysis. Considering the complex interdependence of processes in modern economies, compliance with ISO standards on LCA seems practically impossible. Therefore, decisions shall be made regarding which unit processes shall be modeled by the study and the level of detail to which these unit processes shall be studied. In fact, leaving out insignificant inputs and outputs from a system is generally referred to cutoff in LCA. Several criteria are used in LCA practice to decide which inputs to be studied, including a) mass, b) energy and c) environmental relevance. In this study, the limitation of system boundary was defined by including the materials and processes that have significant mass and environmental impact contributions, which can add to the inherent uncertainty in the model. As noted by Suh et al., (2004), there are several difficulties in selecting a system boundary based only on these criteria, for example there is no theoretical or empirical basis that guarantees that a small mass or energy contribution will always result in negligible environmental impacts. Heinonen et al. (2016) analyzed the cutoff impacts of an incomplete assessment from two perspectives of materials and building systems.

Moreover, LCA studies suffer from errors caused by the truncation of the production system boundary (Lenzen, 2000). In LCA practice, truncations are made at production stages of various order, depending on data availability and/or significance. For instance, Treloar (1997) and Lenzen, (2000) simulated the amount of possible truncation in conventional LCI based on the process-flow-diagram approach using input-output analysis techniques. The results show that 31% of total 135 industries had truncation errors of higher than 50% if the upstream inputs from the third tier and beyond are omitted, which indicates that important contributions may lie in far upstream inputs and cutting them off may result in a significant underestimation.

The other main source of uncertainty is the software selection. In a recent study, Herrmann and Moltesen (2015) compared the results of an LCA using SimaPro and GaBi, with a random sample of 100 unit processes. They found that although most of the results are practically identical, some differences, in particular for impact assessment, are so large that they could influence the conclusions drawn from the LCA. These differences come primarily from differences or errors in the databases of the two LCA software programs, which makes them very challenging to find for ordinary or even skilled LCA software users.

In this study, GaBi was used mainly because it is one of the leading software tools for life cycle assessments and it has one of the largest LCA databases worldwide (PE-International). The other reason was that the extension database XIV, which includes detailed information on construction materials was accessible for this research. However, there were a few issues regarding specific model parameters in the GaBi software, which could potentially enlarge to the inherent uncertainty in the model. First, in order to build a model for stone wool, it was required to include basalt sand and sea shells sand. Since, there were not available in the construction database, it was decided to use quicklime and sand as substitute materials to model the production of stone wool in Iceland. Secondly, considering the results of ODP impacts from concrete based on GaBi database, the value was found to be unusually low compared to ODP impact of other materials. So, it was decided to compare the results with SimaPro database. The impact factors per 1 kg of concrete in GaBi and SimaPro are 1.74E-12 and 3.71E-09, respectively. Figure 21 illustrates the significance of construction materials in total ODP impacts, when the ODP impacts from concrete is estimated from these two databases.

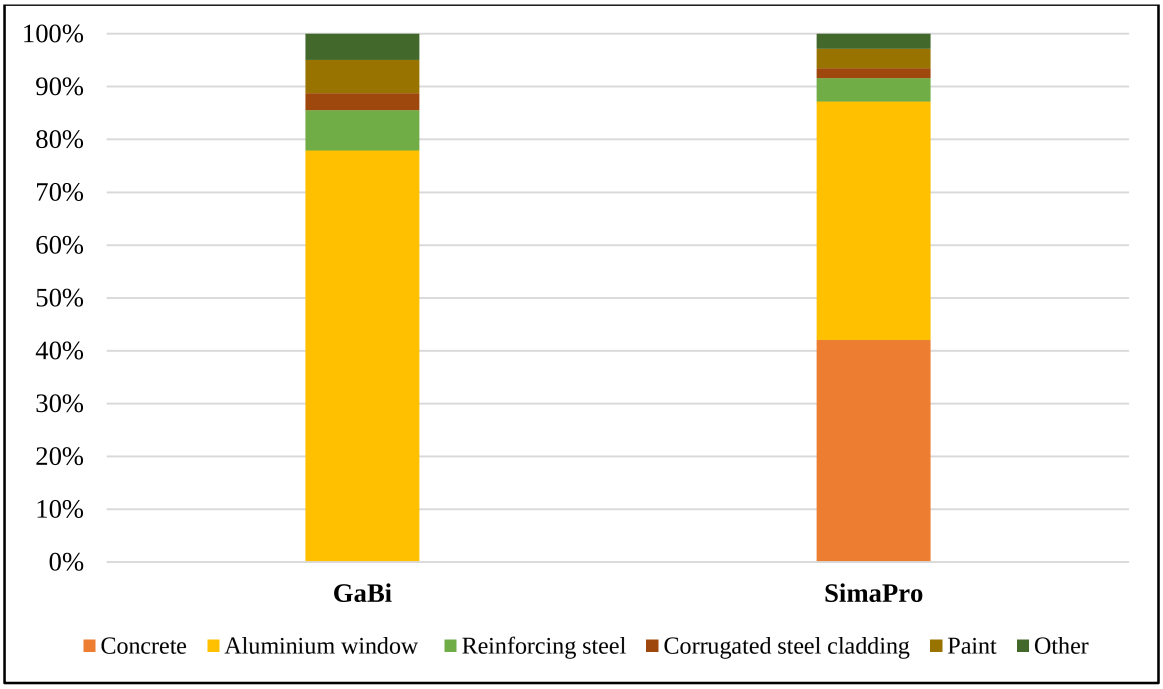

Figure 21: Comparison of material's contribution to total ODP impact using the ODP factor for concrete from GaBi and SimaPro

Based on figure 21, the share of concrete in total ODP based on SimaPro information (42%) is much higher than the value obtained from GaBi database.

5.3 Further developments

Based on the insights from uncertainty analysis, the following steps are proposed to extend this study:

- The first modification step is to extend the data collection phase to enhance the accuracy of inventory dataset in order to minimize the uncertainty from imprecise input parameters, e.g. information about the production process of imported materials.
- To implement a more holistic approach, this analysis could be improved by extending the system boundary in two directions:
    - first, by running a full life-cycle assessment, the so called “cradle to grave” which includes 16 stages;
    - Secondly by estimating other relevant impacts such as land use, soil waste and water consumption.
- Bearing in mind the concept of sustainable built environment, it’s necessary to assess the impacts of using alternative materials or recycled resources.
- Literature review informed us that there is a significant gap in the research in the building sector looking at other impact categories than GWP. Therefore, it’s valuable to use normalization techniques to get a better sense of the risk and threat associated with other impact categories.
- There is a need to apply other LCA tools such as SimaPro for the same case study in order to compare the impacts assessment results. Besides, the advantages and limitation of both tools will be identified.

6 Conclusions

Buildings play a key role in our lives and society as a complex system. Furthermore, the GHGs from the building sector have more than doubled globally since 1970. However, in Iceland, electricity and heat consumed in buildings are produced from low-carbon energy sources (IPCC, 2007). Thus, the predominant share of all the GHGs caused over the lifecycle of a building very likely relate to the GHGs embodied in the materials, which are also imported to Iceland. The goal of this study was to analyze the environmental impacts of materials used in the structure and envelope of the Vættaskóli-Engi building in Reykjavik, Iceland in terms of global warming potential, ozone depletion potential, human toxicity, acidification and eutrophication, during four modules of A1-A4[16], as defined in the standard EN 15804.

The overall environmental impacts of the Vættaskóli-Engi building from four modules of A1-A4 in terms of GWP, ODP, HT, AP and EP are estimated to be 1490 ton CO_2 eq, 0.0305 kg CFC 11 eq, 0.262 CTUh, 5.5 kmol of H+ eq, 13 kmol of N eq, respectively; which are equal to 298 kgCO_2 eq/sqm, 6.11E-06 kg CFC 11 eq/sqm, 5.22E-05 CTUh/sqm, 1.10 Mole of H+ eq/sqm and 2.56 Mole of N eq/sqm. As expected concrete, aluminum windows and reinforcing steel represent in total between 70%-85% of total environmental impacts. The aluminum windows are the major contributor to HT and AP impacts accounting for 40% and 32% of total HT and AP impacts, respectively. Reinforcing steel and concrete are found to be the main sources of eutrophication by 27% and 26%. Based on the results of environmental assessment, reducing the usage of concrete, aluminum windows and reinforcing steel would have high-yield results for the building's overall environmental impacts.

The total GWP impact from A1-A3 modules is 289 KgCO_2eq/sqm, which is comparable to previous studies. In terms of GWP impact, concrete, aluminum windows and reinforcing steel represent 44%, 23% and 18% of total GWP impact, respectively.

To reduce the environmental impacts from concrete, the focus should be on cement production process, considering the result of this analysis on the significant contribution (more than 95%) of cement in total CO_2 emissions from concrete. As a result, the Cement Sustainability Initiative (OECD/IEA and World Business Council for Sustainable Development, 2009) suggests three pathways to reduce the environmental impacts of the concrete industry by promoting efficient technologies for new and existing production plants, increasing awareness of alternative fuels and encouraging clinker substitution such as fly ash, blast furnace slag and silica fumes. To reduce the environmental impacts from aluminum, the production reaction can be minimized by controlling the process to prevent a drop in alumina concentrations, which triggers the process (Fischedick et al, 2014). Regarding the steel, the coal and coke consumed in conventional iron-making process should be substituted with natural gas, charcoal or biomass in order to lower the emissions.

Based on the developed model in GaBi, the environmental impacts of stone wool produced in Iceland, are estimated. Compared to literature, the estimated GWP impact from 1 kg of

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[16] Four modules include raw material extraction (A1), transportation to manufacturing site (A2), manufacturing of construction materials (A3) and transportation to the construction site (A4).

stone wool (0.433 kg.CO_2 kg-eq) was found to be much lower. The main reason is the significant consumption of electricity in the stone wool production, which is generated in hydropower and geothermal plants with very low emissions. It was found that the production of 1 kg of stone wool in Iceland emits between 59-67% less CO_2 compared to the similar process in Germany, UK and EU. The contribution of stone wool on all five impact categories are found to be very low (0.001-1.1%).

Considering the fact that significant share of construction materials are imported to Iceland, it's important to assess the environmental impacts from transportation needed from source country to Iceland and from seaport to the construction site (stage A4). The share of transportation of all impacts varies significantly across five impact categories. It represents 25.6% and 31.4% of acidification and eutrophication impacts, while the impacts of transportation on the other impact categories are insignificant (less than 5%).

Although this research was carefully prepared, I am still aware of its limitations and shortcomings. First of all, it should be noted that, according to the boundary of system defined for this study, I only assessed the environmental impacts of four modules (A1-A4) of whole life cycle stages, as defined in the standard EN 15804, which covers raw material extraction, transportation to manufacturing site, manufacturing of construction materials and transportation to the construction site. To interpret the results, it should be considered that, surface materials, electric systems and plumbing as well as the emissions from the construction work, use stage and end of life were excluded from this analysis. Considering the climate condition in Iceland, it's expected that the share of energy consumption in the construction site is significant. According to Marteinsson, (2002), energy consumption in construction site for a multifamily house was around 1 GJ/m2 floor area, which was around 21% of total energy consumed for construction materials, transportation and in construction site. Other sources of uncertainties including the system boundary selection, software selection, developed model, chosen methodology and variability between sources have been discussed in chapter 5.

Despite the recognized limitation in the developed model, this analysis provides valuable insights regarding the environmental impacts of materials used in the structure and envelope of the Vættaskóli-Engi building. The identification of major contributors to each impact category (global warming potential, ozone depletion potential, human toxicity, acidification and eutrophication), is the first step to detect the most effective mitigation measure. The following steps are proposed to extend this study:

- Extend the data collection phase to enhance the accuracy of inventory dataset in order to minimize the uncertainty from imprecise input parameters, e.g., information about the production process of imported materials.
- To implement a more holistic approach, this analysis could be improved by extending the system boundary in two directions:
    - first, by running a full life-cycle assessment, the so called "cradle to grave" which includes 16 stages;
    - Secondly by estimating other relevant impacts such as land use, soil waste and water consumption.
- Literature review informed us that there is a significant gap in the research in the building sector looking at other impact categories than GWP. Therefore, it's valuable to use normalization techniques to get a better sense of the risk and threat associated with other impact categories.

References

Adalberth, K., Almgren, A., Peterson, E.H., (2001): Life-cycle assessment of four multi-family buildings, International Journal of Low Energy and Sustainable Buildings. 2, pp. 1–21.

Ascough, J.C., Maier, H.R., Ravalico, J.K., Strudley, M.W., (2008): Future research challenges for incorporation of uncertainty in environmental and ecological decision making. Ecol. Model. 219: 383- 389.

Athena Institute, Eco-Calculator. Ontario, Canada.

Aze, T., Barry, J., Bellerby, R.G., Brander, L., Byrne, M., Dupont, S., Gattuso, J.P., Gibbs, S., Hansson, L., Hattam, C., Hauton, C., Havenhand, J., Fosså, J.H., Kavanagh, C., Kurihara, H., Matear, R.J., Mark, F.C., Melzner, F., Munday, P., Niehoff, B., Pearson, P., Rehdanz, K., Tambutte, S., Turley, C.M., Venn, A., Warnau, M. Young, J.R., (2014): An Updated Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity (CBD Technical Series ; 75) / S. Hennige , J. Roberts and P. Williamson (editors) , Montreal, Québec, Canada, Secretariat of the Convention on Biological Diversity, 99 p., ISBN: 92-9225-527-4 .

Aziz, M.A., (2005): Environmental Impact Assessment of Highway Development in T.F. Fwa, the Handbook of Highway Engineering, CRC Press.

Baitz, M., Makishi-Colodel, C., Kupfer, T., Pflieger, J., Schuller, O., Hassel, F., Kokborg, M., Fong L., (2011): GaBi Database and Modelling Principles, PE-International.

Baldursson, F.M., Johannesson, S., (2004): Countervailing Power in the Icelandic Cement Industry, Institute of Economic studies, Working paper series: W04:11, Faculty of Economics and Business Administration, University of Iceland.

Baskar, S., and Baskar, R., (2005): Environmental Assessment and Planning. Introduction to Environmental Sciences, First Edition (Eds. R.S. Khoiyangbam and Navindu Gupta), TERI Press, New Delhi, INDIA, ISBN: 978-8-1-799345- 5-5, 1-623

Bayer, C., Gamble, M., Gentry, R., Joshi, S., (2010): AIA guide to LCA Building in practice, Georgia Institute of Technology, The American Institute of Architects, Washington, DC 20006.

Biello, D., (2008): Cement from CO2: A Concrete Cure for Global Warming? Scientific American.

Billiton Technology BHP; (2012). LISA (LCA in Sustainable Architecture).

Biswas, W.K., (2014): Carbon footprint and embodied energy consumption assessment of building construction works in Western Australia. International Journal of Sustainable Built Environment, pp. 179–186.

Blanchard, S., Reppe, P., (1998): Life Cycle Analysis of a Residential Home in Michigan. Master thesis, University of Michigan

Bondar, D., Lynsdale, C., Ramezanianapour, A., Milestone, N., (2007): Alkali activation of natural pozzolan for geopolymer cement production. International Conference on Sustainable Construction, Materials and Technologies, pp. 313–317.

Boustead, I., (2004): Boustead model V5. 0: operating manual, Boustead Consulting Ltd, UK.

BRE Group. BREEAM. Watford, UK.

BRE Group. Envest 2. Watford, UK.

Building and fire research laboratory, BFRL, BEES 3.0.

United Nations, (1987): Our Common Future - Brundtland Report. Oxford University Press, p. 204.

Cabeza, L., Rincón, L., Vilariño, V., Pérez, G., Castell, A., (2014): Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: a review, Renewable Sustainable Energy Review, 29, pp. 394–416.

Cellura, M., Longo, S., Mistretta, M., (2011): Sensitivity analysis to quantify uncertainty in life cycle assessment: the case study of an Italian tile, Renew. Sustain. Energy Rev. 15 (9) 4697–4705

Ceramic Tile and Stone Consultants, Available at http://www.ctasc.com/, accessed July 2015.

Cullen, J.M., Allwood, J.M., Bambach, M.D., (2012): Mapping the Global Flow of Steel: From Steelmaking to End-Use Goods. Environmental Science & Technology 46, 13048 – 13055. doi: 10.1021 / es302433p, ISSN: 0013-936X.

Curran, M.A. (Ed.), (2012): Life cycle assessment handbook: a guide for environmentally sustainable products. John Wiley & Sons.

Davíðsdóttir, B., Agnarsson, S., (2010): the cost effectiveness of mitigating greenhouse gas emissions in Iceland, ISBN 978-9979-9956-8-5, University of Iceland.

De Schryver, A.M., Brakkee, K.W., Goedkoop, M.J., Huijbregts, M.A.J., (2009): Characterization Factors for Global Warming in Life Cycle Assessment Based on Damages to Humans and Ecosystems. Environmental Science and Technology 43 (6), 1689–1695.

Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC Text with EEA relevance

Dee, N., Baker, J., Drobny, N., Duke, K., Fahringer, D., (1972): Environmental evaluation system for water resource planning (to Bureau of Reclamation, U.S. Department of Interior). Battelle Columbus Laboratory, Columbus, Ohio, January, 188 pages.

Dee, N., Baker, J., Drobny, N., Duke, K., Whitman, I., Fahringer, D., (1973): An environmental evaluation system for water resource planning. Water Resources Research, Vol. 9, No. 3, June, 523-535.

EC-JRC, (2010): ILCD Handbook. Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment, p115.

EC-JRC, (2011): International Reference Life Cycle Data System (ILCD) Handbook – General guide for Life Cycle Assessment – Detailed guidance, European Commission - Joint Research Centre - Institute for Environment and Sustainability, First edition March 2010. EUR 24708 EN. First. Luxembourg: Publications Office of the European Union.

Ecobilan P. TEAM/DEAM. Ecobilan, Price Waterhouse Coopers, Bethesda, MD; (2001).

Ecofys, Fraunhofer Institute for Systems and Innovation Research and Öko-Institut, (2009): Methodology for the free allocation of emission allowances in the EU ETS post 2012, sector report for the lime industry, report for the European Commission, Ecofys, Utrecht, Netherlands.

EN 15804+ A1, Sustainability in construction works – Environmental product declarations – Core rules for the product category of construction products.

EuLA, 2012 EuLA Environmental Data Spreadsheet on 2011 European Lime Association, Brussels, Belgium.

FAO, (1996): Environmental Impact Assessment and Environmental Auditing in the Pulp and Paper Industry, FAO Forestry Paper, No.129, FAO, Rome.

Fischedick, M., Roy, J., Abdel-Aziz, A., Acquaye, A., Allwood, J.M., Ceron, J.P., Geng, Y., Kheshgi, H., Lanza, A., Perczyk, D., Price, L., Santalla, E., Sheinbaum, C., Tanaka, K., (2014): Industry. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer,O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann.

Fischer, C., Werge, M., (2009): EU as a Recycling Society: present recycling levels of municipal waste and construction & demolition waste in the EU. ETC/SCP working paper 2/2009. European Topic Centre on Sustainable Consumption and Production, Copenhagen.

Fruehan, R.J., (1998): The Making, Shaping and Treating of Steel - Steelmaking and Refining Volume, The AISE Steel Foundation.

Georgiadou, M., (2014): Future-proofed energy design approaches for achieving low-energy homes: Enhancing the code for sustainable homes. Buildings, 4, 488–519.

Glued Laminated Timber Association UK 2010 available at www.glulam.co.uk

Goedkoop and Spriensma (2000): Eco-indicator 99, A damage oriented method for lifecycle Impact assessment, methodology report.

Gruiz, K., Meggyes, T., Fenyvesi, E., (2014): Engineering Tools for Environmental Risk Management: 1. Environmental Deterioration and Contamination - Problems and their Management, CRC Press, 478 pages.

Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A. de, Oers, L. van, Wegener Sleeswijk, A., Suh, S., Udo de Haes, H.A., Bruijn, H. de, Duin, R. van, Huijbregts, M.A.J., (2002): Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background. Kluwer Academic Publishers, ISBN 1-4020-0228-9, Dordrecht, 692 pp

Haapio, A., Viitaniemi, P., (2008): A critical review of building environmental assessment tools, Environmental Impact Assessment Review, 7, pp. 469–482.

Habert, G., Arribe, D., Dehove, T., Espinasse, L., Le Royc, R., (2012): Reducing environmental impact by increasing the strength of concrete quantification of the improvement to concrete bridges. J. Clean. Prod. 35, 250-262.

Hammond, G.P., Jones, C.I., (2008): Embodied energy and carbon in construction materials. Proceedings of the Institution of Civil Engineers - Energy, 161 (2), pp. 87-98

Heijungs, R., Guinée, J., Huppes, G., Lankreijer, R.M., Udo de Haes, H.A., Wegener Sleeswijk, A., Ansems, A.M.M., Eggels, P.G., van Duin, R., de Goede, H.P., (1992): Environmental Life Cycle Assessment of products. Guide and Backgrounds. Centre of Environmental Sciences (CML), Leiden University, Leiden.

Heinonen, J., Säynäjoki, A., Junnonen, J., Pöyry, A., Junnila, S., (2016): Pre-use phase LCA of a multi-story residential building: Can greenhouse gas emissions be used as a more general environmental performance indicator?. Building and Environment, 95, Pages 116–125. doi:10.1016/j.buildenv.2015.09.006

Henriques Jr, M.F., Dantas, F., Schaeffer, R., (2010): Potential for reduction of CO2 emissions and a low-carbon scenario for the Brazilian industrial sector. Energy Policy 38, 1946 – 1961. doi: 10.1016 / j.enpol.2009.11.076, ISSN: 0301- 4215.

Herrmann, I.T., Moltesen, A., (2015): Does it matter which Life Cycle Assessment (LCA) tool you choose? – a comparative assessment of SimaPro and GaBi. Journal of Cleaner Production, 86, 163–169. doi:10.1016/j.jclepro.2014.08.004

Huijbregts, M.A.J., (1998): Application of uncertainty and variability in LCA. Part I. A general framework for the analysis of uncertainty and variability in life cycle assessment. International Journal of LCA; 3(5):273–80.

HEIG-VD, (2012): ECO-BAT eco balance assessment tool. 09/01.

Hendriks, C.A., Worrell, E., Price, L., Martin, N., Ozawa Meida L., de Jager, D., Riemer, P., (1999): Emission Reduction of Greenhouse Gases from the Cement Industry, Greenhouse Gas Control Technologies, Cairns, Australia.

Hofstetter, P., (2002): United States. Environmental protection agency. Office of research and development, National Institute of Standards and Technology (US), User preferences for life-cycle decision support tools: evaluation of a survey of BEES Users.

IEA (2009): Energy Technology Transitions for Industry. Strategies for the Next Industrial Revolution. International Energy Agency, Paris.

IEA (2012): Tracking Clean Energy Progress. Energy Technology Perspectives 2012, Excerpt as IEA Input to the Clean Energy Ministerial. Paris, France, 82 pp.

IEA, (2013): Transition to Sustainable Buildings: Strategies and Opportunities to 2050, Paris, France.

Imbabi, M.S., Carrigan, C., McKenna S., (2013): Trends and developments in green cement and concrete technology, International Journal of Sustainable Built Environment, vol 1, issue 2, pp. 194–216.

International Standard 14040: (2006a) Environmental management- Life cycle assessment: Principles and framework. ISO14040, Geneva

International Standard 14041: Environmental management-Life cycle assessment-goal and scope definition and inventory analysis; International Organization for Standardization (ISO): Geneva, Switzerland, 1998.

International Standard 14044: (2006b) Environmental management—Life cycle assessment: Requirements and Guidelines. ISO14044, Geneva

International Standard ISO/TR 14049: Environmental management-Life cycle assessment-Examples of application of ISO 14041 to goal and scope definition and inventory analysis; International Organization for Standardization (ISO): Geneva, Switzerland, 2000.

IPCC, 2007 Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Geneva: IPCC)

IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582 pp.

JRC / PBL (2013): Emission Database for Global Atmospheric Research (EDGAR), Release Version 4.2 FT2010. European Commission, Joint Research Centre (JRC) / PBL Netherlands Environmental Assessment Agency.

Junnila, S., Horvath, A., (2003): Life-cycle Environmental effects of an office building, Journal of Infrastructure systems, 9 (4), pp. 157–166

Junnila, S., Horvath, A., Guggemos, A.A., (2006): Life-Cycle assessment of office buildings in Europe and the United States. Journal of Infrastructure systems, 12, 10–17.

Kohler, N., Moffatt, S., (2003): Life-cycle analysis of the built environment. UNEP Industry and Environment April – pages 17-21

Kofoworola, O.F., Gheewala, S.H., (2008): Environmental life cycle assessment of a commercial office building in Thailand, International Journal of Life Cycle Assessment, 13, pp. 498–511

Kreissig, J., Kummel, J., (1999): Baustoff-Ökobilanzen. Wirkungsabschätzung und Auswertung in der Steine-Erden-Industrie. Hrsg. Bundesverband Baustoffe Steine + Erden e.V.

Leopold, L.B., Clarke, F.E., Hanshaw, B.B., Balsley, J.R., (1971): A procedure for evaluating environmental impact. Geological Survey Circular 645, Government Printing Office, Washington, D.C. 13 pp.

Lenzen, M., (2000): Errors in Conventional and Input-Output—based Life—Cycle Inventories. Journal of Industrial Ecology, 4: 127–148. doi: 10.1162/10881980052541981

Marteinsson, B., (2002): Materials and energy use in buildings, 9th International Conference on Durability of Building Materials and Components Brisbane Convention & Exhibition Centre, Australia, 17–21 March.

Marteinsson, B., (2013): Assessment of service lives in the design of buildings a development of the factor method, Licentiate thesis, KTH’s Research School – HiG Center of Built Environment, Gävle, Sweden.

McKinsey & Company (2009): Pathways to a Low-Carbon Economy: Version 2 of the Global Greenhouse Gas Abatement Cost Curve.

Minx, J., Baiocchi, G., Peters, G., Weber, C., Guan, D., and Hubacek, K., (2011): A “Carbonizing Dragon”: China’s Fast Growing CO2 Emissions Revisited, Environ. Sci. Technol., 45, 9144–9153.

O′Brien, E., Guy, B., Lindner, AS., (2006): Life cycle analysis of the deconstruction of military barracks: Ft. McClellan, Anniston, AL, Journal of Green Building, 4 pp. 166–183.

Ochoa Franco, L., (2004): Life cycle assessment of residential buildings. Digital dissertations, Colorado State University Libraries (UMI 3161658).

OECD/IEA and the World Business Council for Sustainable Development, (2009): Cement Technology Roadmap.

PE-international, (2015): GaBi: Product Sustainability Software. Version 6.0, Germany.

Peterson EH. (1997): Database and inventory tool for building components and buildings environmental parameters, SBI report 275, Danish Building Research Institute, Denmark.

Phipps. Phipps and Sustianability. Available online: http://phipps.conservatory.org/project-greenheart/green-heart-at-phipps/center-for-sustainable-landscapes.aspx (accessed on 6 December 2015).

PRé Consultants, SimaPro. Amersfoort, the Netherlands.

Ramesh T., Prakash R., Shukla K.K., (2012): Life cycle energy analysis of a residential building with different envelopes and climates in Indian context, Appl. Energ., 89, 193-202.

Rawlinson, S., Weight, D., (2007): Sustainability: Embodied carbon, Building Magazine, 12, pages 88-91.

Robertson, A.B., Lam, F. C. F., Cole, R. J., (2012): A Comparative Cradle-to-Gate Life Cycle Assessment of Mid-Rise Office Building Construction Alternatives: Laminated Timber or Reinforced Concrete. Buildings, 2, 245-270.

Rosenbaum, R. K., Bachmann, T. M., Gold, R. S., Huijbregts, M. A. J., Jolliet, O., Juraske, R., Kohler, A., Larsen, H. F., MacLeod, M., Margni, M., McKone, T. E., Payet, J., Schuhmacher, M., Meent, D., vande, Hauschild, M. Z., (2008): USEtoxsthe UNEP-SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. International Journal of Life Cycle Assessment, 13 (7), 532–546.

Sand, H., Lorenzen, K.H., Nittegaard, CH.B., (2012): Survey of green legislation and standards in the construction area in the Nordic countries (Background Note ISBN 978-82-8277-027-9) Oslo, NO: Nordic Innovation. Retrieved January 15, 2013, from http://nordicinnovation.org/is/ritverk/survey-of-green-legislation-and-standards-in-theconstruction-area-in-the-nordic-countries/

Scheuer, C., Keoleian, G.A., Reppe, P., (2003): Life cycle energy and environmental performance of new university building: modelling challenges and design implications, Energy and Buildings, 35 pp. 1049–1064

Seppälä, J., Posch, M., Johansson, M., Hettelingh, J.P., (2006): Country-Dependent Characterization Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator. The International Journal of Life Cycle Assessment 11 (6), 403 - 416.

Sharma, A., Saxena, A., Sethi, M., Shree, V., Varun, (2011): Life cycle assessment of buildings: a review, Renewable & Sustainable Energy Reviews, 1 pp. 871–875

Sharrard, A.L., Matthews, H.S., Ries, R.J., (2008): “Estimating construction project environmental effects using an input-output based hybrid life-cycle assessment model.” Journal of J. Infrastructure systems, 14(4), 327–336.

Singh, A., Berghorn, G., Joshi, S., Syal, M., (2011): Review of life-cycle assessment applications in building construction, Journal of Architectural Engineering, 1, pp. 15–23.

Sorensen, J.C., Moss, M.L., (1973): Procedures and programs to assist in the environmental impact statement process. Available from Dr. Sorensen, Inst. of Urban and Reg. Development, U. of California, Berkeley, California. 36 pp.

Steinull HF (The Icelandic mineral fiber (rock fiber) insulation factory), Available at http://steinull.is/mineral-fiber-insulation/, accessed July 2015.

Sturgis, S., Roberts, G. (2010): Redefining zero: carbon profiling as a solution to whole life carbon emission measurement in buildings, London, RICS Research Report.

STATSBYGG, (2011): “KLIMAGASSREGNSKAP.NO/ VERSJON 3 - A model for calculation of life cycle greenghouse gas emissions for buildings“, Norwegian government agency.

Suh, S., Lenzen, M., Treloar, G.J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J., Norris, G., (2004): System boundary selection in life-cycle inventories using hybrid approaches. Environmental Science and Technology 38 (3), 657–664.

Taibi, E., Gielen, D., Bazilian, M., (2011): The potential for renewable energy in industrial applications. Renewable and Sustainable Energy Reviews. doi: 10.1016 / j.rser..08.039, ISSN: 1364-0321.

Takeda, K., Anyashiki, T., Sato, T., Oyama, N., Watakabe, S., Sato, M., (2011): Recent Developments and Mid- and Long-Term CO2 Mitigation Projects in Ironmaking. Steel Research International 82, 512 – 520. doi: 10.1002 /srin.201100034, ISSN: 1869-344X.

The European Parliament and the Council of the European Union. Directive 2010/31/EU of the European parliament and of the council on the energy performance of buildings (recast). Official Journal of the European Union 2010, 153, 13–35.

Thiel, C.L., Campion, N., Landis, A.E., Jones, A.K., Schaefer, L.A., Bilec, M.M., (2013): A materials life cycle assessment of a net-zero energy building. Energies; 6:1125–41.

Thormark, C., (2002): A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. Building and environment, 37(4), 429–435.

Tingley, D., Davison, B., (2011): Design for deconstruction and material reuse. Proceedings of the ICE - Energy, 164, 195-204.

Treloar, G.J., (1997): Extracting embodied energy paths from input–output tables: towards an input–outputbased hybrid energy analysis method, Economic Systems Research, 9(4), 375-391.

Trusty, W., Horst, S., (2005): LCA tools around the world, Building Design and Construction pp. 12–16.

Tukker, A., de Koning, A., Wood, R., Hawkins, T., Lutter, S., Acosta, J., Rueda Cantuche, J.M., Bouwmeester, M., Oosterhaven, J., Drosdowski, T., Kuenen, J., (2013): Exiopol – development and illustrative analyses of a detailed global MR EE SUT/IOT. Econ. Syst. Res. 25, 50–70.

Úlfarsson, S.O., (2011): Vistferilsgreining á timbureiningahúsi frá vöggu til grafar University of Iceland, MSc Thesis.

U.S. Green Building Council, 2008. LEED rating systems. Retrieved September. July/15th, 2008.

Van der Sluijs, J., Craye, M., Funtowicz, S., Kloprogge, P., Ravetz, J., Risbey, J., (2005): Combining quantitative and qualitative measures of uncertainty in model-based environmental assessment: the NUSAP system. Risk Anal. 25 (2): 481-492.

VTT 2012 Use and Service Ability of Properties (available at: www.vtt.fi/research/technology/use and service ability of properties.jsp?lang=en, accessed 10 July 2012)

Wang, S., (2007): Life Cycle Assessment of Residential Building Energy Consumption in Severe Cold Region. Master thesis, Harbin Institute of Technology

Warner, M. L., Preston, E.H., (1973): Review of environmental impact assessment methodologies. Battelle Columbus Labs, Columbus, Ohio.

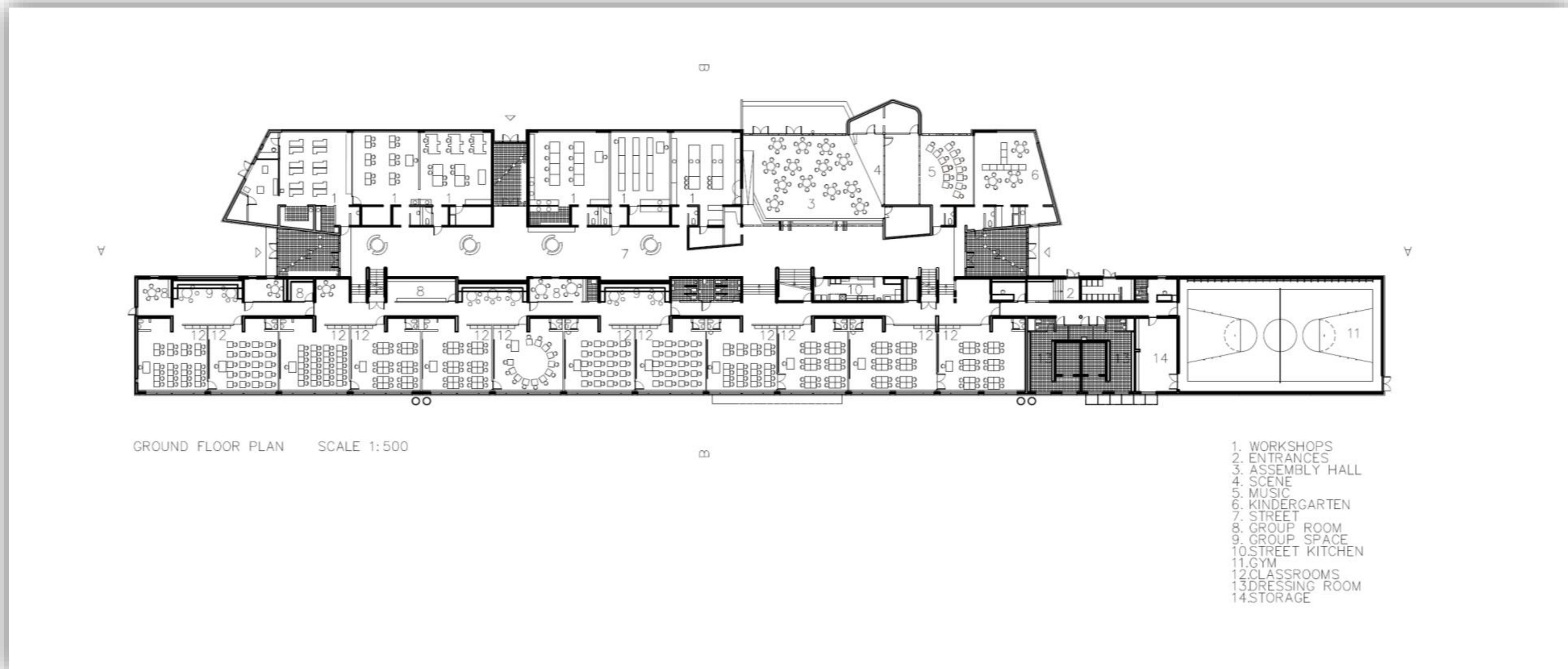
Westman, W.E., (1985): Ecology, Impact Assessment and Environmental Planning. John Wiley & Sons, Toronto, Ont.

World Meteorological Organization (WMO), 2011, Executive Summary: Scientific Assessment of Ozone Depletion: 2010, 46 pp., Geneva, Switzerland.

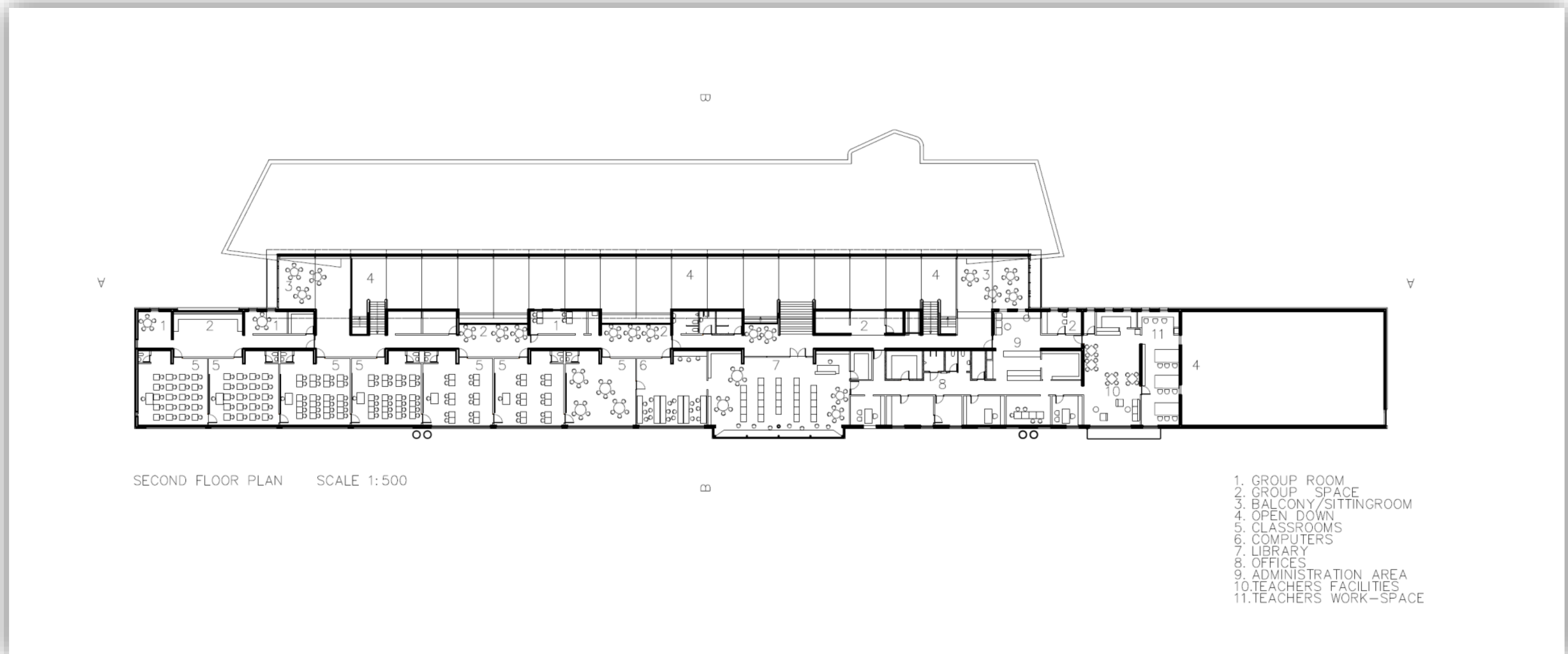
World Steel Association (2011): Life cycle assessment methodology report methodology report, ISBN 978-2-930069-66-1, Brussels, Belgium.

Appendix

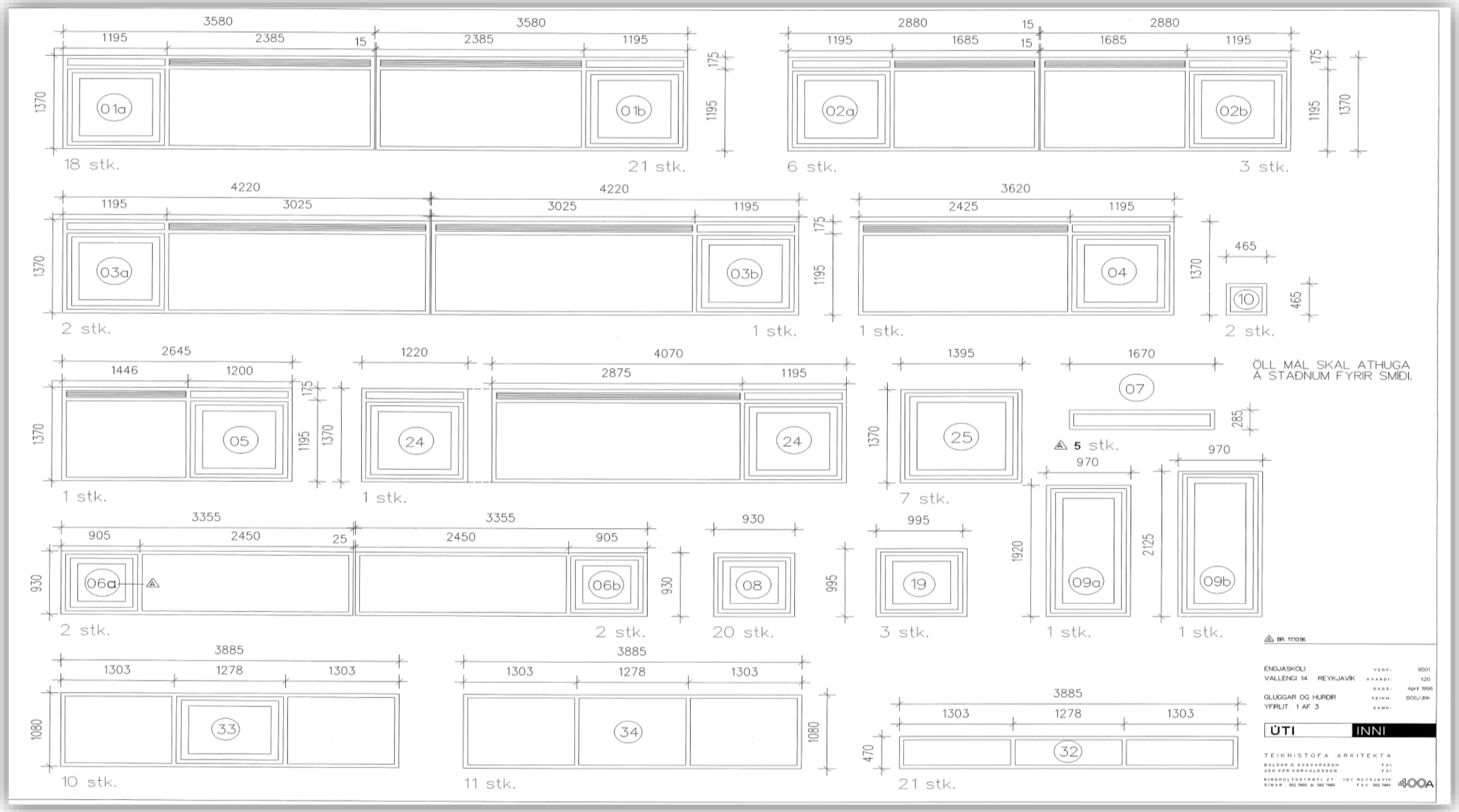
A1. Ground floor plan



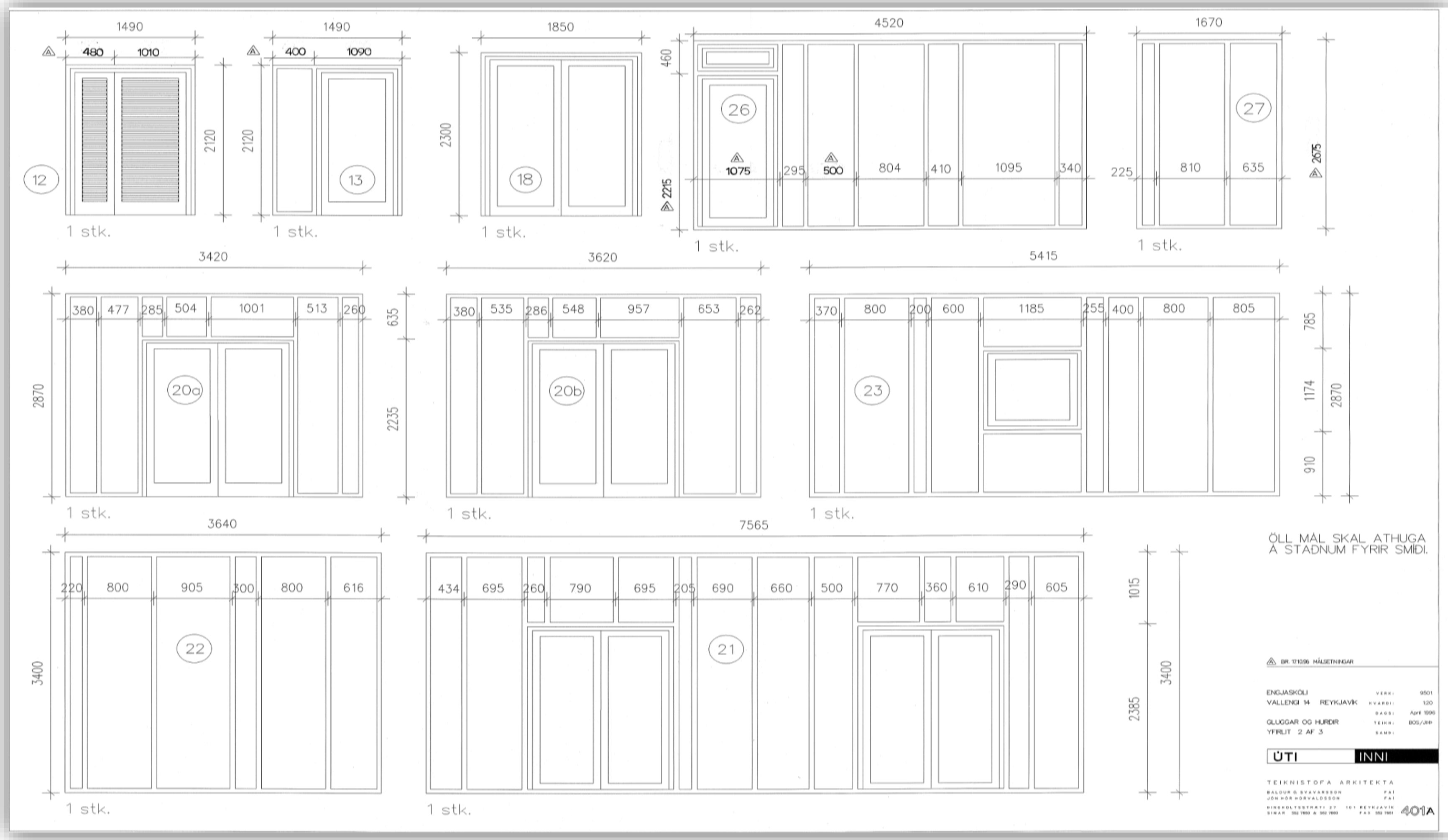
A2. Second floor plan



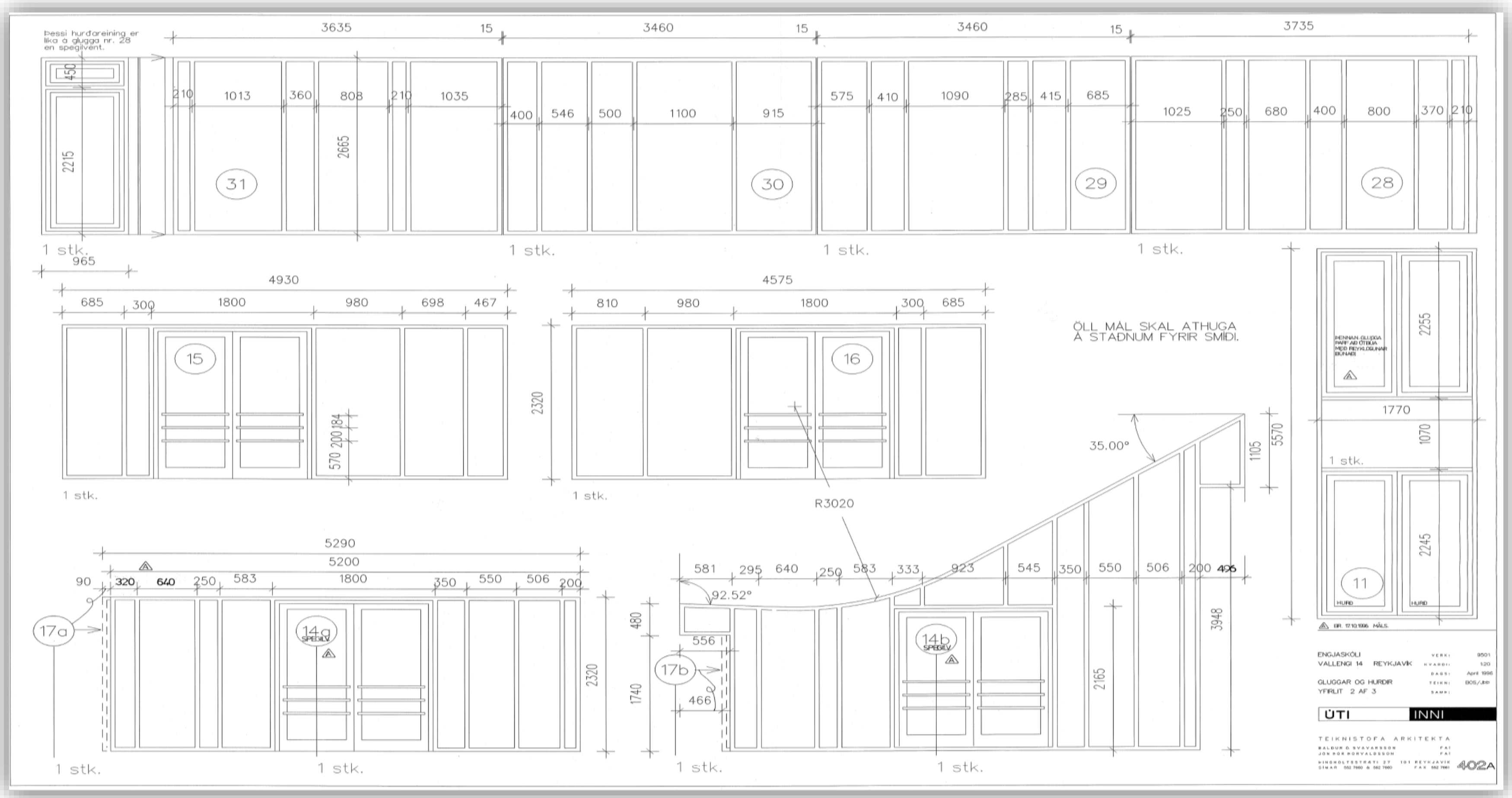
A3. Windows - drawing 1



A4. Windows - drawing 2



A5. Windows - drawing 3



B1. Overall Environmental impact assessment of modules A1-A4 (materials and transportation) used in Vættaskóli-Engi school

Components	Quantities	Unit	Density (kg/m³)	GWP (Kg CO2 eq.)	ODP (Kg CFC 11 eq.)	HT (CTUh)	AP (Mole of H+ eq.)	EP (Mole of N eq.)
Concrete	2505.00	m³	2248	6.38E+05	9.81E-06	3.49E-02	1.16E+03	3.31E+03
Aluminum window	670.09	m²		3.29E+05	2.38E-02	1.05E-01	1.76E+03	2.71E+03
Reinforcing steel	175000.00	Kg	7850	2.46E+05	2.12E-03	4.39E-02	1.44E+03	3.42E+03
Concrete roofing tile	131.75	m³	2100	6.37E+04	6.83E-06	3.14E-03	1.14E+02	3.75E+02
plaster	148.55	m³	2000	5.12E+04	8.84E-07	2.24E-02	9.13E+01	3.33E+02
Extruded polystyrene	400.50	m³	32	3.60E+04	2.65E-06	1.48E-03	1.24E+02	3.10E+02
Corrugated steel cladding	1.69	m³	7850	2.45E+04	9.92E-04	3.65E-02	1.66E+02	3.81E+02
Reinforcing mat	17197.81	kg		2.41E+04	2.08E-04	4.31E-03	1.41E+02	3.36E+02
Gypsum plaster board	7851.40	m²	800	2.45E+04	1.49E-03	1.19E-03	3.10E+02	8.28E+02
Expanded Polystyrene	210.00	m³	25	1.47E+04	9.18E-07	5.73E-04	5.25E+01	1.31E+02
Hard pressed stone wool	306.75	m³	80	1.10E+04	3.27E-07	1.40E-03	2.89E+01	1.01E+02
Paint	13060.00	m²	1350	1.02E+04	1.92E-03	3.18E-03	1.95E+01	1.65E+02
Plywood board	13.39	m³	575	5.63E+03	6.27E-08	1.18E-03	6.86E+01	2.14E+02
Underroof membrane	2670.00	m²		3.16E+03	1.32E-07	9.67E-04	7.87E+00	2.19E+01
Glued laminated timber	15.42	m³	515	3.87E+03	2.38E-07	1.28E-03	3.30E+01	9.98E+01
Lightweight stone wool	234.35	m³	32	3.35E+03	1.00E-07	4.26E-04	8.80E+00	3.09E+01
Built up asphalt	1230.00	m²		5.00E+02	5.28E-10	7.06E-06	4.35E+00	1.21E+01
insulation, stone wool	12.30	m³	100	5.49E+02	1.65E-08	7.00E-05	1.44E+00	5.06E+00
Polyethylene High density	0.12	m³	950	1.84E+02	1.95E-08	1.04E-05	8.26E-01	2.02E+00
Total				1.49E+06	3.05E-02	2.62E-01	5.52E+03	1.28E+04
Per one square meters of gross floor area Vættaskóli-Engi				**2.97E+02**	**6.11E-06**	**5.24E-05**	**1.10E+00**	**2.56E+00**

B2. Environmental impacts assessment of modules A1-A3 (raw material, transport and manufacturing) of Vættaskóli-Engi school

Components	Quantities	Unit	GWP (Kg CO2 eq.)	ODP (Kg CFC 11 eq.)	HT (CTUh)	AP (Mole of H+ eq.)	EP (Mole of N eq.)
concrete	2505.00	m³	6.36E+05	9.80E-06	3.45E-02	1.14E+03	3.23E+03
Aluminum window	670.09	m²	3.26E+05	2.38E-02	1.05E-01	1.64E+03	2.39E+03
Reinforcing steel	175000.00	Kg	2.22E+05	2.12E-03	4.23E-02	6.83E+02	1.30E+03
Concrete roofing tile	131.75	m³	6.36E+04	6.83E-06	3.12E-03	1.14E+02	3.71E+02
plaster	148.55	m³	5.06E+04	8.82E-07	2.22E-02	8.60E+01	3.04E+02
Extruded polystyrene	400.50	m³	3.47E+04	2.64E-06	1.40E-03	8.36E+01	1.96E+02
Corrugated steel cladding	1.69	m³	2.28E+04	9.92E-04	3.64E-02	1.09E+02	2.26E+02
Reinforcing mat	17197.81	kg	2.18E+04	2.08E-04	4.16E-03	6.71E+01	1.28E+02
Gypsum plaster board	7851.40	m²	1.67E+04	1.49E-03	7.66E-04	4.81E+01	1.03E+02
Expanded Polystyrene	210.00	m³	1.42E+04	9.16E-07	5.41E-04	3.59E+01	8.48E+01
Hard pressed stone wool	306.75	m³	1.06E+04	3.26E-07	1.31E-03	2.58E+01	8.47E+01
Paint	13060.00	m²	9.97E+03	1.92E-03	3.17E-03	9.35E+00	1.38E+02
Plywood board	13.39	m³	4.70E+03	5.90E-08	1.15E-03	3.54E+01	4.52E+01
Underroof membrane	2670.00	m²	3.10E+03	1.31E-07	9.63E-04	5.75E+00	1.60E+01
Glued laminated timber	15.42	m³	3.32E+03	2.36E-07	1.26E-03	1.27E+01	3.21E+01
Lightweight stone wool	234.35	m³	3.25E+03	9.97E-08	4.00E-04	7.87E+00	2.59E+01
Built up asphalt	1230.00	m²	3.70E+02	NR	NR	NR	NR
insulation, stone wool	12.30	m³	5.32E+02	1.64E-08	6.57E-05	1.29E+00	4.24E+00
Polyethylene High density	0.12	m³	1.74E+02	1.94E-08	9.77E-06	4.81E-01	1.05E+00
Total			1.44E+06	3.05E-02	2.58E-01	4.11E+03	8.78E+03
Per one square meters of gross floor area Vættaskóli-Engi			**2.88E+02**	**6.11E-06**	**5.15E-05**	**8.21E-01**	**1.76E+00**

B3. Environmental impacts assessment of module A4 (transportation to construction site) of Vættaskóli-Engi school

Components	Quantities	Unit	GWP (Kg CO2 eq.)	ODP (Kg CFC 11 eq.)	HT (CTUh)	AP (Mole of H+ eq.)	EP (Mole of N eq.)
Concrete	2505.00	m³	1.62E+03	7.05E-09	4.26E-04	1.52E+01	8.15E+01
Aluminum window	670.09	m²	3.52E+03	1.44E-08	2.21E-04	1.14E+02	3.21E+02
Reinforcing steel	175000.00	Kg	2.35E+04	9.60E-08	1.57E-03	7.53E+02	2.12E+03
Concrete roofing tile	131.75	m³	7.87E+01	3.42E-10	2.06E-05	7.39E-01	3.95E+00
plaster	148.55	m³	5.63E+02	2.45E-09	1.48E-04	5.29E+00	2.83E+01
Extruded polystyrene	400.50	m³	1.25E+03	5.09E-09	7.84E-05	4.05E+01	1.14E+02
Corrugated steel cladding	1.69	m³	1.60E+03	6.50E-09	5.70E-05	5.73E+01	1.55E+02
Reinforcing mat	17197.81	kg	2.31E+03	9.44E-09	1.54E-04	7.40E+01	2.09E+02
Gypsum plaster board	7851.40	m²	7.81E+03	3.18E-08	4.25E-04	2.62E+02	7.26E+02
Expanded Polystyrene	210.00	m³	5.11E+02	2.09E-09	3.21E-05	1.66E+01	4.66E+01
Hardpressed stone wool	306.75	m³	3.26E+02	1.42E-09	8.55E-05	3.06E+00	1.64E+01
Paint	13060.00	m²	2.76E+02	1.11E-09	7.55E-06	1.01E+01	2.72E+01
Plywood board	13.39	m³	9.30E+02	3.77E-09	3.30E-05	3.32E+01	9.01E+01
Underroof membrane	2670.00	m²	6.49E+01	2.65E-10	4.08E-06	2.11E+00	5.92E+00
Glued laminated timber	11.30	m³	5.54E+02	2.24E-09	1.52E-05	2.03E+01	5.46E+01
Lightweight stone wool	234.35	m³	9.95E+01	4.33E-10	2.61E-05	9.34E-01	5.00E+00
Built up asphalt	1230.00	m²	1.30E+02	5.28E-10	7.06E-06	4.35E+00	1.21E+01
insulation, stone wool	12.30	m³	1.63E+01	7.09E-11	4.28E-06	1.53E-01	8.20E-01
Polyethylene High density	0.12	m³	1.06E+01	4.34E-11	6.68E-07	3.46E-01	9.69E-01
Total			4.51E+04	1.85E-07	3.32E-03	1.41E+03	4.02E+03
Per one square meters of gross floor area Vættaskóli-Engi			**9.03E+00**	**3.70E-11**	**6.64E-07**	**2.83E-01**	**8.04E-01**