Defining a reference building according to LEED v4, to enable comparison of LCA alternatives

Olsson, Anna

Steko, Anel

Master thesis in Energy-efficient and Environmental Buildings Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centers and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programs and 2 300 subject courses offered by 63 departments.

Master Program in Energy-efficient and Environmental Building Design

This international program provides knowledge, skills and competencies within the area of energy-efficient and environmental building design in cold climates. The goal is to train highly skilled professionals, who will significantly contribute to and influence the design, building or renovation of energy-efficient buildings, taking into consideration the architecture and environment, the inhabitants' behavior and needs, their health and comfort as well as the overall economy.

The degree project is the final part of the master program leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

Examiner: Dennis Johansson
Supervisor: Charlotte Retzner, Mikael Lantz

Keywords: LEED, LEED v4, LCA, Life-cycle assessment, Building Life-Cycle Impact Reduction, Baseline Building

Thesis: EEBD - XX/15

Abstract

In this thesis the possibility of defining a general reference building, or so-called Baseline Building representing Swedish multi-family dwellings is investigated. The scope of the research is limited to analyze the multi-family dwellings of 3-8 stories. If succeeded the results should represent a general Baseline Building according to the new LEED v4 credit, Building Life-Cycle Impact Reduction. The credit requires a whole building life-cycle assessment to be carried out in order to evaluate environmental effects cause by the building design. However difficulties occur when developing a Baseline Building since no reference point is known. This leads to uncertainties when trying to improve the building design, since the reference point contains major variations.

A suggested Baseline Building was derived by analyzing five questions from surveys conducted on the Swedish building stock, during 2000-2009. These questions considered the building shape, structural components, and manufacturing method of the structural component, façade material and roofing material. Through the statistical analysis it was concluded that the most common building shape consisted of two building shapes, Apartment Block and Building Block. The choice of structural element consisted of partly prefabricated concrete elements for both building shapes. Furthermore plaster was found to be the most common façade material and metal sheet the most common roofing material. Despite this, no general Baseline Building that covered all building elements was obtained through the statistical review, due to high variations in greenhouse gas emissions caused by different construction types. The results should instead be used as material suggestions for the building envelope and structural elements of a Baseline Building. The results from the investigation are intended to guide project teams in selecting appropriate materials in an early design stage regarding the Baseline Building design.

As the final step sensitivity analysis were conducted by defining different construction and material types of a Baseline Building design and analyzed in a simplified LCA tool. From the LCA study we could conclude that the structural elements affected the LCA results the most. In conclusion the structural elements should be analyzed in early design phase through a “what if” scenarios to improve the LCA outcome.

Acknowledgements

This project has been performed within the master program Energy-efficient and Environmental Building Design (EEBD) at the Faculty of engineering, LTH, Lund University.

We would like to take the opportunity to thank the persons that in different ways have contributed to this master thesis.

First of all we would like to thank our supervisors at Skanska, Björn Berggren and Jeanette Sveder-Lundin, for their knowledge in the field of this thesis. Their guidance and feedback has been very helpful to finalize this thesis.

We would also like to thank our supervisors Charlotte Retzner and Mikael Lantz and our examiner Dennis Johansson who gave us helpful input regarding this subject.

Finally, a special thanks to our family and friends for their continuous support.

Helsingborg, May 2015
Anna Olsson
Anel Steko

Definition list

ASTM C272	American Society for Testing and Materials
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
Addenda	Continuous maintenance of published standards regarding additional items
Baseline Building	Designed reference point when evaluating energy and LCA improvements. LEED v4 refers to a Baseline Building for when evaluating improvements
BBR 22	The latest version of BBR,
Boverket	Swedish National Board of Housing, Building and Planning
DOE-2	Energy analysis program for buildings
E-waste	Electronic waste, computers, printers, fax machines etc.
Errata	Continuous maintenance of typographical errors, misprints, misspellings and grammatical errors to the published standard or guidelines
EnergyPlus	Energy analysis program for buildings
EPD	Environmental Product Declaration, document verifying the environmental performance of a product or service, based on LCA
IES	Illuminating Engineering Society
Multi-family dwellings	Houses for more than one house hold
PBF	Plan- och Byggförordning, translation: Planning and Building regulation
Proposed design	Optimized building design based on results from Baseline Building
Reference building	Baseline Building

Table of content

1 Introduction

1.1 Background

The industrialization has not always been considered harmful to the environment. In the 1800s, it was desirable to have industry in the neighborhood where black smoke poured out from the chimney. In those days the factories were seen as the future and symbolized success. When the negative side effects were realized in the 1900s different strategies were developed in order to reduce the environmental impacts (Rydh et al., 2002).

Today the construction industries have developed different methods to keep track of the environmental effects caused by buildings. One solution used by the construction industry is to incorporate green building program in the design process. One of these programs is the American, Leadership in Energy and Environmental Design (LEED), which was studied in this thesis. Today there are 196 LEED certified projects in Sweden compared to 27 560 buildings in the United States. Out of all certified projects, residential multi-family buildings only account for a small portion, most of the LEED certified buildings are offices owned by corporates (U.S. Green Building Council, 2012-2015).

LEED certified buildings are designed to lower the operating costs and increase assets value, reduce waste sent to landfills and reduce the emissions of greenhouse gases etc. LEED was studied in this thesis since it recently released a new version, LEED v4, which includes a new credits regarding life-cycle assessment (LCA). This new credit in LEED was chosen for this thesis since it addresses a new field within the construction industry, a whole life-cycle assessment. The new credit Building Life-Cycle Impact Reduction encourages projects to make early design decisions in order to reduce the environmental impact (U.S. Green Building Council, 2013).

The LCA credit introduces two models, a Baseline Building and a proposed building. Projects pursuing the credit are required to create a Baseline Building that is used as a reference point. The LCA credit is achieved by displaying relative reductions of emission outlets by investigating different design alternatives. Reductions are based on a Baseline Building design and Proposed Building design. Where's the Baseline Building is created to represent common building design including the structural element and building envelope. While the Proposed Building is improved through "what if" scenarios in the Baseline Building design, to display a reduction of emission outlets compared to the Baseline Building.

According to interviewed LCA practitioners there exist difficulties when creating a Baseline Building. This is because of uncertainties in the choice of materials for the Baseline Building. LEED states that the Baseline Building should represent common material and construction choices in the development of a Baseline Building. However no recommendations are found in LEED v4, regarding appropriate materials or constructions for the structural elements and building envelope. Because of this the relative emission reduction will vary significantly depending on how each project develops there Baseline Building.

1.2 Purpose

This thesis investigates the possibility of creating a general reference building, or so-called Baseline Building, that fulfills both Swedish regulations and requirements found in LEED v4. The purpose is to evaluate the possibility of creating a common Baseline Building that represent all Swedish multi-family dwellings, which would act as a common reference point. This thesis will provide guidance for project teams in the early design phase, when creating their Baseline Building. This is presented in a step-by-step guidance in which material requirements, appropriate material choices, appropriate design measures etc. are discussed.

The following main questions are investigated:

- *How should a reference building be defined according to LEED v4?*
- *Is it possible to define a general reference building applicable to Swedish conditions?*
- *Which building components contribute the most to greenhouse gases (global warming potential, CO_2-eqv.)?*

1.3 Scope and limitations

The scope of the thesis is limited to two different areas, first regarding the building model and its location, secondly limitations of the chosen LCA tool.

Building model

The building types chosen to analyze include newly constructed 3-8 story multi-family dwellings. The boundary is based on Swedish building regulations, PBF, which state specific requirements for different story heights. The lower limit is based on mandatory requirement for accessibility and usability found in PBF chapter 3, 4§:

> *"Building shall be accessible for people with reduced mobility and orientation capacity, access to elevator should be available except for residential building with two stories or lower."*

The upper limit is linked to the fire protection requirements intended for high-rise residential buildings (+8 stories). Residential buildings over eight stories contain higher requirements for accessibility to fire evacuation, found in BBR 5:321. These increase the building cost.

The building location is set to represent one climate zone according to LEED v4 requirements. For this reason Malmö is chosen as building location.

Building dimension and design is gathered from conceptual building designs created by Skanska. The building materials is gathered through statistical analysis, which only includes data from 2000-2009.

LCA

The LCA is limited to only include one impact category Global Warming Potential (GWP), greenhouse gases, as CO_2-equivalents. This is due to limitations in the chosen datasets, which only include CO_2-equivalents for global warming potential.

1.4 Disposition of report

The report is divided into four parts, the three first parts, chapter 2, 3 and 4, are used for gathering necessary information regarding background, requirements and guidelines found in LEED, LCA, building regulations and standards. Each part is followed by results, which describes necessary information for modeling a Baseline Building. These results also answer the questions stated for each part. The fourth part, chapter 5, contains the process of creating a Baseline Building in compliance with the results found in the first three parts. In addition to the development of a Baseline Building, a sensitivity analysis regarding the effect of different design alternatives are investigated and their impacts on the emission outlet.

Chapter 2

Chapter 2 investigates modifications made in the newest version of LEED v4 and describes requirements specified to model a Baseline Building. The findings from LEED describe the necessary requirements when pursuing the LCA credit Building Life-Cycle Impact Reduction in LEED v4.

Questions to answer:

- *What is needed to reach the credit Building Life-Cycle Impact Reduction for new constructions in LEED v4?*
- *Which requirements are mandatory to fulfill when designing a Baseline Building according to LEED v4?*

Chapter 3

The third chapter describes the American building energy efficiency code ASHRAE 90.1-2010, and its connection to LEED v4. LEED v4 refers to specific requirements in ASHRAE 90.1-2010 when developing a Baseline Building design and Proposed Building design. The standard is mandatory to follow when pursuing the LCA credit Building Life-Cycle Impact Reduction in LEED v4. The findings from building standards present a comparison between the requirements found in ASHRAE 90.1-2010 and the Swedish building standard BBR 22.

Questions to answer:

- *Which requirements are mandatory to follow when designing a Baseline Building according to LEED v4?*
- *Are there any similarities between ASHRAE 90.1-2010 and BBR 22?*

Chapter 4

Chapter 4 describes mandatory ISO standards to follow when conducting LCA for a Baseline Building and Proposed Building design. The LCA studies include specific requirements for method, structure and allowed datasets in LCA studies.

Questions to answer:

- *What should is included in ISO 14 040 and ISO 14 044?*
- *What is included in a cradle-to-grave LCA?*

Chapter 5

The fifth chapter uses the results from the previous chapters to develop a Baseline Building according to LEED v4. The fifth chapter includes the process for developing a Baseline Building. Analysis of statistical data regarding common material is presented, as well as a step-by-step process in developing a Baseline Building. Finally a LCA study is conducted for the Baseline Building design and proposed design measures to reduce the environmental impacts.

Questions to answer:

- *Which design measure is allowed to vary?*
- *What is the relative impact reduction caused by the proposed design measure?*

1.5 Method

As a first step of this report, see Figure 1, necessary information and requirements regarding how to develop a Baseline Building according to LEED v4 was studied. Requirements and information regarding the Baseline Building is stated in the reference guide of LEED v4. The complete LEED v4 reference guide was collected from USGBC website.

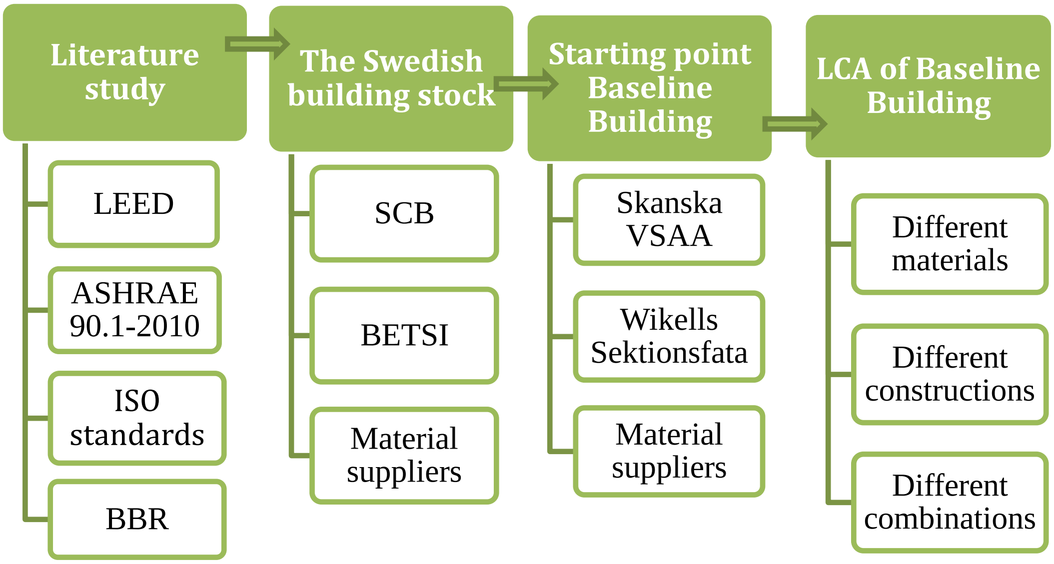


Figure 1. Method description.

From the study it was learned that requirements stated in appendix G of ASHRAE 90.1-2010 standard and various ISO standards were required. These were needed to fully understand the required documentation process when pursuing the LCA credit in LEED v4. The ASHRAE 90.1-2010 standard and its user manual were received at Skanska. To understand how the method for conducting an LCA has changed, a literature study of this was conducted, the literature was found at LUBsearch and in the library at Campus Helsingborg. The ISO standards were collected at Skanska and LTH.

Since the Baseline Building is located in Sweden, Swedish building requirements should be fulfilled. For this reason the latest building standard, BBR 22 was studied. The building standard, BBR 22 was found at their website.

Since none of the studied standards or manuals described a starting point for the Baseline Building, investigations where necessary to find common building materials and construction types. Statistical analysis was conducted on SCB survey results regarding material selection in multi-family dwellings, during 2000-2009. Along with the SCB results, information derived from BETSI project was combined. The BETSI project included technical status of multi-family dwellings including U-values. These where needed to describe the performance level of the building envelope. In addition material and assembly information from material suppliers where used to fill out any necessary gaps.

After the Swedish building stock was analyzed, common building materials and construction types used in multi-family dwellings was answered. The next step included to develop the Baseline Building according to the requirements stated in

LEED v4 and ASHRAE 90.1-2010. For this reason a building design was needed. Building dimensions where gathered from Skanska representing conceptual building designs. In addition each building component was assessed through Wikells section data to determine the amount of material for each construction. Construction types missing in Wikells was answered through contact with material suppliers.

When the Baseline Building was designed, a sensitivity analysis was conducted to discover which materials had the highest emission outlet. The best environmental performance was assessed to a Proposed Building design which altered the material selection, construction type and building component combination. Requirements regarding allowed design alternations were followed from the specified requirements of LEED v4, ASHRAE standard and ISO standards.

2 LEED

This chapter contains gathered information regarding the environmental certification system LEED. This part presents general background information, what is included in LEED and the LCA credit, Building Life-Cycle Impact Reduction. At the end of this part the results of this chapter is presented.

2.1 General background

Leadership in Energy and Environmental Design (LEED) was developed by the U.S. Green Building Council (USGBC) to reduce the growing environmental problems caused by the construction industries, and to create more sustainable societies. The framework of the certification scheme is structured to assist identification, implementation and measuring of sustainable building designs. Including both buildings and whole neighborhoods in an early design stage. LEED certification scheme is a market driven, voluntary, consensus tool which serves as guidelines towards sustainable building designs. The aim is to promote conversion to a greener and more sustainable environment. Achieved by optimizing the use of natural resources, maximizing the positive and minimize the negative effects on the environment and human health at the same time promoting a high quality indoor environment. The framework, which guides users in their design process, consists of a set of achievable credits and mandatory prerequisites that promote sustainable building solutions. To achieve a LEED-certification projects must collect points through credits and at the same time comply with mandatory prerequisites (U.S. Green Building Council, 2013).

The first LEED pilot version (LEED version 1.0) was developed in 1998. After extensive modifications LEED version 2.0 was first released in 2000. Since the first release LEED has been updated several times to include technical solutions, new markets and building types. LEED version 2.1 and 2.5 were released during 2002 and 2005. Since it first started LEED has grown and adapted with technical advances in the construction industry. Thus the certification system has contributed to awareness in climate changes and health effects caused by the building industry (U.S. Green Building Council, 2009). LEED is updated continuously, following the development in technology and practice made in the construction industry. During the update process members of the U.S. Green Building Council (USGBC), committees, and subcommittees review the new versions to ensure that LEED meets the need of the growing market sector (U.S. Green Building Council, 2013).

2.2 Impact categories

LEED is defined by seven main goals. These goals and visions are divided by how they improve human health and environmental aspects into so-called Impact Categories.

The goals and visions describe what LEED projects should accomplish:

- Reverse contribution to Global Climate Change
- Enhance Individual Human Health and Well-being

- Protect and Restore Water Resources
- Protect, Enhance and Restore Biodiversity and Ecosystem Services
- Promote Sustainable and Regenerative Material Resources Cycles
- Build a Greener Economy
- Enhance Social Equity, Environmental Justice, and Community Quality of Life (Owens, 2013)

LEED has established seven impact categories that contribute to the goals and visions by different weighting of the total points. LEED v4 introduced major changes to the impact categories, compared to previous version; to better correspond with LEEDs goals and visions. The allocation in LEED v4 is presented in Figure 2.

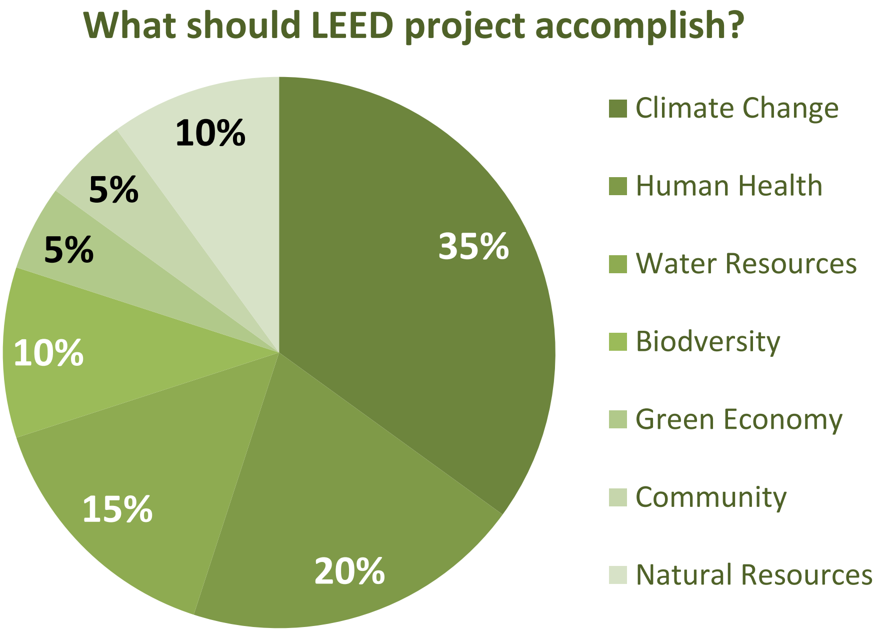


Figure 2. Allocation of the Impact Categories in LEED v4.

The approach is similar to the previous LEED 2009 version. All impact categories are weighted, where some categories are considered to have a larger importance and relevance to the construction industry. While other impact categories may be important for the environmental problems, but are less probable to be reduced by the construction industry. A larger percentage of the total points have been allocated to LEED v4 for the impact category Climate Change, compared to LEED 2009 (Owens et al., 2013).

2.3 LEED categories

LEED has transformed throughout the years, where credits and prerequisites have been renewed, combined or altered. LEED version 2009 had five categories containing mandatory prerequisites and optional credits existed in the rating system Building Design and Construction (BD+C) for New Construction. The LEED categories contain requirements when assessing credits and prerequisites to comply with to reach different levels of certifications. The categories from previous LEED 2009 and LEED v4 are compiled in Table 1.

Table 1. Comparison between previous LEED version 2009 and LEED v4

LEED 2009	**Points**	**LEED v4**	**Points**
Base points			
-	-	Integrative Process (IP)	1
-	-	Location & Transportation (LT)	16
Sustainable Sites (SS)	26	Sustainable Sites (SS)	10
Water Efficiency (WE)	10	Water Efficiency (WE)	11
Energy & Atmosphere (EA)	35	Energy & Atmosphere (EA)	33
Materials & Resources (MR)	14	Material & Resources (MR)	13
Indoor Environmental Quality (IEQ)	15	Indoor Environmental Quality (EQ)	16
Additional points			
Innovation in Design (ID)	6	Innovation (IN)	6
Regional Priority (RP)	4	Regional Priority (RP)	4

LEED v4 follows the same base point principle as in previous version, LEED 2009, with a maximum of 100 base points and 10 additional points for the categories Innovation in Design (ID) and Regional Priority (RP). In LEED v4 the distribution of points has been reallocated with regards to the new allocation of impact categories. In addition to the reallocation of points, new categories have been developed in LEED v4. The categories include now an Integrative Process (IP) and Location and Transportation (LT) (U.S. Green Building Council, 2013).

The location and transport (LT) category contains transferred credits from previous LEED 2009 category Sustainable Sites (SS). Where's the Integrative process (IP) includes a new credit for new construction. The credit is intended to create synergize in early design decisions through interrelationships in the project team. (U.S. Green Building Council, 2014). A roadmap is shown in Figure 3, displaying modifications of prerequisites and credits between LEED 2009 and LEED v4.

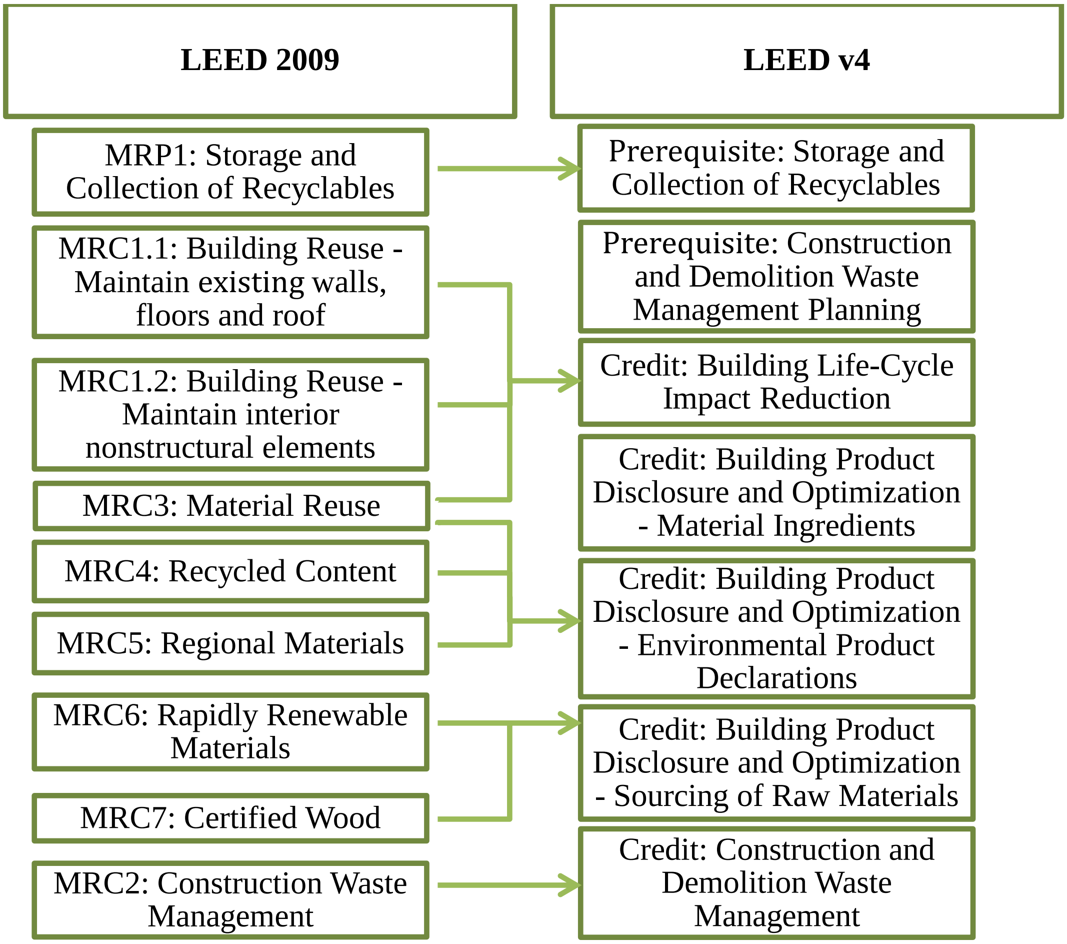


Figure 3. Road map displaying changes made between LEED 2009 and LEED v4, in the Material and Resource category

Prerequisites

The prerequisite, storage and collection of recyclables from LEED 2009 have been transferred to LEED v4 with minor additions. The prerequisite now include additional materials for dedicated storage, where the project should choose two of the three materials.

The new materials include:

- Batteries
- Mercury-containing lamps, and
- E-waste.

LEED v4 include one new prerequisite, which is closely connected to the construction and waste management credit in LEED 2009. The new prerequisite

Construction and demolition waste management planning states that all projects shall include a construction waste management (CWM) plan.

Credits

The Building Life-Cycle Impact Reduction credit in LEED v4 includes major modifications. The credit is new and combines criteria from three credits in LEED 2009 into one credit in LEED v4, see Figure 3. The credit is intended to reduce embodied energy, reduce waste and reduce impacts associated with material extraction, processing, transport, maintenance and disposal. Criteria from MRC1.1 and MRC1.2 are combined into option 3, Building and Material Reuse, for the new credit Building Life-Cycle Impact Reduction. These state how walls, floors and interior nonstructural elements should be reused for achieving the credit through option 3. New to the criteria is the possibility to incorporate both structural and nonstructural elements

The credit Building product disclosure and optimization - environmental product declarations combines criteria from MRC3, MRC4 and MRC5. Some materials that were excluded from the criteria in the past, have now been included in the new LEED v4 credit. Materials such as mechanical fixtures, fittings and rough-in materials that are considered nonmoving mechanical, electrical and plumbing (MEP) components, may now be included.

The modifications include:

- MRC3: Materials reuse – Materials that are reused are no longer required to be repurposed
- MRC4: Recycled content – No changes is made to the requirements
- MRC5: Regional materials – The 500 mile (805 km) radius have been decreased to 100 miles (160 km). The definition now includes the distribution and purchase location, which extends the scope to include all points of manufacture.

The credit Building product disclosure and optimization - sourcing of raw materials have combined multiple criteria from previous LEED 2009 version. These include the criteria found in MRC6 and MRC7, which include minor changes from previous version.

The modifications include:

- MRC6: Rapidly renewable materials – Bio based materials are no longer defined by the harvest cycle of the raw materials. Instead the products must meet the Sustainable agriculture standard to count for this credit.
- MRC7: Certified wood – No changes is made to the requirements.

LEED v4 introduces a completely new credit, Building product disclosure and optimization - material ingredients.

As mentioned before, the CWM plan from MRC2 credit in LEED 2009 have transformed in a prerequisite. In addition to this, the credit has been transferred to LEED v4 credit Construction and demolition waste management.

The credit includes the following modifications:

- The credit includes added compliance options for the total waste reduction per gross floor area
- Multiple material streams must now be diverted to earn the credit for diversion of waste (option 1)
- Alternate Daily Cover (ADC) is specifically excluded from diversion calculations. LEED 2009 allowed ADC to count for as diverted waste
- Waste-to-energy is now allowed to count as a diversion method as long the European Union's requirements for waste management are meet (U.S. Green Building Council, 2014).

2.3.1 Building Life-Cycle Impact Reduction (MR)

The Material and Resources (MR) credit, Building Life-Cycle Impact Reduction investigates the life-cycle of permanently installed materials. The environmental impacts caused by materials are assessed from a life-cycle perspective with a minimum requirement of cradle-to-grave perspective. When recycled materials are available, the life-cycle perspective could be extended to cover a cradle-to-cradle perspective. The intention is to offer a life-cycle approach to reduce the environmental impacts caused by the building materials and increase resource efficiency (U.S. Green Building Council, 2013).

The intent of the credit is "to encourage adaptive reuse and optimize the environmental performance of products and materials" (U.S. Green Building Council, 2013). The credit requires a reduction of environmental impacts based on design decisions in an early design phase stage, preferable before selecting the structural and building envelope materials. The credit rewards points for different projects types, where options for reusing resources from existing buildings and by a making an in-going LCA. Since there are various ways of fulfilling this credit, there are four different options to choose from. Option 4, Whole-Building Life-Cycle assessment rewards projects three points when achieving 10 % reduction in three of six possible impact categories, presented in Table 2. The impact category Global Warming Potential is mandatory for all projects and was included in previous LEED 2009. However none of the impact categories are allowed to increase more than 5 % compared to Baseline Building. In addition to the three points, an extra point is awarded through the Innovation credit. The Innovation (IN) credit, option 1, rewards projects that "achieve significant, measurable environmental performance using a strategy not addressed in the LEED green building rating system". This is achieved by displaying reduction in all six impact categories, instead of only three as LEED v4 requires. (U.S. Green Building Council, 2013).

Table 2. Impact categories assessed in "Building Life-Cycle Impact Reduction"

Impact Categories
Global warming potential (greenhouse gases), CO_2-eqv.
Depletion of the stratospheric ozone layer, in kg CFC-11
Acidification of land and water sources, in moles H+ or kg SO2
Eutrophication, in kg nitrogen or kg phosphate
Formation of tropospheric ozone, in kg NOx or kg ethane
Depletion of nonrenewable energy resources, in MJ

Both the Baseline Building and Proposed Building design must fulfill functional equivalence. These include the following parameters to be equal in both designs:

- Be of comparable size
- Have the same function
- Have the same gross area
- Have the same orientation
- Have the same system boundary, a cradle-to-grave analysis. All life-cycle stages regarding the building structure and enclosure should be analyzed, according to the definition in ISO 21930, following sections A1 - A4, B1 - B7 and C1 - C4. Parameters that are not defined may be changed across the baseline and proposed building
- Have the same operating energy performance, which is defined in EA prerequisite Minimum Energy Performance
- Have the same service life at least 60 years, to include products maintenance and replacement cycle
- Use the same software tool and datasets when conducting a life-cycle assessment, chosen datasets must be compliant with ISO 14 044 (U.S. Green Building Council, 2013)

Step-by-step guidance for Building Life-Cycle Impact Reduction, option 4

The follow part presents a step-by-step guidance described in LEED v4. The guidance describes how option 4, whole building life-cycle assessment, for the credit Building Life-Cycle Impact Reduction should be carried out (U.S. Green Building Council, 2013).

Step 1 **Calculate existing building surface area and reuse existing building**

The scope of the LCA should be a cradle-to-grave assessment, from design to demolition. The LCA should follow the system boundaries A1-A4, B1-B-7 and C1-

C4 according to ISO 21930 for the building structure and enclosure. This includes the product stage, construction process, use stage and end-of-life stage.

Products
The Baseline Building contains mandatory products to include when conducting an LCA. These products include structural elements and building envelope materials. The following building components should either be included, excluded or optional.

Included:

- Footing and foundations
- Structural pillars, columns etc.
- Structural wall assembly (from cladding to interior finishes)
- Structural floors and ceilings (not including finishes)
- Roof assemblies
- Parking structures, exclude parking lots
- Stair constructions

Excluded:

- Electrical and mechanical equipment and controls, plumbing fixtures, fire detection and alarm system fixtures, elevators and conveying systems
- Exclude excavation and other site development

Optional:

- Interior nonstructural walls or finishes may be included, but earn no additional credit

Step 2 **Select appropriate tools and datasets for LCA assessment**

The choice of LCA tool and dataset should be carefully reviewed to ensure the most suitable option is chosen for the project. The choice of dataset will determine whether a LCA specialist is required or not.

Tools/software and datasets must be:

- The LCA tool or software must be used for both the Baseline Building design and Proposed Building design. The dataset used in the tools/software must be compliant with ISO 14044 and relevant data sets for the project location must be selected
- The tool must be ensured to enable a whole building life-cycle assessment including the relevant impact categories

LCA tool selection
When assessing the Building Life-Cycle Impact Reduction several LCA tools can be used. All LCA tools use imbedded datasets, based on LCA standards. The data is specific to the building location, material manufacturer and regional electricity production. Different LCA tools require different levels of knowledge, where limitations exist in the possibility of modifying or adding data. These are divided in two categories, one for non-LCA-practitioners and one for LCA-practitioners.

Design team LCA tools are simplified LCA tools and are intended for non-LCA practitioners. These programs use simplified calculated methods where the LCA calculation runs in the background and do not allow users to modify or add data.

Examples of these programs are:
- ATHENA Impact Estimator
- Envest 2
- LCADesign

LCA practitioner tools require a LCA specialist, which is familiar with calculating factors and choosing appropriate datasets. These tools/software allow more flexibility where the LCA is based on product-by-product assessment and require different methodologies for the products examined. The practitioner aggregates all products into a whole building life-cycle assessment.

Examples of these programs are:
- SimaPro
- GaBi

Step 3 Create model Baseline Building

Identify the baseline early in the design process
Once the project scope is determined, all building components of the building envelope should be defined. These include exterior walls, roof, joists, and slab-on-grade, vertical fenestration and skylights. Each building component should be defined according to the performance requirements defined in ASHRAE 90.1-2010, appendix G. Area of exterior walls, roofs and joists may differ between the Baseline Building design and Proposed Building deign to allow optimization of building design and material choice in building components.

Customize the Baseline Building for the project to create the proposed building
When the Baseline Building is created the design and material choices should be varied in order to accomplish positive environmental effects on the chosen impact categories. The final design results in a Proposed Building that meets needs of the

project and at the same time presents improvements from the Baseline Building design.

The following parameters are necessary to keep the same to enable an accurate comparison:

- **LCA scope requirements**. The functional unit and the system boundary should be the same
- **Size**. The gross floor area must be the same. The two designs can have different massing, however the gross area has to be the same
- **Function**. The two buildings need to have the same function
- **Orientation**. The two buildings must have the same orientation
- **Location**. Both buildings have to be located in the same climate zone defined in ASHRAE 90.1-2010, the buildings also have to be assumed to be on the same site
- **Operating energy performance**. Both models must meet the prerequisite "Minimum Energy Performance" by adhering to the requirements in ASHRAE 90.1-2010. Increasing wall mass or insulation in the Baseline Building to show dematerialization in the Proposed Building is not allowed

Input the Baseline Building in the chosen tool

When the Baseline Building is defined, the input data of the model design should be inserted in an appropriate LCA tool. The tool is used to benchmark the environmental impacts of various design alternatives. The results should be saved to enable comparison with the Proposed Building design and submitted to USGBC. Each design modification should be saved as a new LCA version so the project team can compare the embodied impacts of design alternatives. USGBC does not expect updated documentation for iterations of the LCA model during construction.

Step 4 Select relevant impact measurement systems

In this stage the appropriate output units for each LCA impact indicator should be selected based on the impact categories chosen to pursue.

Step 5 Use LCA to make design decision that reduce environmental impacts

In this step the proposed LCA model should be used to perform "what if" scenarios that analyses and support design decisions, but also to evaluate and select superior environmental assemblies and materials.

LEED v4 provides the following examples:

- “Comparing the environmental consequences of building footprint and shape”
- “Evaluating different structural system types, such as load-bearing walls versus columns”
- “Defining the selection of building products and assemblies”
- “Optimizing structural system design (e.g. column spacing, slab depth)

Step 6 Incorporate final LCA result

The final step shall include a review of the results and incorporate the decisions of the design and material choices. Moreover a LCA narrative needs to be developed that describes the LCA assumptions, scope and baseline and proposed building.

The LCA narrative shall include:

- LCA summary, showing outputs for each chosen impact category, global warming potential mandatory for all projects
- Table showing the relative percentages of all impact categories between the Baseline Building and Proposed Building design. Each design alternative that resulted in a change between the baseline and Proposed Building design needs to be described
- Data sets used to represent each material or assembly must be described, proxies may be deemed acceptable.
- Verification that the same data set is used for the parameters, which are necessary to keep the same
- The used database for characterization of the model and impact categories needs to be described
- Data source regarding the product replacements used in both building designs

International tips

The Baseline Building is based on minimum performance requirements regarding the structure and enclosure materials. These requirements are found in ASHRAE 90.1-2010 and should be followed for all projects. Projects outside the U.S. are expected to develop a Baseline Building representing typical construction materials for their region meeting regional building performance requirements. Additional documentation for meeting the regional requirements may be needed for reaching the credit (U.S. Green Building Council, 2013).

Required documentation

- Description of LCA assumptions, scope, and analysis process for Baseline Building and proposed building
- Life-cycle impact assessment summary showing outputs of Proposed Building with percentage change from Baseline Building for all impact indicators (U.S. Green Building Council, 2013)

2.3.2 Minimum Energy Performance (EA)

The intent of the prerequisite is "to reduce the environmental and economic harms of excessive energy use by achieving a minimum level of energy efficiency for the building and its systems". Compliance with this prerequisite can be achieved by three alternative options, where Option 1 addresses whole-building energy simulation. As mentioned before the energy performance of the Baseline Building and Proposed Building design must meet the requirements of the prerequisite. The following section describes the prerequisite of LEED v4 (U.S. Green Building Council, 2013).

Option 1: Whole-building energy simulation

The energy performance for the Proposed Building has to demonstrate a minimum energy improvement of 5% (New Constructions BD+C), when comparing with the Baseline Building. The Baseline Building is created by changing the building envelope performance of the Proposed Building design to the requirements found in appendix G of ASHRAE 90.1-2010 (U.S. Green Building Council, 2014). The performance requirements of appendix G are used to determine the starting point of the building performance. The requirements include performance of the building envelope, HVAC, lightning, power etc. These requirements are usually applied to the proposed building energy model by changing the ingoing parameters to reflect the Baseline Building.

Additional credits are available under the credit "optimize energy performance" in LEED v4. The credit allows project teams to achieve up to 18 additional points when improving the energy performance with 50% compared to the Baseline Building for new constructions (U.S. Green Building Council, 2013).

Modeling of the Proposed Building must meet the following criteria:

- Compliance with mandatory provisions found in ASHRAE 90.1 – 2010, Appendix G, with errata or a USGBC-approved equivalent standard for projects outside the U.S.
- Include all energy consumption and cost within the building project
- Include a comparison between a Baseline Building and the proposed building. The Baseline Building must comply with ASHRAE 90.1 – 2010, Appendix G, with errata or a USGBC-approved equivalent standard for projects outside the U.S.

Documentation of the energy models (proposed- and Baseline Building) has to contain input assumptions of the unregulated loads. Unregulated loads (plug loads) includes equipment loads through electrical components such as office equipment and printers. These could cause unrealistic results if managed incorrectly. Both the baseline- and Proposed Building should document the unregulated loads used in the simulations.

The following calculation method should be used:

- ASHRAE 90.1-2010
- Alternatively, COMNET Modeling Guidelines and Procedures to record measures, which reduced the amount of, unregulated loads

2.4 Certification process

The certification process in LEED follows a four-step approach, which is presented in Figure 4. The contents of each step are explained in this chapter gathered from USGBC website (U.S. Green Building Council, 2015).

Figure 4, the certification process in LEED

Step 1. Register

Before registering the LEED project, certain requirements must be fulfilled. One of these is that all LEED projects need to meet the Minimum Project Requirements. The requirements contain criteria that each project needs to comply with before pursuing for LEED certification.

All projects:

- "Must be in a permanent location on existing land". This means all projects pursuing for LEED v4 certification must be constructed and operated on permanent and existing land. Projects that are intended to move at any point during their lifetime are not eligible for pursing LEED certification.
- "Must use reasonable LEED boundaries". Reasonable boundaries means that all land associated with the project and is used for the buildings typical operations must be included. This includes primary land usage by the occupants, hardscape, septic or storm water treatment and landscaping.
- "Must comply with project size requirements". All LEED projects need to comply with specific size requirements listed for each rating system. For example the rating system Building design and Construction (BD+C) contains a minimum gross floor area of 93 square meters (1.000 square feet) (U.S. Green Building Council, 2014).

When the minimum project requirements are attained an appropriate rating system is chosen for the project. Each project is then registered at LEED online. LEED online is a new web-based tool that is used for simplifying the documentation process through- out the certification process.

LEED contains five different rating systems, presented in Table 3, which addresses the needs in different projects and building types. Each rating system has a set of achievable credits and prerequisites that guides the user to make appropriate design and operational decisions in an early stage to achieve the pursued credits and prerequisites.

Table 3. The five different rating systems in LEED

Rating Systems in LEED	Abbreviation
Building Design and Construction	(BD+C)
Interior Design and Construction	(ID+C)
Building Operations and Maintenance	(O+M)
Neighborhood Development	(ND)
Homes	(HOMES)

LEED projects must be registered under a single rating system for the total gross area, regardless if the project includes a mixed usage. In cases when several rating systems appear suitable for the project the 60/40 rule should be used, see Figure 5, to select an appropriative rating system. The rule specifies that the entire gross floor area should be assigned with appropriative rating system for each building part. The resulting percentages of the total gross area are then used to determine the appropriate rating system.

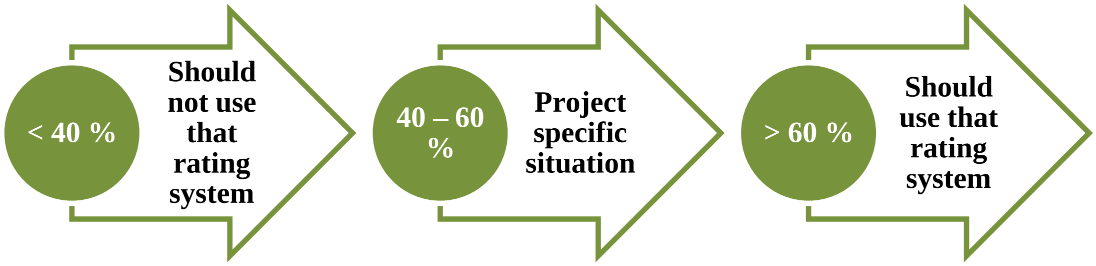


Figure 5. The 60/40 rule for choosing rating system for LEED

A rating system should not be used if less than 40 % of the total gross floor area is appropriate for that rating system. If a rating system is suitable for 60 % or more, then it should be used for the project. If the rating system falls between 40-60 % of the total gross floor area, then the rating system needs to be assessed based on the project situation and decided accordingly (U.S. Green Building Council, 2014).

When the minimum program requirements have been fulfilled and the rating system has been chosen the application should be submitted through LEED online. The project is first registered when the project owner sings the certification agreement and submits payment for the project. Thereafter the project will be accessible in LEED online where the documentation process begins.

Step 2. Apply

At this step all prerequisites connected to the chosen rating system together with the credits each project wish to pursue shall be documented in LEED online. These shall be achieved by information collection, performed calculations and analysis. All analysis and documentation should be gathered at LEED online where after Green Building Certification Institute (GBCI) reviews which prerequisites and credits is achieved.

The project has to reach all prerequisites connected to the selected rating system and at the same time collect enough credits to reach the certification level. All documentation needed to reach specific prerequisites and credits are later submitted for a preliminary review. During the preliminary review technical advice is given if additional correction is needed to achieve the pursued credits.

Step 3. Review

GBCI will review the application once the documentation has been submitted for the preliminary review. The documentation will be evaluated in compliance with credits and prerequisites through technical reviews. GBCI will notify the applicants within 20-25 business days if additional information is needed to reach the prerequisites and credits chosen for the specific rating system. The results given in the preliminary review can be accepted as final or add new or revise the documentation or attempt to reach additional credits before the final review.

A final review stage is optional and offered to projects that require supplementary or additional information in their application. GBCI allows alterations being made to the application, and suggest the additional documentation to be handed in within 25 business days after receiving the preliminary review. GBCI will notify within 20-25 business days if additional revisions are needed or present the final certification score. The final LEED certification will be given including information regarding the approved and denied prerequisites and credits. Just like in the preliminary review the results can either be accepted as final, or revised and resubmitted through an appeal.

Projects are allowed additional rounds of reviews by sending an appeal. This additional round of review is connected with a fee, which varies depending on the complexity involving the prerequisites and credits involved. The same approach applies as before preliminary and final review when assessing the submitted documentation regarding the prerequisites and credits. Additional appeals can be made if the project wishes to include more credits or renew the application.

Step 4. Certify
Once the application is complete and the result from the final review is accepted, the project will be “closed out” meaning the certification level is final. The LEED-certification consists of four different levels of certification. The number of points is related to the achieved credits, see Table 4. Platinum is the highest level of certification and certified is the lowest (U.S. Green Building Council, 2015).

Table 4. Certification levels in LEED

Certification Level	Earned points
LEED Certified	40-49
LEED Silver	50-50
LEED Gold	60-79
LEED Platinum	80+

2.5 Findings from LEED
The following chapter answers the two questions:

- *What is needed to reach the credit Building Life-Cycle Impact Reduction for new constructions in LEED v4?*
- *Which requirements are mandatory to fulfill when designing a Baseline Building according to LEED v4?*

When assessing the MR credit, Building Life-Cycle Impact Reduction, option 4, specific requirements are mandatory to follow for compliance. Option 4, whole building life-cycle assessment should be used for new constructions (BD+C) which could lead to earning 3-points. A Baseline Building should be modeled to define the starting point for the LCA. The Baseline Building design should be determined in early design process, which allows comparison between different design alternatives for the Proposed Building design. The LCA shall be conducted for the buildings structural elements and building enclosure. Optional material components may be included in the LCA, although no additional points are earned. These include interior non-structural walls and finishes.

According to LEED v4, structural elements and building envelope include the following building components:

- Footing and foundations
- Structural pillars, columns etc.
- Structural wall assembly (from cladding to interior finishes)
- Structural floors and ceilings (not including finishes)
- Roof assemblies
- Parking structures, exclude parking lots
- Stair constructions

LEED v4 does not describe which materials or products are appropriate to select when creating the required building components for a Baseline Building. Each project is instead required to design the Baseline Building according to typical materials used in local building constructions. This provides projects with the flexibility of choosing the materials or products used in the required building components. However the Baseline Buildings envelope still needs to fulfill the performance and material requirements stated in ASHRAE 90.1-2010 regarding the building envelope.

When comparing the Proposed Building design to the Baseline Building design, some parameters are required to be equal. These include:

- Same LCA system boundaries (cradle-to-grave)
- Same size (total gross floor area)
- Same intended function (e.g. office, residential, school etc.)
- Same orientation
- Location
- Operating energy performance, EA prerequisite Minimum Energy Performance

Both design alternatives, baseline building and proposed building, must have the same energy performance and at the same time comply with the prerequisite of Minimum Energy Performance. This is achieved by demonstrating a building performance improvement of 5 % for new constructions. The energy improvement is compared to the same building design with the exception of performance values. For the energy Baseline Building the performance requirements of ASHRAE 90.1-2010, appendix G are applied. The Proposed Building energy performance is then compared to the one with applied performance values from appendix G.

LEED does not specify clearly when the Proposed Building design regarding the energy and LCA model should be created. One solution is to design the Baseline Building for LCA purposes first, where the material selection is chosen with regards to the performance requirements of appendix G. The Proposed Building is created through sensitivity analysis of material variation in the structural elements and building envelope. The two models, baseline building and proposed building design are ensured to follow the same energy performance. When the proposed energy model is finished all new parameters regarding the structural elements and building envelope is updated accordingly in the two LCA models. These include building envelope performance, HVAC, power, and lightning requirements. By doing this the Proposed Building regarding energy performance can be duplicated for the LCA study. Following this interactive procedure for developing both the energy models and LCA models ensure the energy performance is equal. The Baseline Building is modeled to represent typical material selection of the building envelope and structural elements. The performance of the building envelope needs to follow the performance of the Proposed Building energy model.

To achieve the MR credit, Building Life-Cycle Impact Reduction, a minimum of 10 % reduction needs to be demonstrated by the Proposed Building compared to the Baseline Building. The reduction shall be demonstrated for three out of six impact categories, where Global warming potential is mandatory for all projects. None of the six impact categories are allowed to increase with more than 5 %, compared to the Baseline Building. Another point is available through the Innovation (IN) credit by achieving 10 % reduction on all six impact categories.

There are six impact categories to choose from when conducting a LCA, these include:

- Global warming potential (greenhouse gases), CO2-eqv.
- Depletion of the stratospheric ozone layer, in kg CFC-11
- Acidification of land and water sources, in moles H+ or kg SO2
- Eutrophication, in kg nitrogen or kg phosphate
- Formation of tropospheric ozone, in kg NOx or kg ethane
- Depletion of nonrenewable energy resources, in MJ

For the LCA study the system boundary needs to be the same in both building, cradle-to-grave for at least 60 years of service life. The LCA should include life-cycle stages regarding the structural elements and building envelope materials, in accordance with ISO 21930. The LCA-stages A1 - A4, B1 - B7 and C1 - C4 should be assessed for each chosen impact category. The chosen datasets and tool must be compliant with ISO 14 044. The performance requirements and product requirements for the chosen materials are found in ASHRAE 90.1-2010.

3 Building standards

In the following chapter general information and requirement stated in the building standards ASHRAE 90.1-2010 and BBR 22 are presented. The intention is to present the requirements referred to in ASHRAE 90.1-2010 by LEED v4 for designing a Baseline Building. In the end of this part results from ASHRAE 90.1-2010 and BBR 22 are presented together with a comparison of the two standards.

3.1 ASHRAE 90.1-2010

3.1.1 General background

Standard 90 was the precursor to the ASHRAE-standard. Standard 90 was published in 1975 and has since then been renewed several times and republished in 1980, 1989, and 1999. The revisions were made according to ANSI and ASHRAE maintenance procedures. As the technical innovation and economical aspects started to change faster, the ASHRAE Board of Directors voted in 1999 to place the standard under a continuing maintenance. This resulted in several updates each year through submission of addenda and/or errata (ANSI/ASHRAE/IES Standard 90.1-2010, 2010).

The new approach has been executed since the 2001 edition, since then the standard has been published each fall of every third year. The new arrangement allowed revisions to be submitted in form of addenda and errata within the deadline for the upcoming edition. Approved addenda and errata are applied to the current version and included in the new edition every third year. Committees welcome users to leave suggestions of improvements to the standard, where they are invited to use a continuous maintenance procedure regarding the forthcoming version. A standardized form Continuous Maintenance Proposals (CMP) is included in the back of each version, where users are allowed to submit addenda and errata. When the committees approve addenda and/or errata, notices are published on ASHRAE and IES web sites. The 2010 edition includes 109 addenda, which were approved by ASHRAE and IES Boards of Directors in previous 2007 edition. Also all known text errors found in the previous 2007 edition were corrected in the latest 2010 edition. The 90.1 standard is a dynamic document, which evolves together with the technical advances within the construction industry. There are significant changes made in the 2010 edition from the previous edition (ANSI/ASHRAE/IES Standard 90.1-2010, 2010).

Changes in the 2010 edition:

- Expanded Scope, which allows the 90.1 Standard to cover receptacles and process loads (e.g. data centers)
- More stringent requirements on the building envelope
- Lowered lighting power density, additional occupant sensing controls, mandatory daylighting requirements and a new five-zone exterior lightning power density table have been added

- Higher equipment efficiencies, energy recovery demanded in more applications, economizers required in 4 more climates and more requirements on energy-conserving controls
- Modeling requirements, for LEED certification, have been refined and expanded (ANSI/ASHRAE/IES Standard 90.1-2010, 2010).

3.1.2 Appendix G

LEED v4 refers to the Performance Rating Method in Appendix G when defining the Baseline Building and the proposed design. The rating may be based on either annual energy operating cost or energy consumption, depending on the evaluation method of the rating authority. The method for designing the Baseline Building and the Proposed Building designs is often used by energy-efficient and green building programs such as LEED. Option 4 of the MR credit, Building Life-Cycle Impact Reduction in LEED v4, states that the results shall be presented for each impact category in unit per gross floor area (e.g. CO2-eqv/m^2). The Performance Rating Method in appendix G provides a methodology for designers when comparing the Baseline Building performance with the Proposed Building performance. The method is intended for rating purposes only, it does not provide compliance with the Standard 90.1 standard. However, when simulating the Baseline Building all mandatory and prescriptive requirements in Standard 90.1 should be applied (ANSI/ASHRAE/IES Standard 90.1-2010, 2011).

The Baseline Building and Proposed Building shall comply with the mandatory provisions and requirements found in sections 5.4, 6.4, 7.4, 8.4, 9.4 and 10.4 presented in Table 5. The mandatory building envelope provisions and requirements found in section 5.4 are necessary to comply with when pursuing the MR credit, Building Life-Cycle Impact Reduction in LEED v4. LEED v4 requires that building envelope and structural components are included when pursuing the MR credit for life-cycle assessment (ANSI/ASHRAE/IES Standard 90.1-2010, 2011).

Table 5. Displaying chapter and description which include mandatory provisions.

Mandatory provisions	Chapter description
5.4	Building envelope
6.4	Heating, ventilation and air conditioning
7.4	Service water heating
8.4	Power
9.4	Lightning
10.4	Other equipment

The basic rule for modeling the Proposed Building envelope is to use final architectural drawings to determine the dimensions, building shape, surface orientations, opaque construction assemblies etc. The Baseline Building should have the same physical design as the proposed building.

Building components that should be kept the same:

- Conditioned floor area
- Roof, wall, glazing and other surface areas
- Surface tilts and orientations.

The Performance Rating Method, appendix G, is useful when comparing the energy performance of a building to the minimum requirements of the standard. Several green building programs exist that gives points when operating a certain percentage better than the standard 90.1. One of these includes the USGBC's LEED rating system, which states a prerequisite for complying with the minimum requirement of Standard 90.1, and offers points when reaching over the minimum requirements.

All simulations performed to the Baseline Building and Proposed Building shall be documented and submitted to the rating authority for example, USGBC. The documentation shall include a description of the project, simulation program used (including version type), results from the performance value for both models, percentage improvement etc. (ANSI/ASHRAE/IES Standard 90.1-2010, 2011.

The calculation for determining the improved performance of the Proposed Building design is calculated in percentage improvement as following:

$$100 \cdot \frac{(Baseline\ building\ performance - Proposed\ building\ perforance)}{Baseline\ building\ performance}$$

All computer simulations of both the Baseline Building design and Proposed Building design shall use the same:

- Simulation program
- Climate data
- Purchased energy rates (if cost is used as the metric)
- Schedules of operation (except for adjustments needed to account for energy efficiency features).

DOE-2 and EnergyPlus are two simulation programs that are suitable to use when simulating the energy performance of both building designs. Specific requirements of accepted simulation programs are mentioned in Appendix G (ANSI/ASHRAE/IES Standard 90.1-2010, 2011).

Both the Baseline Building and Proposed Building needs to be located in the same climate zone. Tables D1 - D3 lists climate zones for United States and Canadian territory with additional to international climate zones. Projects outside the United States not listed in the international climate zone shall be determined by using the major climate type definitions. International projects outside the United States not covered in table D3 in appendix D of ASHRAE 90.1-2010. Should instead determine their climate zone through thermal criteria described in Table 6. The thermal criteria is set on either heating degree-days (HDD) for 18°C or cooling degree-days (CDD) for 10°C. The mean value of HDD18°C and CDD10°C shall be determined for the specific location (ANSI/ASHRAE/IES Standard 90.1-2010, 2010).

Table 6. Major climate type definitions

Zone number	Climate type	Thermal Criteria
1	Very Hot-Humid (1A), Dry (1B)	5000 < CDD10°C
2	Hot-Humid (2A), Dry (2B)	3500 < CDD10°C ≤ 5000
3A, 3B	Warm-Humid (3A), Dry (3B)	2500 < CDD10°C ≤ 3500
3C	Warm-Marine	CDD10°C ≤ 2500 and HDD18°C ≤ 2000
4A, 4B	Mixed-Humid (4A), Dry (4B)	CDD10°C ≤ 2500 and 2000 < HDD18°C ≤ 3000
4C	Mixed-Marine	2000 < HDD18°C ≤ 3000
5A, 5B, 5C	Cool-Humid (5A), Dry (5B), Marine (5C)	3000 < HDD18°C ≤ 4000
6A, 6B	Cold-Humid (6A), Dry (6B)	4000 < HDD18°C ≤ 5000
7	Very Cold	5000 < HDD18°C ≤ 7000
8	Subarctic	7000 < HDD18°C

Mandatory provisions regarding the building envelope are stated in section 5.4. These describe the provisions and requirements on insulation installment, maximum air leakage, and rating of doors and windows. The building envelope contains specific performance requirements for conditioned spaces, and should either comply with non-residential, residential or semi heated requirements. These requirements are specific to the chosen climate zone. Section 5.4 refers to additional requirements found under section 5.5 or 5.6 and 5.8. Section 5.5 and 5.6 regards the chosen compliance path, where section 5.8 regards product information and installation requirements of insulation and fenestration and doors, see Figure 6 (ANSI/ASHRAE/IES Standard 90.1-2010, 2010).

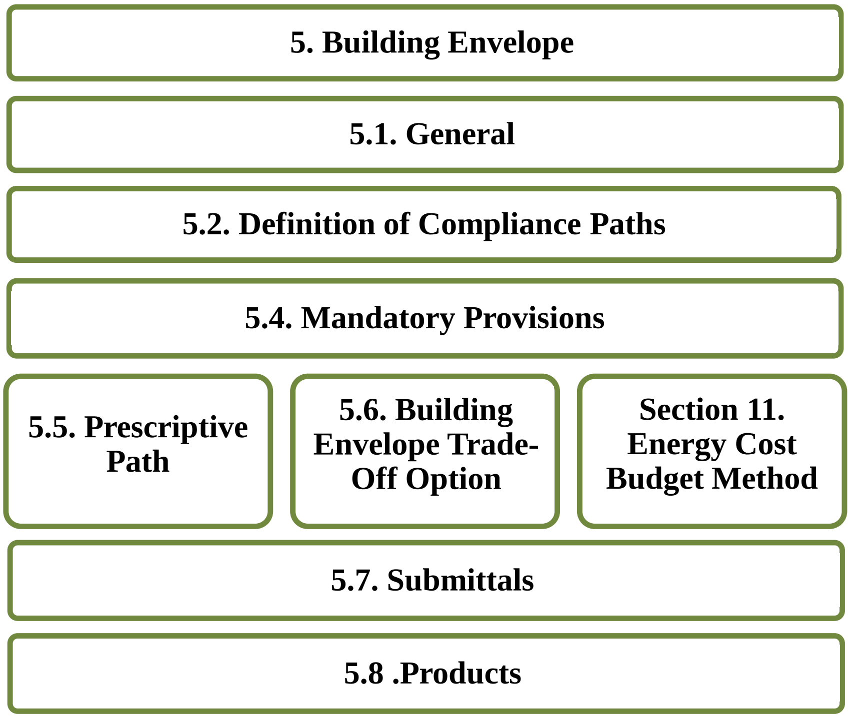


Figure 6. Layout of chapter 5 Building envelope.

Prescriptive building envelope option

The Prescriptive Path contains building envelope requirements for conditioned spaces which are divided for each climate zone 1-8. The investigated location Malmö is located in climate zone 5, which limited the investigation to this climate zone.

The requirements are specified for eight different building components of the building envelope. The first six are presented in Table 7. Each criteria set includes all prescriptive requirements on roofs, floors, walls etc. These contain requirements off insulation level, minimum R-value and maximum U-value for a set of building products. The requirements are divided in three conditioning categories, nonresidential, residential and semi heated spaces. These requirements are found under section 5.5 Prescriptive Path and are mandatory to comply with when following the Compliance Method (ANSI/ASHRAE/IES Standard 90.1-2010, 2010).

Table 7. Summary of building envelope performance requirements for residential conditioned space.

Climate zone 5		
Opaque elements	**Assembly U-value in W/(m^2·K) according to ASHRAE 90.1-2010**	
Roofs	Insulation entirely above deck	0.273
	Metal Building	0.312
	Attic and other	0.153
Walls. above-grade	Mass	0.453
	Metal Building	0.391
	Steel-framed	0.365
	Wood-framed and other	0.291
Walls. below-grade	Below-grade wall	0.678
Floors	Mass	0.363
	Steel-joist	0.214
	Wood-framed and other	0.188
Slab-on-grade floors	Unheated	0.935
	Heated	1.489
Opaque doors	Swinging	2.839
	Non swinging	2.839

Requirements of fenestrations are divided into vertical glazing and skylights, which are presented in Table 8. Fenestrations are grouped depending on the frame-type. Where the maximum U-value and Solar-heat gain coefficient (SHGC) is presented for each frame type. The fenestration area is limited to a window-to-wall ratio between 0-40 % of the total exterior wall area. Criteria for skylights are limited to 5 % of the total roof area, which also include specific U-value and SHGC for each skylight type. The window-to-wall limitations are specific for the prescriptive method, which only allow building with the same WWR to follow the Prescriptive Path (ANSI/ASHRAE/IES Standard 90.1-2010, 2010).

When using the Prescriptive Path each envelope component needs to comply with the prescriptive requirements of the standard and the mandatory provisions. Although there are possibilities to do some area-weighting averaging where one construction fails to meet the requirements as long as other constructions perform better (ANSI/ASHRAE/IES Standard 90.1-2010, 2010).

Table 8. ASHRAE Criteria for fenestration, prescriptive path, climate zone 5

<table>
<tr><th colspan="3">Climate zone 5</th></tr>
<tr><th>Fenestration</th><th colspan="2">Fenestration in percentage according to ASHRAE 90.1-2010</th></tr>
<tr><td rowspan="4">Vertical glazing</td><td>Nonmetal framing (all)</td><td rowspan="4">0 - 40 % of wall</td></tr>
<tr><td>Metal framing (curtain wall/storefront)</td></tr>
<tr><td>Metal framing (entrance door)</td></tr>
<tr><td>Metal framing (all other)</td></tr>
<tr><td rowspan="2">Skylight with Curb. Glass</td><td>0 - 2.0 %</td><td rowspan="6">0 - 5 % of roof</td></tr>
<tr><td>2.1 - 5 %</td></tr>
<tr><td rowspan="2">Skylight with Curb. Plastic</td><td>0 - 2.0 %</td></tr>
<tr><td>2.1 - 5 %</td></tr>
<tr><td rowspan="2">Skylight without Curb. All</td><td>0 - 2.0 %</td></tr>
<tr><td>2.1 - 5 %</td></tr>
</table>

Building Envelope Trade-Off Option

This method involves more work than the Prescriptive Path method, which offers designers more flexibility, where Building Envelope Trade-Off Option is permitted. Surfaces areas for each exterior wall and semi exterior wall must be calculated where wall areas must be calculated for each orientation. A short description between the difference of a Prescriptive Path and Building Envelope Trade-Off Option is shown in Table 9 (ANSI/ASHRAE/IES Standard 90.1-2010, 2010).

Table 9. Comparison of Prescriptive Path and Building Envelope Trade-Off Option

	Prescriptive Path	**Building Envelope Trade-Off Option**
Fenestration area	Window area is limited to a window-to-wall ratio of 40%, and skylights are limited to 5% of the roof area.	Fenestration area is allowed to be greater than 40% as long as the envelope performance is improved over the requirements in the prescriptive option.
Area take-offs	It is only necessary to verify that the window-to-wall ratio and/or skylight-roof ratio and material components follow the requirements.	Surface areas have to be calculated for each type and class of construction. Additionally the window and wall areas must be calculated for all major weather directions including, NE, SE, SW and NW.
U-factor compliance	Not necessary when using the R-value option.	Required.

Product information and installation requirements
Section 5.8, Product information and installation requirements contain specific requirements for products and states approved laboratory testing of each product. The products include insulation, fenestration and doors, baffles, lighting fixtures, ducts, plenums etc. The requirements are mandatory and are specific for each material (ANSI/ASHRAE/IES Standard 90.1-2010, 2010).

The requirements include, but are not limited to:

- Insulation materials shall have a clearly identified R-value identification mark provided by the manufacturer
- Insulation shall be installed in accordance with the manufacturers guidance and recommendations
- Loose-fill insulation shall not be used in attic/roof spaces where the slope of the ceiling is more than three in twelve
- All insulation shall be installed with full contact to the inside surface, all cavities should be filled with the insulation material
- Insulation on exterior surfaces should be covered with a protective material to prevent damage from sunlight, moisture, wind etc.
- Attics and mechanical rooms shall be provided with sufficient space to access the equipment without damaging the insulation
- Insulation materials with ground contact, slab-on-grade, shall have a water absorption rate of maximum 0,3% when tested with accordance to ASTM C272
- U-factor, SHGC, air leakage rate shall be provided by the manufacturer and listed on a nameplate for each product (ANSI/ASHRAE/IES Standard 90.1-2010, 2010)

3.2 BBR 22

3.2.1 General background

Boverket is the approved authority in Sweden that specifies the laws and regulations regarding constructions and buildings. These laws are called Boverkets byggregler (BBR) and were first published on the 1st of January 1994. The BBR regulations are restricted by the Swedish parliament and government (Boverket, 2014). BBR includes regulations that are mandatory, these regulations are based on the building laws found in Plan- och bygglagen (PBL) and Plan- och byggförordningen (PBF) (Boverket, 2015). Aside from the regulations, BBR also includes general advices that comply with the building laws, these are not mandatory but following these ensures compliance with the building laws. A general advice are not binding, instead they only give recommendations how the building laws could be fulfilled (Boverket, 2014). BBR is based on functional requirements where a certain function should be fulfilled.

3.2.2 Building envelope requirements, BBR 22

BBR 22 only includes guidelines for compliance with Swedish national building regulations. These are divided into 9 chapters which are presented in Table 10.

Table 10. Chapters in BBR 22

Chapter	Content
1	Introduction
2	General rules
3	Accessibility, housing design, room height and operating areas
5	Fire protection
6	Hygiene, health and environment
7	Noise protection
8	Safety in use
9	Household energy

Building envelope requirements

BBR 22 includes specific building envelope requirements, these are presented as a mean U-value ($W/(m^2 \cdot K)$) for the whole building envelope. The building envelope includes exterior walls, exterior roof, slab on-grade, thermal bridges, windows and entrance doors. The mean U-value requirements is set to 0,40 $W/(m^2 \cdot K)$.

The mean U-value is weighted through the equation, see (1). Where definition of the heat transfer coefficient and thermal bridges complies with the two standards, SS-EN ISO 13789:2007 and SS 2430 (Boverket, 2015).

$$U_m = \frac{(\sum_{i=1}^{n} U_i A_i + \sum_{k=1}^{m} l_k \Psi_k + \sum_{j=1}^{p} \chi_j)}{A_{om}} W/(m^2 \cdot K) \qquad (1)$$

Where:

- U_i The heat transfer coefficient stated in $W/(m^2 \cdot K)$, for each building component
- A_i The area of the building component is calculated from the inside of a heated space (m^2). For windows and doors the area should include the frame dimensions
- Ψ_k Is the heat transfer coefficient stated in $W/(m \cdot K)$, for linear thermal bridge
- l_k The length of indoor air in contact with the thermal bridge (m)
- X_j Is the heat transfer coefficient stated in W/K of a point shaped thermal bridge
- A_{om} The total area enclosed by the building envelope which separates the heated inside spaces from the outside (m^2). The building envelope includes all building components that separate the outside from

inside, including separating heated spaces from semi-heated (Boverket, 2015)

Daylight requirements
BBR 22 requires that all rooms occupied more than temporarily should provide sufficient access to direct daylight. This should be accommodated by the choice of orientation and design. The amount of daylight is not specified instead a general advice of minimum 10% window-to-floor area should be fulfilled (Boverket, 2015).

3.3 Findings from Building standards

The following chapter answers the two questions:

- *Which requirements are mandatory to follow when designing a Baseline Building according to LEED v4?*
- *Are there any similarities between ASHRAE 90.1-2010 and BBR 22?*

ASHRAE 90.1-2010 states specific performance requirements for materials used in the building envelope. These include exterior walls above and below grade, roofs, joists, slab-on-grade, opaque doors and fenestrations. LEED v4 refers to appendix G in ASHRAE 90.1-2010 when designing a Baseline Building for LCA purposes. Appendix G contains the performance rating method, which is used as a baseline for energy-efficient and green building programs. The Performance Rating Method provides a methodology for designers and energy analyst for calculating energy-efficient improvements. The improvements are based on a Baseline Building complying with the requirements of the standard. However LEED v4 refers to this method when modelling a Baseline Building both for the energy performance and LCA purposes. This result in the same requirements specified for both analyses. Nevertheless the LCA Baseline Building design and Proposed Building design only account for the structural elements and building envelope materials.

The Performance Rating Method refers to the mandatory provisions in the building envelope, HVAC, service water heating, power, lighting and other equipment. In the LCA baseline design only the mandatory provisions of the building envelope is required. Furthermore these refer to compliance path requirements, where either the Prescriptive Path 5.5 or Building Envelope Trade-Off Option 5.6 should be used. Choosing an appropriate compliance path is mandatory for complying with the requirements. The choice of compliance path is depending on the building design, where simple building shapes with a window-to-wall ratio between 0 - 40 % allow project teams to select a prescriptive path. The Prescriptive Path is a straightforward approach where a set of performance requirements are stated for each building component, for each climate zone. When complex shapes and designs are used in the Baseline Building the Building Envelope Trade-Off Option should be selected. In addition performance requirements of the building envelope components and product information and installation requirements 5.8 should be fulfilled. Building envelope requirement in section 5.5 include minimum R-values on insulation materials and maximum U-value for the assembly of building components. These include exterior walls, roofs, slab-on-grade, floors, windows and opaque doors. Section 5.8 specifies a set of mandatory provisions regarding installation of insulating materials, maximum air leakage and rating of doors and windows in the building envelope.

BBR on the other hand states functional requirements on building components of the building envelope. The functional requirement is intended to capture a specific function for the building envelope performance. The compliance path for reaching the function is unrestricted and allows various design options. As opposite to ASHRAE that uses a more detailed approach in the creation of the building envelope.

The main difference between the requirements found in BBR and ASHRAE are that BBR states functional requirements, while ASHRAE states specific performance requirements.

Following detailed performance requirements stated in ASHRAE will result in a Baseline Building which could be used to analyze the energy performance. In a similar way the Baseline Building design can be created for LCA purposes. In other words the mandatory requirements for the building envelope stated in ASHRAE represent a Baseline Building. In difference to the requirements in BBR which are based on U_{mean}-values for the total building envelope, this enables projects to select and account for different type of materials.

Table 11. Differences in climate envelope requirements between ASHRAE 90.1-2010 and BBR 22

Climate zone 5			
	ASHRAE		**BBR**
Opaque elements	**Assembly U-factor in W/(m^2·K) according to ASHRAE 90.1-2010**		**U_m-factor in W/(m^2·K) according to BBR**
Roofs	Insulation entirely above deck	0.273	0.40
	Metal Building	0.312	
	Attic and other	0.153	
Walls. above-grade	Mass	0.453	
	Metal Building	0.391	
	Steel-framed	0.365	
	Wood-framed and other	0.291	
Walls. below-grade	Below-grade wall	0.678	
Floors	Mass	0.363	
	Steel-joist	0.214	
	Wood-framed and other	0.188	
Slab-on-grade floors	Unheated	0.935	
	Heated	1.489	
Opaque doors	Swinging	2.839	
	Non swinging	2.839	
Fenestration	**Assembly max. U**		
Vertical glazing	Nonmetal framing (all)	1.99	
	Metal framing (curtain wall/storefront)	2.56	
	Metal framing (entrance door)	4.54	
	Metal framing (all other)	3.12	
Skylight with Curb. Glass	0 - 2.0 %	6.64	
	2.1 - 5 %	6.64	
Skylight with Curb. Plastic	0 - 2.0 %	6.25	
	2.1 - 5 %	6.25	
Skylight without Curb. All	0 - 2.0 %	3.92	
	2.1 - 5 %	3.92	

Table 11 presents the differences in building envelope requirements found in ASHRAE 90.1-2010 and BBR 22. Complying with both BBR 22 and ASHRAE requirements regarding the building envelope is possible. Compliance is met by fulfilling the performance requirements of maximum U-value of the assemblies and at the same time ensures the U_{mean}-value for all exterior surfaces to comply with the BBR functional requirements of the building envelope.

In addition to the performance requirements for the building envelope, both standards include a fenestration limit. ASHRAE stats the limit in window-to-wall ratio and window-to-roof ratio, while BBR 22 stats it in window-to-floor area. The limits are presented in Table 12.

Table 12. Differences in fenestration requirements between ASHRAE 90.1-2010 and BBR 22

Climate zone 5			
Fenestration	**Fenestration percentage according to ASHRAE 90.1-2010**		**Fenestration percentage according to BBR**
Vertical glazing	Nonmetal framing (all)	0 - 40 % of wall	10 - 100 % of floor area
	Metal framing (curtain wall/storefront)		
	Metal framing (entrance door)		
	Metal framing (all other)		
Skylight with Curb. Glass	0 - 2.0 %	0 - 5 % of roof	
	2.1 - 5 %		
Skylight with Curb. Plastic	0 - 2.0 %		
	2.1 - 5 %		
Skylight without Curb. All	0 - 2.0 %		
	2.1 - 5 %		

4 LCA

In the third part the background of LCA is explained. Thereafter standards used when performing LCA and methods of how to perform LCA are presented. Results are presented in the end of this chapter.

4.1 General background

During the 1960s the environmental awareness increased around the world. One of the reasons for this sudden awareness was the newly released book "Silent spring" written by the American biologist Rachel Carson. The book describes how the chemicals used by the modern human effect its surroundings. These conclusions were known by scientist, but had not reached the wide public or politicians. When the book spread, the side effects of using chemicals led to debates, which resulted in restrictions of chemical usage. Other events such as the energy crisis in 1973 and the Chernobyl disaster in 1986 led to increased awareness about how sensitive our society is to environmental problems. These events and acknowledge forced countries around the world to find solutions for solving this new threat to the environment (Rydh et al., 2002).

The environmental problem has over time gone from being local to global, but also the strategies of solving the problems have changed. In the beginning of the industrialization it was believed that if the pollutants were spread, the nature would take care of it eventually. Although it was ruled out as a solution when the emissions increased and the impact of them were acknowledged. This was the beginning of a new mindset in the industry, it was understood that the whole process of the product had to be analyzed (Rydh et al., 2002).

Most of the initiatives have been made on a global perspective. One of this initiatives were the United Nation's Brundtland report, were the saying sustainable development was spread and its defined as follows:

> *"Development that meet the needs of today without compromising the ability of future generations to meet their own needs"*

Another initiative was made in 1992, it was The United Nation Conference in Environment and Development that was held in Rio de Janeiro. The World Business Council for Sustainable Development (WBCSD) that led the conference had earlier, around 1990, noticed that among companies there were an absence of uniformed rules and terminology, when assessing environmental problems. Therefor the WBCSD started a committee within the International Organization for Standardization (ISO) that would assess this problem. In 1993 the TC 207 committee was established, they were responsible for the environmental management forms, and since then the TC 207 has developed several standards within the so-called ISO 14 000-series. One of these is the environmental management for LCA. Since the Rio de Janeiro conference other conferences and initiatives about how to reduce the human's effect on the environment has been held (Carlson et al., 2011).

4.2 The ISO 14000 series

In the 1990s the usage of LCA increased, the on-going interest led to environmental adjustments in production strategies. This growing interest created an increased demand for LCA analysis that was practical to use in the daily work. During the 1990s ISO started their work with creating a standard for the life-cycle methodology, which was published in 1997 and named ISO 14 040:1997. The ISO 14 040 standard contributed to an increased usage of LCA, but it also gave the user tools for how the results should be communicated. Since then the LCA development has progressed and today it is usable in many different industries thanks to the usage of Environmental Product Declaration (EPD) (Carlson et al., 2011).

> According to ISO 14 040, LCA is a *"compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life-cycle" (Swedish Standards Institute, 2006).*

The LCA is based on two different standards. The ISO 14040 that describes the main principles and structure of how a LCA should be carried out. The other standard, the ISO 14044 defines details and recommendations of how the procedure of assessing an LCA should be carried out. Furthermore there are also specific documentation format to support the documentation process when assessing an LCA, the ISO/TS 14 048. Additional to this there is also two other technical reports for how some parts of the assessment, ISO/TR 14049 is used for goal and scope definition and inventory analysis. The ISO/TR 14047 is used for to impact assessment situations. There exists many more standards in the ISO 14 000 series, and there is an on-going development of new standards and updates of the ISO 14 000 family (Carlson et al., 2011).

The following list presents the latest updated version of the ISO 14 000 families (ISO, u.d.):

- ISO 14040:2006 Environmental management – Life-cycle assessment - Principles and framework
- ISO 14044:2006 Environmental management – Life-cycle assessment – Requirements and guidelines
- ISO/TS 14048:2002 Environmental management – Life-cycle assessment – Data documentation format
- ISO/TR 14049:2012 Environmental management – Life-cycle assessment - Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis

- ISO/TR 14047:2012 Environmental management – Life-cycle assessment - Illustrative examples on how to apply ISO 14044 to impact assessment situations

4.2.1 How to perform an LCA according to ISO 14040/14044

The main principal structure of an LCA is described in ISO 14040. An LCA is carried out in order to reduce environmental impact by choosing the most ideal product. This is done by comparing different products, to be able to decide which product that has the lowest impact on the environment. A product could be defined as “a system, object or service developed to meet the demand” (Rydh et al., 2002). The LCA can be divided into four life-cycle stages, which are presented in following text (Bayer et al, 2010):

Product

- Extraction of the raw material from the nature
- Transporting of the material to the manufacture
- Manufacturing of the material
- Building fabrication and packing and distribution of building projects

Construction Process

- All activities relating to the actual building project construction

Use (Building operation):

- Energy consumption
- Water usage
- Environmental waste generation
- Repair and replacement of building assemblies and systems
- Transport and equipment use for repair and replacement

End-of-life

- Energy consumed and waste produced due to building demolition and disposal of materials to landfills, and transport of waste materials
- Recycling and reuse activities related to demolition waste also can be included and have negative impact

ISO 15 804

The life-cycle stages can be divided into subcategories, so-called module groups, which are used for analyzing an LCA and creating EPDs. The ISO 15 804 describe how to perform an EPD for the construction industry, according to SS EN 15804 (Swedish Standards Institute, 2013):

"An EPD communicates verifiable, accurate, non-misleading environmental information for products and their applications, thereby supporting scientifically based, fair choices and stimulating the potential for market driven continuous environmental improvement."

To describe the life-cycle process the term cradle-to-grave is often used, from when the energy and material is extracted from the nature, cradle, to when it has been reversed to the nature, grave, once again (Carlson et al., 2011). The cradle-to-grave assessment includes the following life-cycle stages:

- Product, A1-A3
- Construction process, A4-A5
- Use, B1-B5
- End-of-life, C1-C4
- (Benefits D)

In this analysis, cradle-to-grave, a fifth module, module D could be included, which contain benefits from the end-of-life. When an EPD is created, only module groups A1-A3 are mandatory, declarations of the other modules are optional. This system boundary creates a cradle-to-gate assessment. Further on the cradle-to-gate option, covers A1-A3 with additional, optional modules, for example A4, see Figure 7 (Swedish Standards Institute, 2013).

PRODUCT			CONSTRUCTION PROCESS		USE					END OF LIFE			
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4
Extraction and upstream production	Transport to factory	Manufacturing	Transport to site	Construction / Installation	Use	Maintenance*	Repair*	Replacement*	Refurbishment*	De-construction	Transport	Waste processing	Disposal
					B6	Operational energy use							
					B7	Operational water use							

*(incl. production and transport of necessary material)

Figure 7. Information module groups in a LCA

The purpose of the LCA is to contribute to product development and improvement, strategic planning, public policy making, marketing and other. These purposes are obtained by following the four phases of LCA, which are stated in ISO 14 040 (Swedish Standards Institute, 2006). An LCA is conducted in four different phases, which are presented in Figure 8, with a description in the following text.

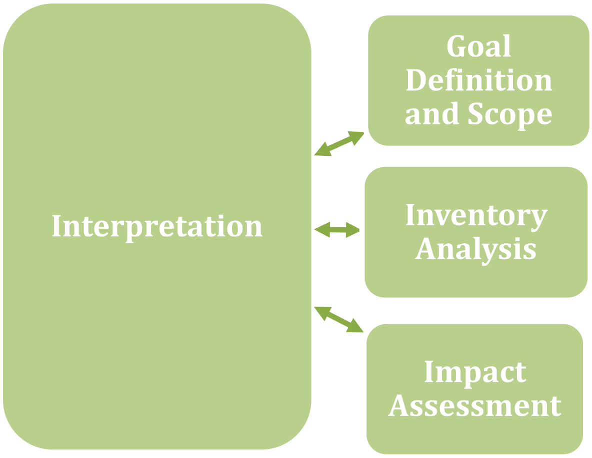


Figure 8. LCA Phases

Step 1. Goal Definition and Scope

In this phase the product that will be analyzed should be presented, also the reason for the analysis, why it is done and what the result should be used for.

This section should contain:

- The scope of the analysis
- What type of analysis that is carried out
- What impact categories that will be evaluated

It might also be necessary to go back to this phase later in the process to optimize and clarify the goal definition and scope.

Step 2. Inventory Analysis

In this phase all data from resources, raw material, waste, emission from the production should be gathered and put in the process flow chart in relation to suitable functional unit. The collected data should present input and output in order to perform a detailed inventory analysis. In this part a software and/or database could be essential, so that a material not have to be analyzed individual every time a LCA is performed. The simplest tools are spreadsheets, but there are also more complicated software's.

Step 3. Impact Assessment

During the impact assessment the emissions from the analyzed product is converted into how the impact on humans and the eco-system. The data from the inventory analysis is categorized in the right impact category. There is none impact framework, which means that the LCA user could choose which categories that should be analyzed.

Step 4. Interpretation
The impact of the product should be evaluated throughout the whole LCA, in order to lower the environmental impact. Therefor could an LCA be seen as an iterative process where it might be necessary to go back and forth between the phases in order to make environmental friendly decisions (Bayer et al, 2010).

4.3 Findings from LCA

The following chapter answers the two questions:

- *What should is included in ISO 14 040 and ISO 14 044?*
- *What is included in a cradle-to-grave LCA?*

Today, an LCA is based on two different standards. The ISO 14040 that describes the main principles and structure of how a LCA should be carried out. The other standard, the ISO 14044 defines details and recommendations of how the procedure of assessing an LCA should be carried out. Further on to there are additional standards within the ISO 14 000 family.

When performing a LCA in accordance with ISO 14040, there are four different life-cycle stages; product, construction process, use and end-of-life. Occasionally a fifth life-cycle stage is included which contains benefits from the end-of-life stage, which is voluntary. The life-cycle stages contain subcategories, so-called module groups. When performing an LCA there are different system boundaries that are used, depending on which module groups that are included.

Two examples of system boundaries are:
Cradle-to-grave:

- Product, A1-A3
- Construction process, A4-A5
- Use, B1-B5
- End-of-life, C1-C4
- (Benefits, D)

Cradle-to-gate:

- Product, A1-A3

LEEDv4 requests that the LCA is performed according to a cradle-to-grave assessment.

5 Development of a Baseline Building

The fourth part explains the method that was used in order to investigate whether it was possible to create a general Baseline Building representing the Swedish building stock. The Baseline Building should include structural element and building components according to the requirements found in LEED, ASHRAE and BBR. As a first step surveys regarding newly built multi-family dwellings in Sweden were analyzed. In addition to these surveys, information was gathered from the BETSI project, Wikells Sektionsfakta, material suppliers and internal data from a construction company. When all information was analyzed, the Baseline Building was created.

5.1 Analysis of the Swedish building stock

Statistical data was gathered to find typical materials/building components used in Swedish buildings. Databases and projects containing building specific information of the Swedish building stock were gathered. The selected data was based on the credit Building Life-Cycle Impact Reduction in LEED v4, which state a Baseline Building should represent typical constructions for their region (U.S. Green Building Council, 2013). In addition to this the Baseline Building should fulfill the criteria and descriptions set in ASHRAE 90.1-2010, according to LEED v4.

The analysis of the Swedish building stock was carried out in a step-by-step approach. In the first step, surveys conducted by SCB were gathered and analyzed to investigate typical building materials used in the building envelope. Secondly information from the Swedish national project BETSI was investigated. Any missing information needed for developing a Baseline Building according LEED v4 was supplemented from material suppliers. As a fourth and final step drawings of standard building designs and constructions were gathered from Skanska internal database (VSAA). Each project/database used for the analysis is presented in Figure 9. The investigated projects and databases are described in the following text.

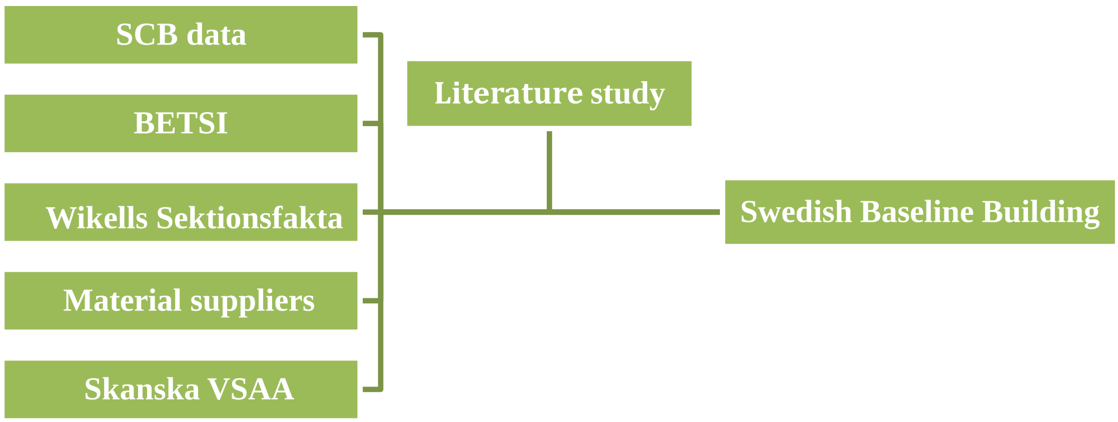


Figure 9. Overview of the data collection process used in this report

SCB data
Statistika CentralByrån (SCB) is roughly translated in English to the Swedish Central bureau of statistics. SCB is a public administrate authority in Sweden, which provides official and public statistics for decision-making, debate and research. The choice of gathered statistics is mainly decided by the Swedish government and various authorities, but also by researches and private businesses.
The purpose of SCB is to develop, produce and distribute statistics, and support international organizations with statistical data (SCB, 2014).

In 2009 SCB changed their policy regarding public information, because of this it was not possible to obtain information of primary data later than 2009. Therefor data from 2009 and earlier was used in order to process the data as desired for this project.

The BETSI-project
In 2006 Boverket got the mission from the Swedish government to investigate the condition of the Swedish building stock. The project named “Byggnaders energianvändning, tekniska status och inomhusmiljö” (BETSI) was carried out all over the country by conducting surveys and inspections. During the period of 2007 – 2008 about 1800 inspections and measurements in 30 different municipalities was carried out. Boverket investigated the buildings energy consumptions, technical status and indoor environment. At the same time the inhabitants got to answer surveys about how they experienced the indoor environment and and questions about their health. The report was finalized first in 2009 where the result of the task was presented. One of the resulting project reports were “Så mår våra hus – Redovisning av regeringsuppdrag beträffande byggnaders tekniska utformning m.m.”, which was used in this investigation (Boverket, 2009).

Skanska VSAA
When all information regarding the building envelope components and material selection was identified, standard building designs were gathered. These were collected from Skanska’s internal database Vårt Sätt Att Arbeta (VSAA) = Our way of working, which provided architectural drawings for standardized multi-family dwelling design.

Wikells Sektionsfakta
Wikells Sektionsfakta contains data regarding ingoing material for different building components. The program was in this case used as a measure to estimate material consumption for each building component. Wikells Sektionsfakta is based on a standard pricelist from different industries in the construction business. Besides material consumption and cost, the program gives the user in information regarding proposed building constructions, waste and time spent by the craftsmen (Wikells Sektionsfakta, 2015).

Material suppliers
Questions regarding windows and doors were excluded in the surveys carried out by SCB and was therefore complemented from material suppliers. Two of the largest Swedish window suppliers, Elitfönster and SP fönster, were contacted in order to find the most common window type sold to newly constructed multi-family dwellings in Sweden.

The following questions were asked:

- Does any statistics of the most common window type for newly produced multi-family dwellings exist?
- Which main components are included in that window?
- Does EPDs exist for that window type?

5.1.1 Data collection

All collected data regarding the structure elements and building envelope of the analyzed buildings were gathered from SCB, primary source, with additional data from the BETSI project, Wikells Sektionsfakta and material suppliers, secondary source. The gathered SCB data contained 11376 conducted surveys regarding newly constructed dwellings between 1995-2009, including information regarding material choice, technical solutions and miscellaneous information. The scope for the data collection was limited to only include the past 10 years of available data 2000-2009 and limited to 3-8 stories multi-family dwellings. The number of surveys within the chosen scope was limited to 2441.

Building material
SCB contain statistical data which was used as a primary source, while the BETSI project and Wikells Sektionsfakta was used as a secondary source, as a complement to the statistical data. The secondary data was used to determine the amount of building materials based on common U-values derived from BETSI project. Additional data and information was gathered from material suppliers to fill out any missing information regarding materials in the primary source.

SCB and the BETSI project were based on different time periods; where SCB gathers yearly statistical data, compared to BETSI, which divide the data in time spans of 10 years (1996-2005). Due to the variations in time periods the comparison between the data in the BETSI project and the processed data from SCB only provides rough estimations of the building envelope performance.

The gathered data was divided into four main components of the building envelope and structural bearing. In addition, two more questions were analyzed regarding common building shapes and manufacturing method. These were selected based on the requirements of LEED v4 when creating a Baseline Building for LCA purpose

(U.S. Green Building Council, 2013). The six questions investigated are presented in **Error! Reference source not found.**.

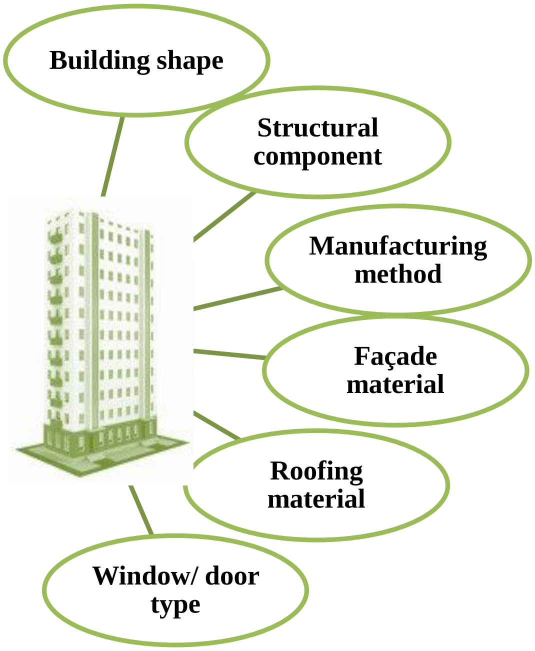


Figure 10. The six questions investigated for determining a Baseline Building.

Each question is connected to a number of variables, containing different material selections of each building component. Five out of six building components are presented in Table 13. The sixth building component windows and doors were excluded in the SCB-surveys. Because of this, additional information regarding window and doors parameters were necessary to complement, which were gathered from contact with material suppliers.

The following ingoing parameters for windows were requested:

- Material included in component
- Number of panes
- Gas
- Low-e coating
- Frame type

Table 13. The five main questions and variables gathered from SCB surveys.

	Building shape	**Structural element**	**Manufacturing method**	**Façade material**	**Roofing material**
Variables	Apartment Block	Wood	Completely prefabricated	Wood	Concrete tiles
	Building Block	Concrete	Partly prefabricated	Concrete	Mud-brick
	External entrance house	Steel	Built-on-site	Brick	Sheet metal
	Terraced house	Other		Lime brick	Felt roof
	Other			Plaster	Other
				Sheet metal	
				Other	

Apartment Block = Lamellhus, BBR definition: *"Houses that have two or more stories above the round and at least two interior staircases. The building is not angled or incorporated with house on the neighboring property."*

Building Block = Punkthus, BBR definition: "*Detached building with several floors above ground with one, usually centrally located, stairwells."*

External entrance house = Loftgångshus, BBR definition: *"Multi-family dwellings with access to the apartments via exterior corridors, an elongated balcony along the building facade. Balcony access may have surface mounted or built staircase*."

Terraced house = Flerbostadsvilla, BBR definition: *"Small villa-like building with a few apartments, however always at least three residential apartments* (Boverket, 071025)*."*

Other All other designs that cannot be defined by the four other alternatives.

5.1.2 Data process and analysis

All surveys gathered from SCB were processed in the computer program, Microsoft Excel. The analysis of the data was carried out in a two separate studies, One-way tables and Cross-Tabulation (The Statistical Services Centre, 2001).

One-way tables use a more straightforward approach since each question was analyzed independently from each other. This analysis was made to find which variable was most common for each question answering the choice of material in building components. The frequencies and percentages of each question was presented in tables which were derived from formulas, where *COUNTIF, VLOOKUP* and *Pivot tables* were used in Microsoft excel.

The survey questions were analyzed to determine which answer that was most common for newly constructed multi-family dwellings in Sweden, of 3-8 stories during 2000-2009. Analyses were conducted for the five different survey questions, presented in Table 14 - Table 18. Each question was coded by SCB, described as SCB code in the tables. Questions regarding materials, where more than one answer could be correct, only the main material choice be selected. For question 11, regarding manufacturing methods, the three different manufacturing methods were missing clear definitions, for what was the difference between the three answers.

Table 14. SCB survey question regarding building shapes

Question 5: What building shape is chosen for the constructed multi-family dwelling?	
SCB Code	**Survey answer**
21	Apartment Block
22	Building Block
23	External entrance house
24	Terrace house
25	Other

Table 15. SCB survey question regarding material in structural component

Question 10: What material is chosen for the building structure?	
SCB Code	**Survey answer**
1	Wood
2	Concrete
3	Steel
9	Other

Table 16. SCB survey question regarding manufacturing method of the structural component.

Question 11: Which type of manufacturing method is used for the structural material?	
SCB Code	**Survey answer**
1	Completely prefabricated
2	Partly prefabricated
3	Built-on-site

Table 17. SCB survey question regarding the facade material.

Question 12: What is the chosen facade material?	
SCB Code	**Survey answer**
1	Wood
2	Concrete
3	Brick
4	Lime brick
5	Plaster
6	Sheet metal
9	Other

Table 18. SCB survey question regarding the roofing material.

Question 13: What is the chosen roofing material?	
SCB Code	**Survey answer**
1	Concrete tiles
2	Mud-brick
3	Sheet metal
4	Felt roof
9	Other

Cross-tabulation

Cross-tabulation method investigates questions in relation to each other to find the most common combination. The combinations were analyzed by using pivot tables to enable a visualization of the available combinations found in the surveys. The analysis was divided into two pivot tables for each building shape. This approach left four of the main components to be sorted in the pivot table. The first two questions, structural element and manufacturing method, were inserted into rows while the remaining two, façade material and roofing material, were used in the columns, as shown in Figure 11.

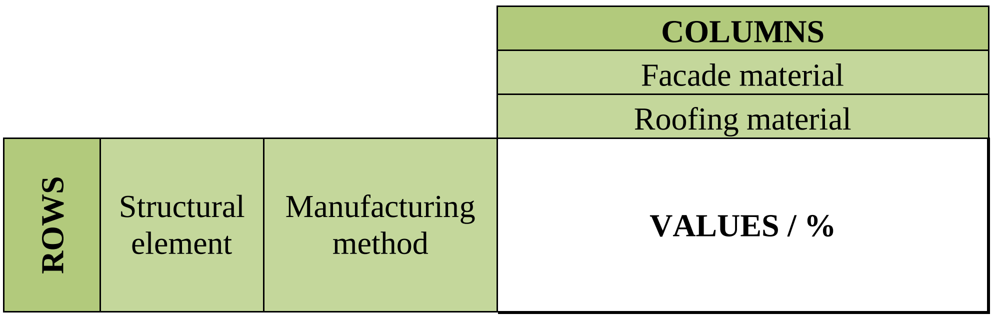


Figure 11. Layout and input values of the studied pivot table.

The pivot table offered a large variety of combinations from the analyzed surveys; these were therefore restricted to only account for the combinations occurring more than 7 % in all of the surveys.

5.2 Starting point for baseline

The following part describes the process of how the Baseline Building was created. As a first step a building design was chosen based on statistical review and conceptual designs from Skanska. The conceptual building design was used as a starting point for the Baseline Building design. Thereafter the material selection for each building component of the building envelope was transferred from SCB, BETSI, and Wikells Sektionsfakta together with information from material suppliers.

5.2.1 Starting point for building design

To be able to create a Baseline Building a defined building design was needed. The building design was obtained from standardized multi-family dwellings created and used by Skanska. These standardized multi-family dwellings contained information regarding building dimensions and construction.

Building dimensions were taken from the drawings. The building dimensions were used to developing the Baseline Building while the material selection for the building envelope and was based on the statistical review. No calculations for dimensioning the constructions were made; the chosen dimensions were only based on assumption from the standardized drawings from Skanska.

5.2.2 Starting point for building components

The constructions for the building components in the Baseline Building were based on the result found in analysis of the Swedish building stock. The constructions were derived from Wikells Sektionsfakta, which was used in order to estimate the quantities of used material in building components. Additional information and definitions were gathered from the largest concrete prefabrication companies in Sweden, Strängbetong and Abetong, to make valid assumptions of construction types.

The calculated U-value of the assumed building components were compared to the BETSI average U-values for multi-family dwellings in 1996-2005. The ASHRAE and BBR requirements for maximum allowed U-value were compared with the calculated results.

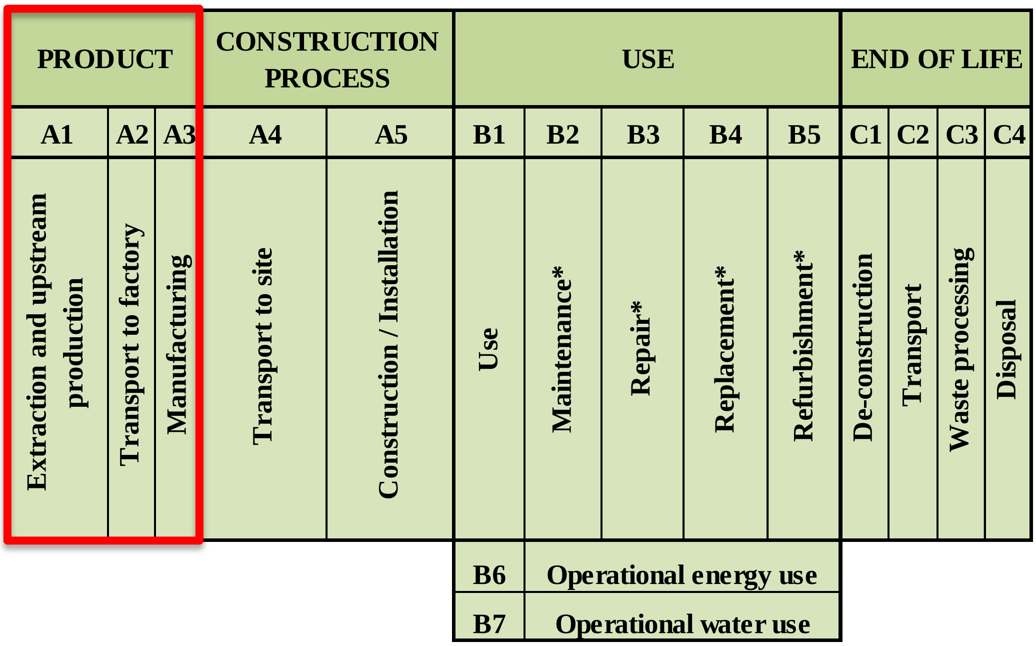
5.3 Analysis of LCA

In this part the LCA of the analyzed building components are presented. The LCA of the building components were analyzed in a simplified LCA tool, which normally is used by Skanska. This part presents how the analysis was carried out, which parameters that were analyzed and how they were varied.

The used simplified LCA tool is a simplified version of the more advanced LCA-program ECO_2. The simplified LCA tool is limited to only analyze the module groups, A1-A3, while ECO_2 can investigate the whole cradle-to-grave system boundary. Both the simplified tool and ECO_2 uses the same emission factors and provides generic data for the different materials. This means that the results that are presented only present a mean value for each material. The emission factors are calculated by IVL, the Swedish Environmental Research Institute (IVL, 2013). Currently the simplified tool used data from 2013. The tool includes sections A1-A3 for the product stage in the LCA, which means that the processes for raw material, transportation to the factory and manufacturing is included. Since LEED also includes B1 - B7 and C1 - C4, the LCA's were not complete, see Figure 12.

Limitations in the simplified LCA tool:

- Only includes LCA group modules A1-A3
- Only produce results for GWP (CO_2-eqv.)
- Has a limited material data base



*(incl. production and transport of necessary material)

Figure 12. Life-cycle stages included in LCA

LCA of starting point

The following building components were included when designing the Baseline Building. These building components were also used for the LCA of the starting point Baseline Building.

The following building components were included in the Baseline Building:

- Slab-on-grade

- Footing (only enclosing part of slab-on-grade)
- Slab
- Roof slab
- Roof construction (incl. coverings)
- Load bearing inner walls
- Exterior walls
- Exterior windows
- Exterior doors

The following building components were excluded in the Baseline Building:

- Stair construction
- Interior finishes of walls
- Footing (load-bearing slab-on-grade constructions)
- Drainage material such as macadam

In the following part the building constructions that were used as a starting point for the Baseline Building are described.
These were investigated to decide which building components that contributed the most to the global warming potential.

LCA for different building components

Furthermore the LCA was carried out in two steps, as a first step 1 m^2 of each building component was analyzed individually, to evaluate which solutions that had the most reduction of CO_2-eqv. A sensitivity analysis was carried out in order to estimate which building components that influenced the outcome of the LCA the most.

The following alternatives were investigated in the sensitivity analysis:

- Different insulation materials
- Different suppliers of reinforcement steel
- Different concrete qualities
- Variation of roofing materials

LCA for whole building

As a second step of the LCA analysis a whole building analysis was carried out. The analysis was also carried out for the three different heights of the buildings, 3, 6 and 8 stories. In this whole building analysis, the solutions with the most reduction of CO_2-eqv was applied.

6 Result

6.1 Analysis of the Swedish building stock

The first part presents the results from the one-way-table study, where each survey question was analyzed. This is followed by the cross tabulation study that analyzes the same questions found in the surveys, but coupled with relations to find the most common combination. Thereafter a summary of common U-values found in the BETSI-project is presented. The combinations that are found to be most common in the survey answers will be used in the development of a Baseline Building.

Building shape

The results show that two building shapes apartment building and Building Block are the most common shapes built in Sweden during 2000-2009, see Figure 13. These two building shapes were analyzed further since they account for 89 % of 2441 conducted surveys. This reduced the number of surveys to 2172 when excluding External Entrance House, Terraced House and Other building shapes.

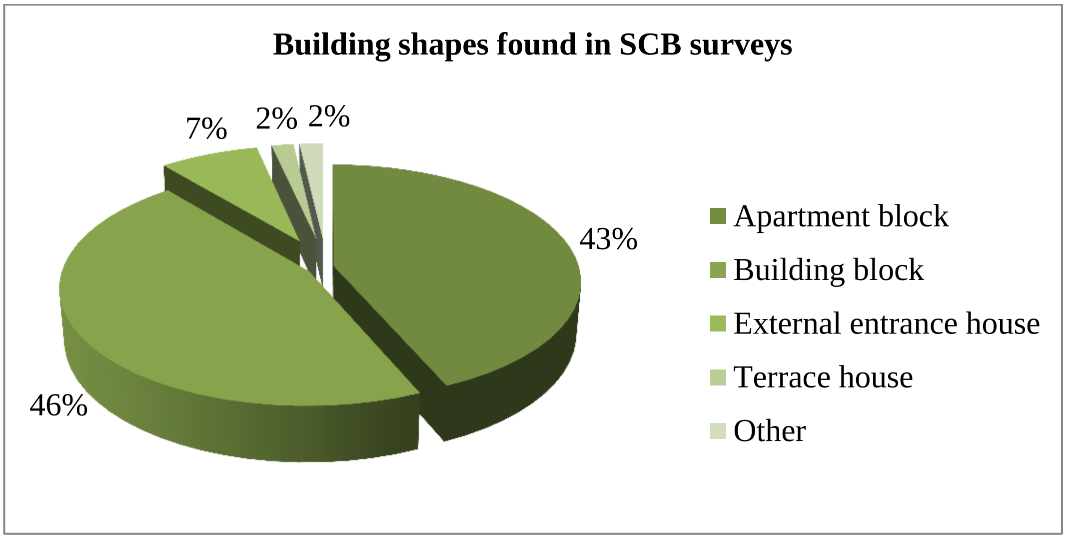
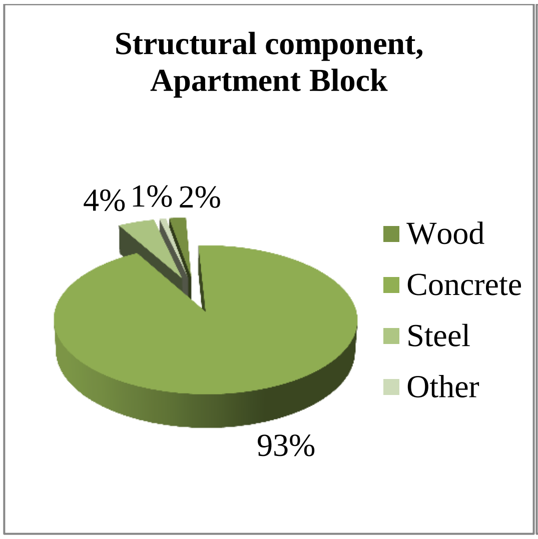


Figure 13. The most common building shapes constructed during 2000-2009.

Structural component

The results show that concrete was the most common material used in the building structure of both building shapes, see Figure 14. When comparing the two results, the Building Blocks have a lower percentage built out of concrete since wooden and steel structure was more common in this case. Both Apartment Blocks and Building Blocks constructed in concrete represent the largest percentage of the total conducted surveys. Due to this only concrete as structural components is analyzed for the manufacturing method. This limits the number of conducted surveys to 1963.



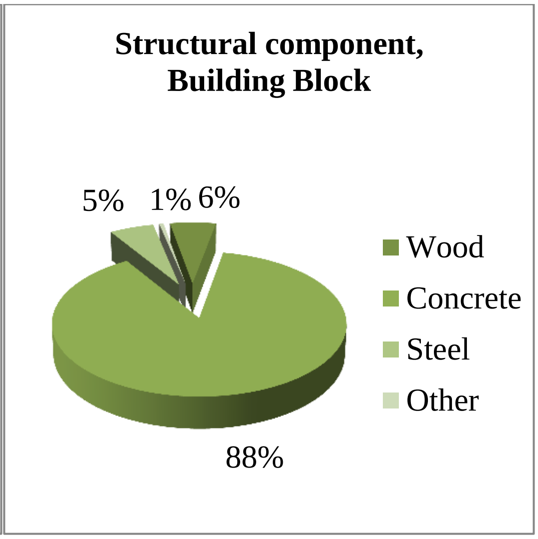
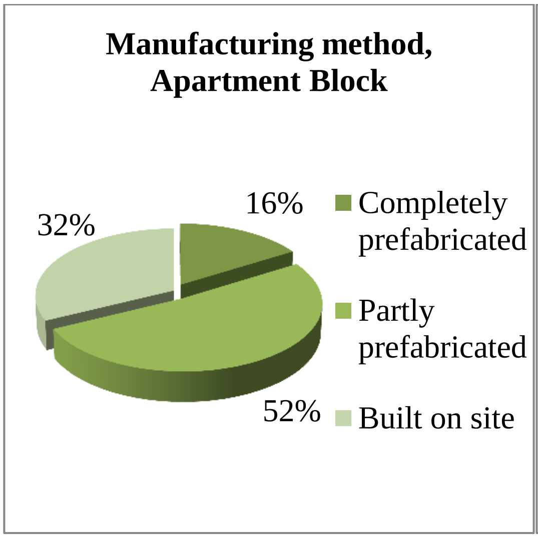


Figure 14. Most common material selection for the structural bearing.

Manufacturing method

The analysis present small variations in manufacturing method between the two building shapes, the frequency of built-on-site is similar for both Apartment Block and Building Block, see Figure 15. The two prefabrication methods, completely prefabricated and partly prefabricated, show slight differences in frequency in relation to the building shape. However for both building shapes, Apartment Block and Building Block partly prefabricated is the most common.



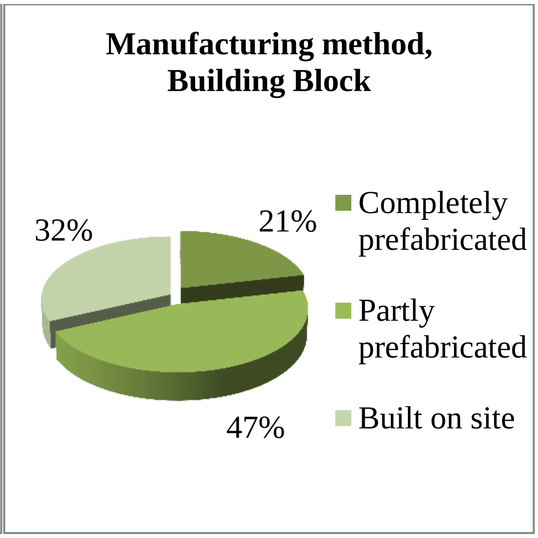


Figure 15. Most common manufacturing method for the structural bearing.

Façade material

There are no significant material variations between the both building shapes, see Figure 16. Plaster is the predominate material used for façade finish for both

Apartment Blocks with 72 % and Building Blocks with 69 %, followed by brick and concrete.

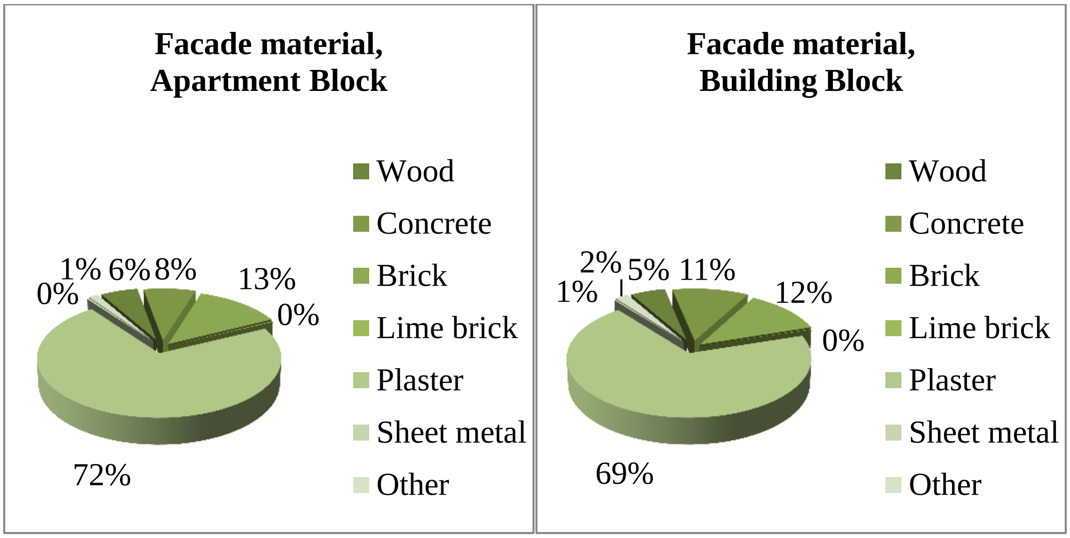


Figure 16. Most common façade material choice of the two building shapes.

Roofing material

Figure 17 presents the differences of material choice in the roofing material for both building shapes. The three most common materials used for both building shapes are metal sheet, roofing felt and concrete tiles, in that order. The biggest difference between roofing materials in Apartment Blocks and Building Blocks is the usage of concrete tiles and roofing felt. Apartment Block has a higher usage of concrete tiles compared to roofing felt and vice versa.

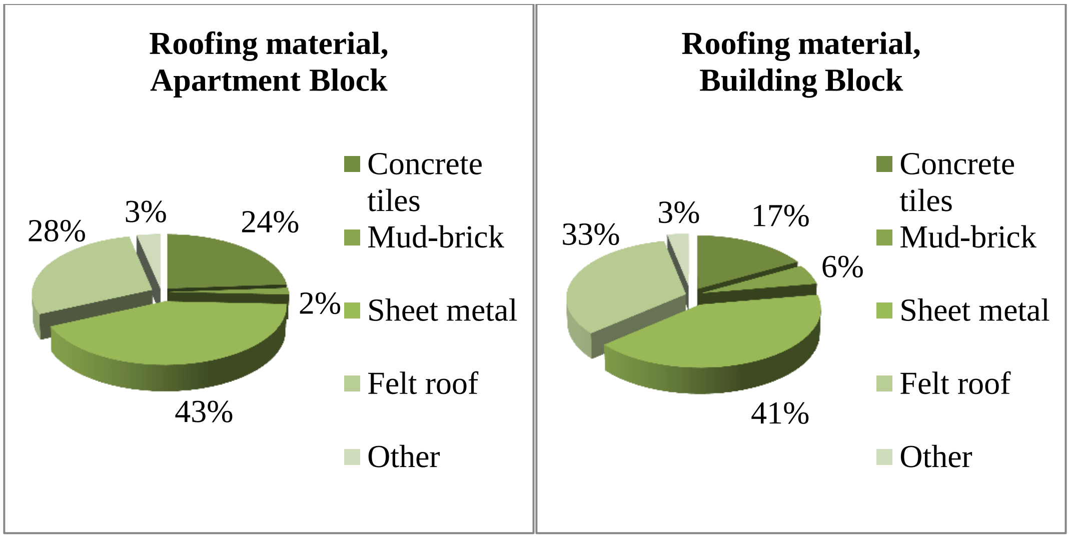


Figure 17. Most common material choice for the roofing materials.

Cross tabulation
Results from the cross tabulation study are presented in tables for each building shape, Apartment Block and Building Block. The results present the most common building materials combinations used in regards to the chosen scope of the thesis.

Apartment Block
The results regarding common combinations used in Apartment Blocks present four combinations that occur more than 7 % of the total number of surveys 2172. Each building shapes is presented alone, where Apartment Block account for 1060 surveys and Building Blocks 1112 for the total.

The most common combination in Apartment Blocks are presented in Table 19. Results show that the most common combination consists of a partly prefabricated concrete structure with plaster façade and metal sheet roofing in 21.1 %. Study show that all four combinations have used concrete as the structural material and plaster as façade material. This matches the results from the one-way table studies, which indicated a high usage of these materials. The only material variation found in the four building combinations affects the manufacturing method, which is either partly prefabricated or built-on-site and variation in the roofing material sheet metal, roofing felt and concrete tiles.

Table 19. The most common building combinations from the cross tabulation study regarding Apartment Blocks.

Apartment Block				
Combination	**1**	**2**	**3**	**4**
Structural component	Concrete	Concrete	Concrete	Concrete
Manufacturing method	Partly prefabricated	Partly prefabricated	Partly prefabricated	Built-on-site
Facade material	Plaster	Plaster	Plaster	Plaster
Roofing material	Sheet metal	Felt roof	Concrete tiles	Felt roof
Percentage	**21.1%**	**8.8%**	**8.7%**	**7.2%**

Similar results were found when analyzing the Building Blocks. The results are presented in Table 20 and displays similar combinations for both building shapes. The most common combination turned out to consist of a partly prefabricated concrete structure with plaster façade and metal sheet roofing, 17.8 %. The spread between the four most common combinations is however smaller for Building Blocks compared to Apartment Blocks.

Both building shapes use concrete in the structural components and plaster in the façade materials. The combinations vary on the manufacturing method of structural concrete and chosen materials in the roof. Combination one, two and four are same for both building shapes, where the percentage varies for each building shape. However the third most common combination presents differences in the choice of manufacturing method and roofing material. The percentages for the third combination in both Apartment Block and Building Block vary slightly in the percentages 8.7 % compared to 8.9 % The third combination of Apartment Blocks use a partly prefabricated concrete structure and concrete tiles in the roofing material, while Building Blocks uses built-on-site concrete structure and sheet metal for the roofing material.

Table 20. The most common building combinations from the cross tabulation study regarding Building Blocks

Building Block				
Combination	**1**	**2**	**3**	**4**
Structural component	Concrete	Concrete	Concrete	Concrete
Manufacturing method	Partly prefabricated	Partly prefabricated	Built-on-site	Built-on-site
Facade material	Plaster	Plaster	Plaster	Plaster
Roofing material	Sheet metal	Felt roof	Sheet metal	Felt roof
Percentage	**17.8%**	**11.3%**	**8.9%**	**7.4%**

6.2 Starting point for Baseline Building

The structural and building envelope components were based on the collected data from SCB surveys analysis and material suppliers. Some assumptions were made for the materials of the statistical analysis; these were made due to the lack of definitions of the chosen construction types.

6.2.1 Starting point for building design

In order to represent the investigated building shapes, Apartment Block and Building Block, two building designs were chosen, Frida and Linnea. The two buildings were within the thesis scope, multi-family dwellings of 3-8 stories. Each building shapes is presented in Figure 18 and Figure 19 with general information in Table 21 and Table 22. The used data for the fenestration is presented in

Appendix B. Fenestrations.

Figure 18. Apartment Block Frida, 3, 6 and 8 stories

Table 21. Building information of Apartment Block Frida

Frida			
General information		**Building dimensions / m**	
Building shape	Building Block	**Length**	34.74
Rooms/apartment	1-4 rooms	**Width**	10.44
Apartment size / m^2	33.5-92.5	**Story height**	2.83
Number of stories	3-8	**Attic height**	0.55
		Roof length	36.40
		Roof width	10.85

Figure 19. Apartment Block Linnea, 3, 6 and 8 stories

Table 22. Building information of Building Block Linnea

Linnea			
General information		**Building dimensions / m**	
Building shape	Building Block	**Length**	17.90
Rooms/apartment	1.5-3 rooms	**Width**	17.30
Apartment size / m²	45-67	**Story height**	2.83
Number of stories	3-8	**Attic height**	1.94
		Roof length	17.80
		Roof width	18.10

The two building dimensions and designs were used for representing the Baseline Building. The most common materials found during the statistical analysis were applied to the structural components and the building envelope. Where each building component slab on ground, roof and wall assemblies, were assumed to reflect common building practices found in Wikells Sektionsfakta database and from internal database from Skanska. These material combinations were combined with the standardized building models to develop the Baseline Building.

Building dimensions were extracted from 2D models, drawn in AutoCad of the two building models, Frida and Linnea. The extracted area is compiled in Table 23 and Table 24, which were used further for calculating materials amounts for different construction methods.

The parameters gathered from Skanska conceptual buildings included:

- Total external wall area
- Total external roof area
- Total gross floor area
- Total slab area
- Total window area
- Number of stories
- Window-to-wall ratio

Table 23. Model input data for Apartment Block Frida

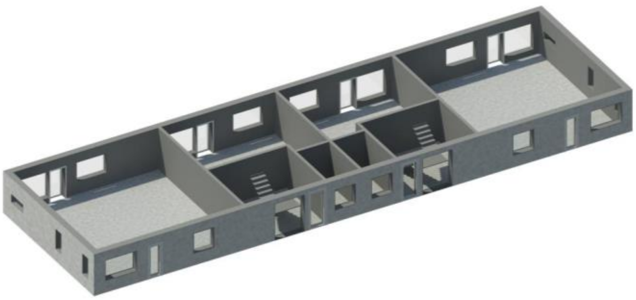
Model input data				
	**Frida**			
	Number of stories			
Building components	**Unit**	**3**	**6**	**8**
Total external wall	m^2	809.4	1504.9	1968.6
Total inner wall area (load bearing)	m^2	142.5	277.8	368.0
Total roof area	m^2	394.9	394.9	394.9
Total slab area	m^2	746.3	1865.6	2611.9
Total footing length	m	92.4	92.4	92.4
Total slab-on-grade area	m^2	373.1	373.1	373.1
Total roof-slab area	m^2	373.1	373.1	373.1
Total window area	m^2	228.9	449.4	596.5
Window-to-wall ratio	%	28	30	30

Table 24. Model input data for Building Block Linnea

Model input				
	Linnea			
	Number of stories			
Building components	**Unit**	**3**	**6**	**8**
Total external wall	m^2	666.0	1263.7	1662.1
Total inner wall area (load bearing)	m^2	379.7	759.5	1012.7
Total roof area	m^2	322.2	322.2	322.2
Total slab area	m^2	619.3	1548.4	2167.7
Total footing length	m	70.4	70.4	70.4
Total slab-on-grade area	m^2	309.7	309.7	309.7
Total roof-slab area	m^2	309.7	309.7	309.7
Total window area	m^2	155.1	313.2	418.5
Window-to-wall ratio	%	23	25	25

6.2.2 Starting point for building components

In the following chapter the assumptions and simplifications regarding the choice of construction type for each building component is explained. The building components are based on results from SCB, Wikells Sektionsfakta and common construction principles. The drawings for the building components are presented in Appendix C. Architectural drawings.

Slab-on-grade

Slab-on-grade was assumed to 100mm of concrete with 300mm of underlying EPS insulation. The amount of reinforcement and construction assembly was collected from Wikells Sektionsfakta. No site development or material filling (macadam) was assumed for the given construction. The slab-on-grade assembly is presented in Table 25.

Table 25. Starting point for slab-on-grade

Material	Quantity	Amount	Unit
100 Concrete C25/30	Area	1.00	m²
Reinforcement	Area	1.20	m²
100 Cellular plastic	Area	1.00	m²
100 Cellular plastic	Area	1.00	m²
100 Cellular plastic	Area	1.00	m²

Joist construction

The joist constructions only include the structural bearing for each floor excluding any finishes made. HD/F joists where chosen for the floor construction in the Baseline Building, the thickness was assumed to 200mm, see Table 26.

Table 26. Starting point for joist

Material	Quantity	Amount	Unit
200 HD/F Concrete C25/30	Area	1.00	m²
Reinforcement	Mass	12.00	kg

Roof covering

Only one question in the analyzed surveys was concerning the roof type, “What is the chosen roofing material?” The statistical analysis only presented the most common roofing material. The results from the analysis show that sheet metal was most commonly used material. The construction type was unknown and assumptions were made on the roof construction, see Table 27.

Table 27. Starting point for roof covering assembly

Material	Quantity	Amount	Unit
Steel roofing	Area	1.00	m²
Paperboard	Area	1.00	m²
22 Tongue and groove panel	Area	1.00	m²
45x145 roof ridge-C14 c1200	Length	1.20	m
45x95 roof ridge-C14 c1600	Length	0.70	m
Nail-plate 60x240x2.0	Pieces	2.20	-
Brackets, nails	Pieces	0.75	-

Roof construction

The roof construction was assumed to be a cold attic, with a concrete roof joist entirely insulated with loose wool insulation. The same concrete quality and construction type was selected as joists between each story, see Table 28.

Table 28. Starting point for roof construction assembly.

Material	Quantity	Amount	Unit
450 loose wool fill	Area	1.00	m²
200 HD/F Concrete C25/30	Area	1.00	m²
Reinforcement	Mass	12.00	kg

External wall

The most common material combinations regarding the external wall were derived from the SCB survey analysis. This included three questions concerning the type of exterior wall:

- What material is chosen for the building structure?
- Which type of manufacturing method is used for the structural material?
- What material is chosen for the façade material?

The results showed the most typical combinations for both building shapes were partly prefabricated concrete structures with a plaster finish. Since the manufacturing methods was not defined the in the surveys each variable had to be assumed. These were based on contact with concrete suppliers, Abetong and Strängbetong and construction engineers at Skanska regarding the construction industries definition of partly prefabricated concrete structures. Based on the information, two assumptions were made of the structural components. The first assumption, partly prefabricated 1, a so-called sandwich construction, included two layers of concrete C25/30 with a layer of EPS insulation in-between and a plaster façade. The wall is delivered finished where the façade material was assumed to be built-on-site. The second version, partly prefabricated 2, was assumed to be a single-element concrete C25/30 construction where the external layer of mineral wool insulation and plaster façade was built-on-site. The material amounts for the assemblies where gathered from Wikells Sektionsfakta database, Skanska VSAA and Strängbetong, see Figure 20, Table 29 and Table 30 for the chosen construction types.

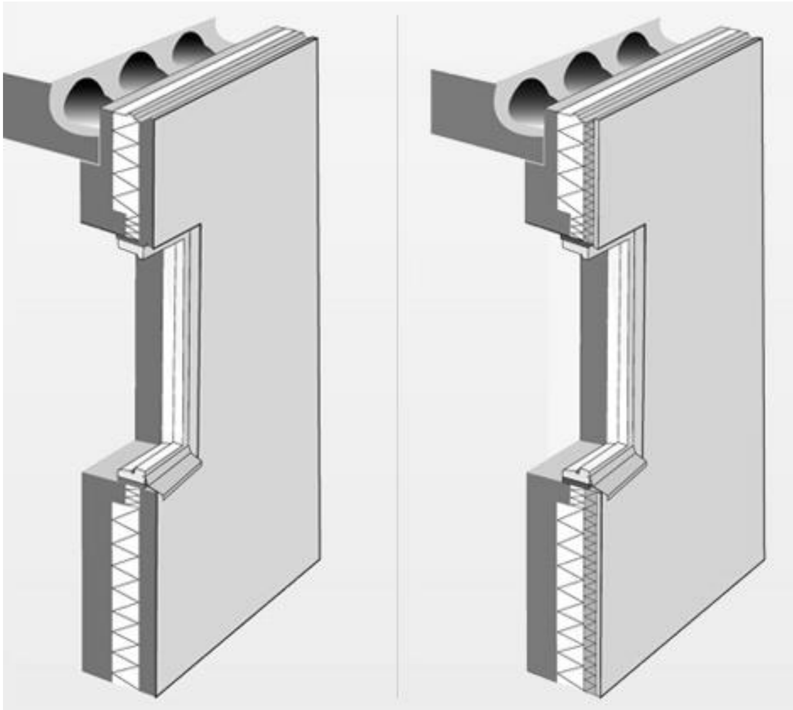


Figure 20. Two construction alternatives regarding the assembly of the exterior wall. Partly prefabricated 1, sandwich wall element and partly prefabricated 2, single-element concrete wall (Strängbetong, 2014).

Table 29. Starting point for Sandwich concrete element assembly

Material	Quantity	Amount	Unit
Plaster	Area	1.00	m²
70 Concrete C25/30	Area	1.00	m²
Reinforcement	Mas	3.80	kg
200 EPS	Area	1.00	m²
150 Concrete C25/30	Area	1.00	m²
Reinforcement	Mass	7.60	kg

Table 30. Starting point for Single-element concrete wall assembly.

Material	Quantity	Amount	Unit
Plaster	Area	1.00	m²
200 Mineral wool	Area	1.00	m²
150 Concrete C25/30	Area	1.00	m²
Reinforcement	Mass	1.00	kg
Reinforcement	Mass	6.60	kg

Windows and doors

One of the largest window suppliers, Elitfönster, was contacted regarding common window types sold to newly constructed multi-family dwellings. Elitfönster had no statistical data to support which was the most sold window for each building type. Elitfönster still they knew within the company that the two products most used for this kind of project were: Elit xceed outwards and Elit xceed inwards. Both windows have a wooden frame and stash with an exterior aluminum covering. The outward window has a lower U-value, but the inward window reduces noise better and was therefore a more common choice for buildings in cities. The U-value of these windows varies up to 1.2 W/(m^2K).

The other producer, SP fönster states that they have two popular window types for multi-family dwellings. These were top-swing windows with a wooden frame and stash with an exterior aluminum covering. The second one was a 2+1 inward going window with wooden frame and aluminum covering. The U-value of these windows varies between 0.9-1.2 W/(m^2K).

From both producers the technical data and EPDs for the different windows were received, which was analyzed in order to pinpoint the most common window for multi-family dwellings. Based on this information from the two window suppliers, the windows were assumed to consist of three glass panes, aluminum coated wooden frames without gas. The same product assembly was assumed for the exterior doors, since doors were glazed in the two building designs, Frida and Linnea.

Summary of U-values from the BETSI-project

To ensure the chosen construction of each building component is represented to the Swedish building stock, U-value calculation were made and compared to BETSI project results. In addition the requirements from ASHRAE and BBR regarding the performance of the building envelope was fulfilled. The results of the building envelope performance and building product assembly are presented in Table 31 – Table 34. These results present the fulfillment of the BBR requirement regarding a maximum of 0.40 W/(m2·K) in mean U-value (Boverket, 2015). The complete U-value calculation is presented in Appendix A. U-value calculation.

Table 31. Evaluation of BBR 22 building envelope U_{mean} requirements, of Linnea building with partly prefabricated exterior wall option 1.

Nr. of stories	Quantity	Unit	Sandwich wall element	Roof construction	Slab-on-grade	Window
3	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	373.20	280.10	280.10	155.10
	A_{om}	m^2	1261.90			
	$\mathbf{U_m}$	$\mathbf{W/(m^2 \cdot K)}$	**0.24**			
6	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	743.40	280.10	280.10	313.20
	A_{om}	m^2	1616.90			
	$\mathbf{U_m}$	$\mathbf{W/(m^2 \cdot K)}$	**0.33**			
8	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	990.30	280.10	280.10	418.50
	A_{om}	m^2	1969.10			
	$\mathbf{U_m}$	$\mathbf{W/(m^2 \cdot K)}$	**0.35**			

Table 32. Evaluation of BBR 22 building envelope U_{mean} requirements, of Linnea building with partly prefabricated exterior wall option 2.

Nr. of stories	Quantit y	Unit	Single-element wall	Roof construction	Slab-on-grade	Windo w
3	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	377.60	284.80	284.80	155.1
	A_{om}	m^2	1102.40			
	$\mathbf{U_m}$	$\mathbf{W/(m^2 \cdot K)}$	**0.27**			
6	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	752.30	284.80	284.80	313.20
	A_{om}	m^2	1635.20			
	$\mathbf{U_m}$	$\mathbf{W/(m^2 \cdot K)}$	**0.33**			
8	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	1002.10	284.80	284.80	418.50
	A_{om}	m^2	1990.30			
	$\mathbf{U_m}$	$\mathbf{W/(m^2 \cdot K)}$	**0.35**			

Table 33. Evaluation of BBR 22 building envelope U_{mean} requirements, of Frida building with partly prefabricated exterior wall option 1.

Nr. of stories	Quantity	Unit	Sandwich wall element	Roof construction	Slab-on-grade	Window
3	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	472.7	334.2	334.2	228.9
	A_{om}	m^2	1369.90			
	U_m	**$W/(m^2 \cdot K)$**	**0.30**			
6	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	953.80	334.20	334.20	449.40
	A_{om}	m^2	2071.50			
	U_m	**$W/(m^2 \cdot K)$**	**0.35**			
8	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	1274.40	334.20	334.20	596.50
	A_{om}	m^2	2539.20			
	U_m	**$W/(m^2 \cdot K)$**	**0.37**			

Table 34. Evaluation of BBR 22 building envelope U_{mean} requirements, of Frida building with partly prefabricated exterior wall option 2.

Nr. of stories	Quantity	Unit	Single-element wall	Roof construction	Slab-on-grade	Window
3	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	477.10	340.40	340.40	228.90
	A_{om}	m^2	1386.80			
	U_m	**$W/(m^2 \cdot K)$**	**0.29**			
6	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	962.60	340.40	340.40	449.40
	A_{om}	m^2	2092.80			
	U_m	**$W/(m^2 \cdot K)$**	**0.35**			
8	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	1286.20	340.40	340.40	596.50
	A_{om}	m^2	2563.40			
	U_m	**$W/(m^2 \cdot K)$**	**0.37**			

Results show compliance with the requirement of maximum mean U-value 0.40 $W/(m^2 \cdot K)$ for the whole building envelope enclosure stated in BBR 22. Furthermore the material specific assembly requirements of ASHRAE for climate zone 5 are fulfilled.

- Roofs insulated entirely above deck is set to 0.273 $W/(m^2 \cdot K)$ compared to the calculated U-value of 0.12 $W/(m^2 \cdot K)$

- Exterior walls of mass material is set to 0.453 W/(m^2·K) compared to the calculated U-value of 0.18 W/(m^2·K)
- Unheated slab-on-grade floor of mass material is set to 0.935 W/(m^2·K) compared to the calculated U-value of 0.12 W/(m^2·K)
- Vertical fenestration with nonmetal framing is set to 1.99 W/(m^2·K) compared to chosen fenestration and doors at U-value 1.05 W/(m^2·K)

The average U-value of fenestrations found in the BETSI projects was found at 1.9 W/(m^2·K), these fulfill the ASHRAE requirements of vertical fenestrations. However the same U-value would increase the mean U-value of the envelope performance above 0.40 W/(m^2·K) for the same window-to-wall ratio. The windows used in multi-family dwellings during 1996-2005 do not represent the thermal performance of windows today.

6.3 Analysis of LCA

6.3.1 LCA for different building components

In the following chapter the result of the LCA for different building components are presented. The analyses were carried out for 1 m^2 for each building component and the result is presented as emissions of kgCO_2-eqv/m^2 for each building component. The first bar in each case represents the starting point for each building component, which is presented in 6.2.2. The used LCA data is presented in Appendix D.

Figure 21 and Figure 22 present the distribution of each building elements effect to the total impact. This presents the effect each building components has on the total value. Concrete exterior walls, load-bearing inner walls and slabs stands for the majority of the total impact. These components regard the structural elements, which are constructed in concrete. The highest reduction was obtained when reducing the amount of cement in the concrete mixtures. This was done by varying the concrete qualities.

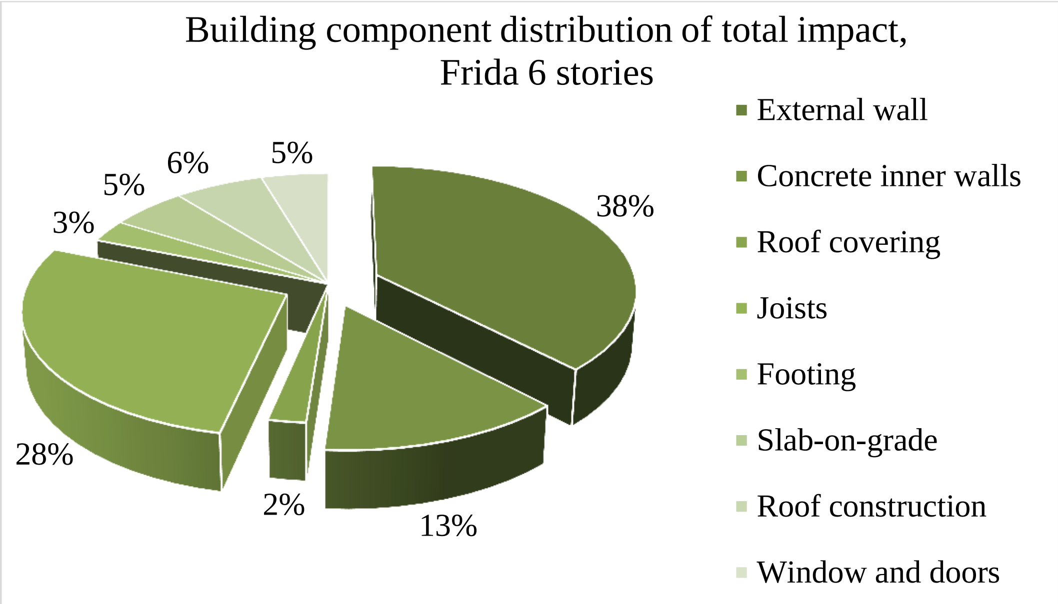


Figure 21. Pie chart presenting the distribution of each building component on the total impact for sandwich concrete element.

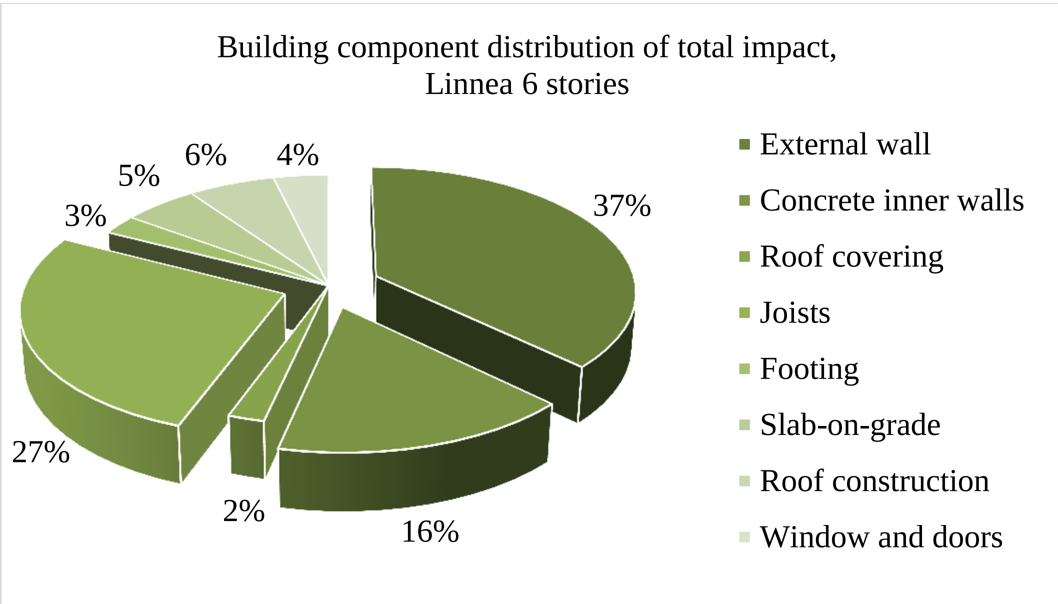


Figure 22. Pie chart presenting the distribution of each building component on the total impact for sandwich concrete element.

Slab-on-grade

In addition to the starting point, three additional alternatives were analyzed for the slab-on-grade construction.

Changes made into the slab-on-grade:
Alternative 1: Concrete C20/25
Alternative 2: Reinforcement steel from Norway supplier
Alternative 3: Combined alternative of 1 and 2

The result presented in Figure 23, indicates that changing either the reinforcement manufacturing country or the quality of the concrete will have the same impact on the outcome for the LCA, both had the reduction of 3 %. These two alternatives combined gave the third alternative, where the total reduction was 6 %.

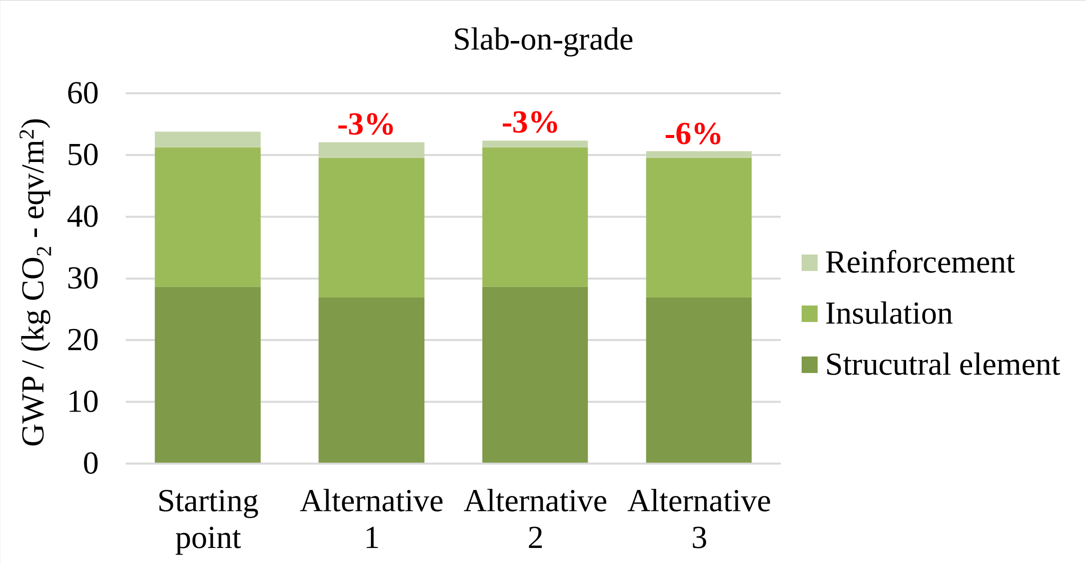


Figure 23. Sensitivity analysis on slab-on-grade construction assemblies.

Footings

The chosen construction type for the footing was varied in three different alternatives, where the results are presented in Figure 24.

Changes made to the footings:
Alternative 1: Smaller U-element (H = 400 mm instead of H = 600 mm)
Alternative 2: Concrete C20/25
Alternative 3: Reinforcement steel from Norway supplier
Alternative 4: Combined alternative of 2 and 3

The results show a reduction for all three alternatives, where the U-element resulted in the highest reduction of 49 %. However the variation of U-element is not used further due to the different profile size. The alternative U-element structure is usually not used for multi-family dwellings, where it is only presented as a possible alternative. Changing the concrete quality and reinforcement manufacturer resulted in a minor improvement of 2 %. The combined alternative 4 presented the highest reduction of 4 %.

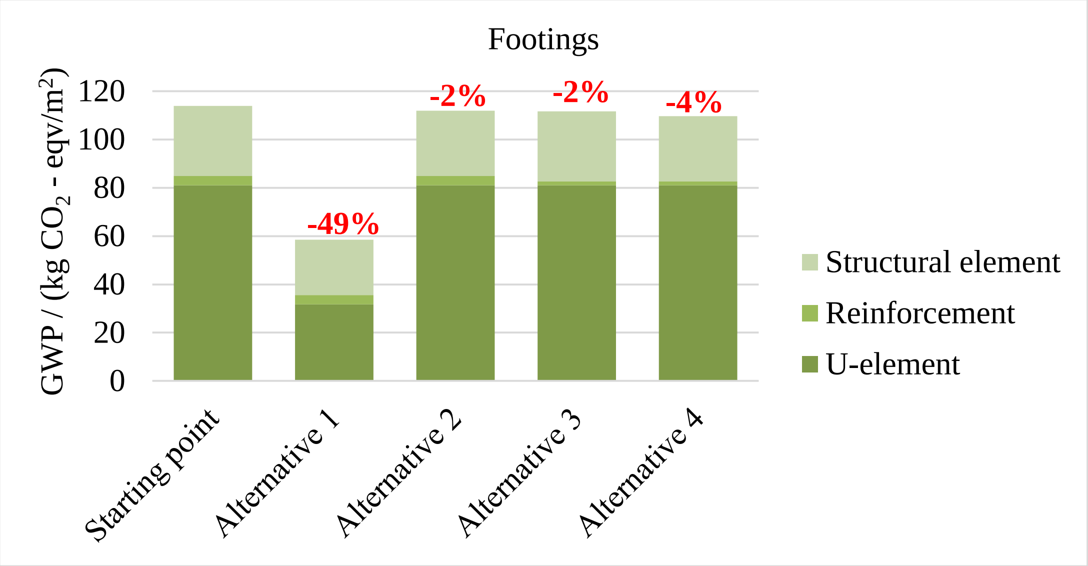


Figure 24. Sensitivity analysis of different footing alternatives and assemblies.

Joist construction
The joist construction was varied both in material and construction choice, see Figure 25.

Changes made to the joist construction:
Alternative 1: Reinforcement steel from Norway supplier
Alternative 2: Concrete C20/25
Alternative 3: Combined alternative of 1 and 2
Alternative 4: Alternative construction, massive concrete joist (plattbärlag)
Alternative 5: Alternative construction, TT joist (TT kassett)

The first two cases varied the reinforcement steel supplier and the concrete quality, gave a reduction of 5 respectively 10 %. The combined results of these two alternatives are presented in alternative 3, which show a reduction of 15 %. When another construction, massive concrete joist (plattbärlag) was used, the impact increased to 43 %. This construction was deemed worse in a LCA perspective compared to HF/F joists. The other construction type, TT joist, decreased the impact with 8 %, however this construction type was not analyzed further due to rare usage in multi-family dwellings. The chosen construction type regarding joist selection should however be analyzed in each project if necessary reductions are needed to reach the 10 % overall goal.

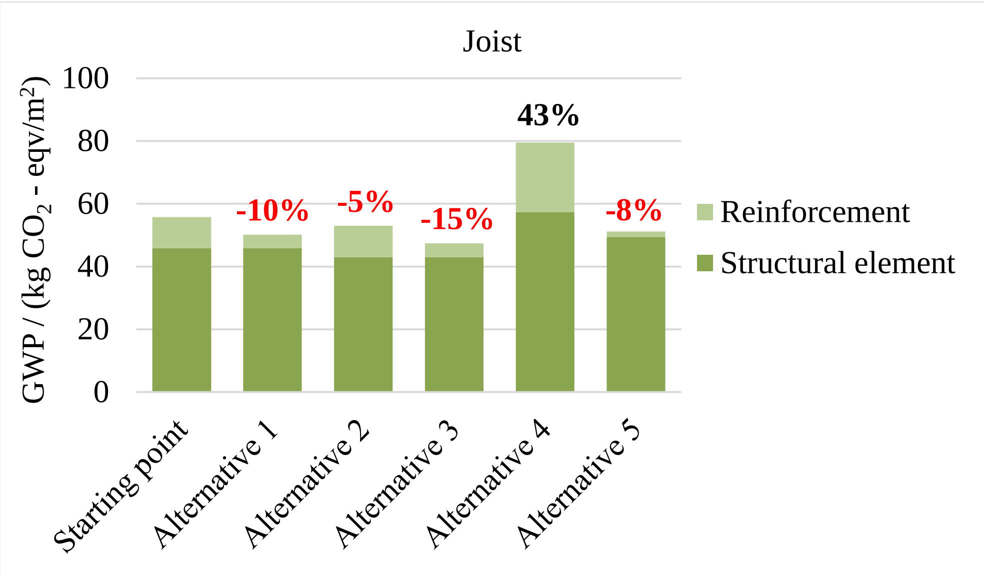


Figure 25. Sensitivity analysis of different alternatives of joist constructions and assemblies.

Roof joist
The roof joist was varied in five different cases, presented in Figure 26.

Changes made to the roof joist:
Alternative 1: Reinforcement steel from Norway supplier
Alternative 2: Concrete C20/25
Alternative 3: Combined alternative of 1 and 2
Alternative 4: Rockwool insulation
Alternative 5: Alternative construction, massive concrete joist (plattbärlag)
Alternative 6: Alternative construction, TT joist (TT kassett)

In the first two cases the starting point was varied by changing the reinforcement steel supplier and concrete quality. The first two gave a reduction with 9 % for the reinforcement steel supplier and with 4 % for the concrete quality. The combined results of alternative 1 and 2, gave a total reduction of 13 %. However when the mineral wool was changed to Rockwool insulation the impact increased with 7 %. The two last cases, considering massive concrete joist, also meant an increase in CO_2-eqv impact of 26 %, due to higher amounts of concrete and reinforcement steel. No further analysis was made on this construction type. However when using a TT-joist cassette the impact was reduced with 7 %. Just as for the joist construction the construction type was not analyzed further due to the rare usage in multi-family dwellings.

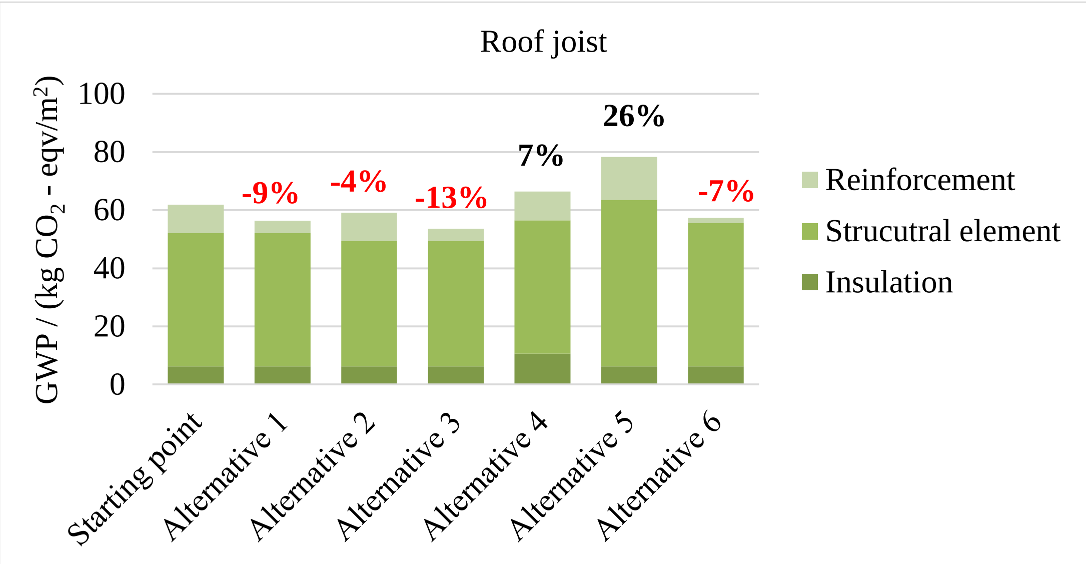


Figure 26. Sensitivity analysis of different roof constructions and assemblies.

Roof covering

The roof covering was analyzed with three different roofing materials. The result is presented in Figure 27.

Changes made to the roof covering:
Alternative 1: Alu-zinc roofing
Alternative 2: Concrete roof tiles
Alternative 3: Roofing felt

The largest reduction was obtained when changing the metal sheet cover with roofing felt. This decreased the impact with 46 %. While changing the roof covering to concrete tiles decrease the impact with 41 %. In addition the smallest reduction was obtained by changing the metal sheet cover to alu-zinc. This resulted with a 10 % reduction.

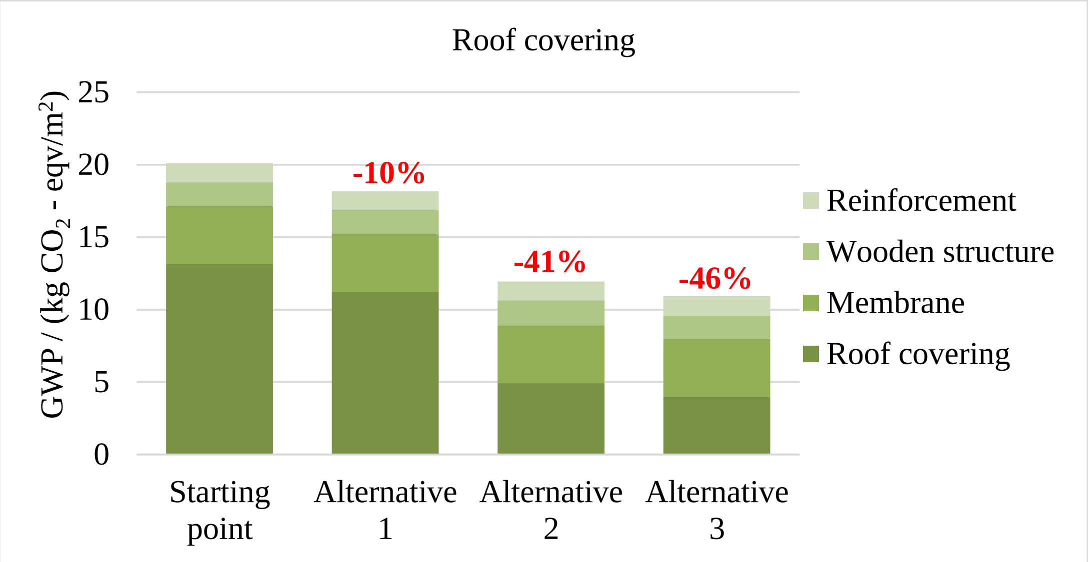


Figure 27. Sensitivity analysis of roof coverings.

External walls
The results from the sensitivity analysis of a sandwich wall element are presented in Figure 28.

Changes made to the sandwich wall element:
Alternative 1: Mineral wool insulation
Alternative 2: Rockwool insulation
Alternative 3: Concrete C20/25
Alternative 4: Reinforcement steel from Norway supplier
Alternative 5: Combined alternative of 3 and 4

When the EPS insulation was changed to mineral wool insulation the CO_2-eqv increase with 8 %. The increase was even greater when Rockwool insulation was used, this resulted in a 22 % increase compared to the starting point. When the concrete quality was changed from C25/30 to C20/25 the impact was reduced with 4 %. However the largest reduction occurred when the material supplier of reinforced steel was changed. This resulted in a 6 % reduction compared to the starting point. When combining the two best alternatives, the combined reduction resulted in a 10 % reduction for alternative 5.

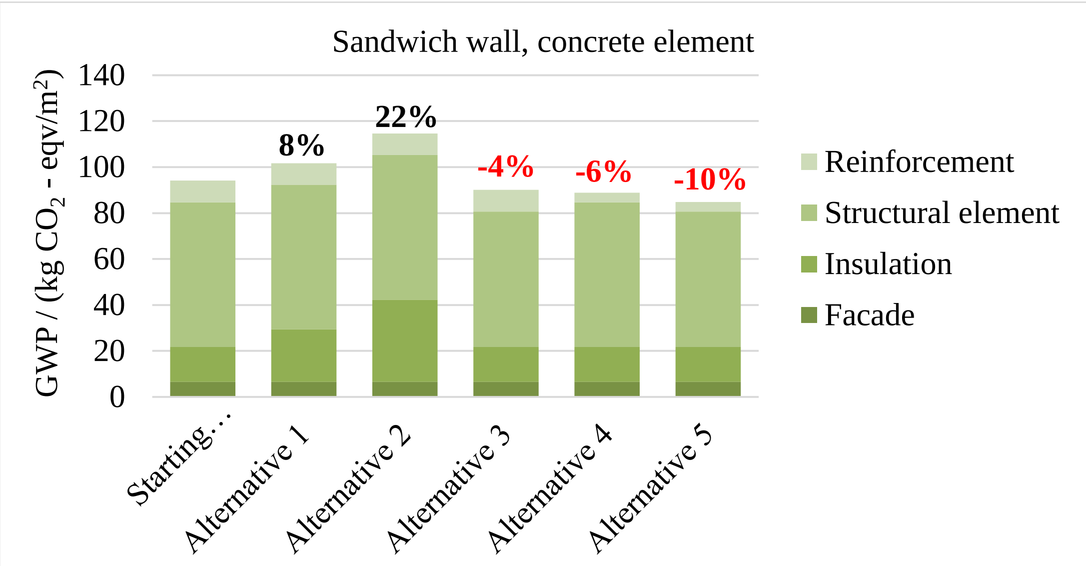


Figure 28. Sensitivity analysis of sandwich wall concrete element.

The results from the sensitivity analysis of a single-element concrete wall are presented in Figure 29.

Changes made to the single-element wall:
Alternative 1: EPS insulation
Alternative 2: Rockwool insulation
Alternative 3: Concrete C20/25

Alternative 4: Reinforcement steel from Norway supplier
Alternative 5: Combined alternative of 1, 3 and 4

When the mineral wool was changed to EPS insulation the CO_2-eqv decreased with 20 %. While the Rockwool insulation resulted in an increase of 3 % compared to mineral wool in the starting point. When the concrete quality was changed from C25/30 to C20/25 the impact was reduced with 3 %. Changing the reinforcement manufacturer decreased the CO_2-eqv impact with 4 %.

Combining the three best alternatives into alternative 5 resulted in a total reduction of 27 %. This is a significant reduction on the single-element concrete wall, compared to the total reduction of sandwich element of 10 %.

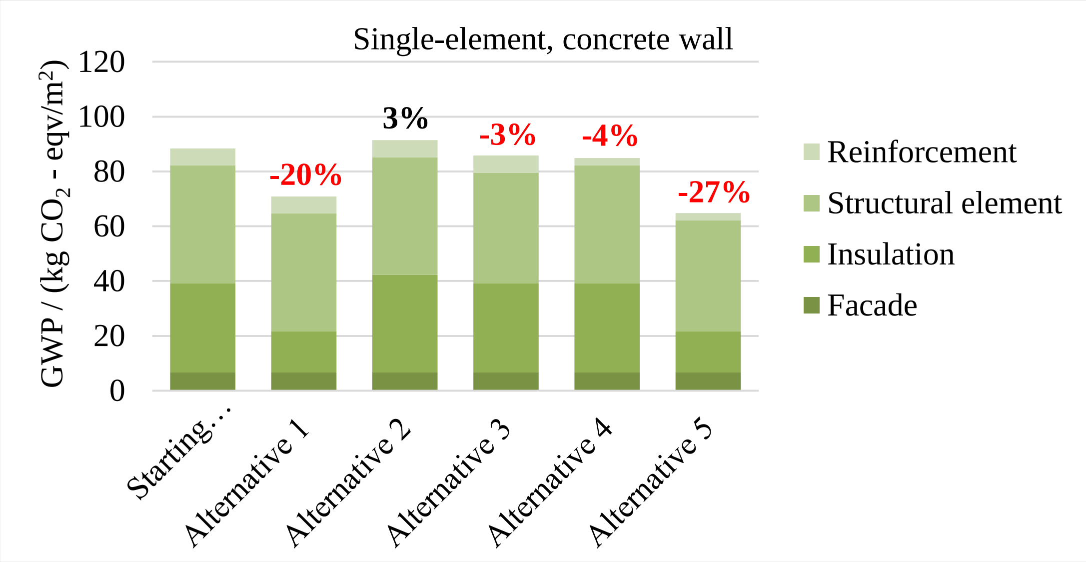


Figure 29. Sensitivity analysis of single-element concrete wall.

Internal load-bearing walls
Load-bearing inner walls were varied in two different starting points, 150mm for starting point 1 and 200mm for starting point 2. These were varied with three alternatives each.

Where the following changes were made:
Alternative 1.1 and 2.1: Concrete C20/25
Alternative 1.2 and 2.2: Reinforcement steel from Norway supplier
Alternative 1.3 and 2.3: Combined alternative of concrete quality and reinforcement steel supplier

The results from both wall dimensions are presented in Figure 30. The 200 mm wall is constructed with more reinforcement compared to the 150 mm wall. Because of this the relative recursion is not linear between both cases. The results show a higher reduction for alternative 1.1 compared to 2.1 when changing the concrete quality. When changing the reinforcement manufacture both alternative 1.2 and 2.2 show improvements of 5 respective 10 %. The combined alternative 1.3 and 2.3 present a total reduction of 10 % respectively 15 %.

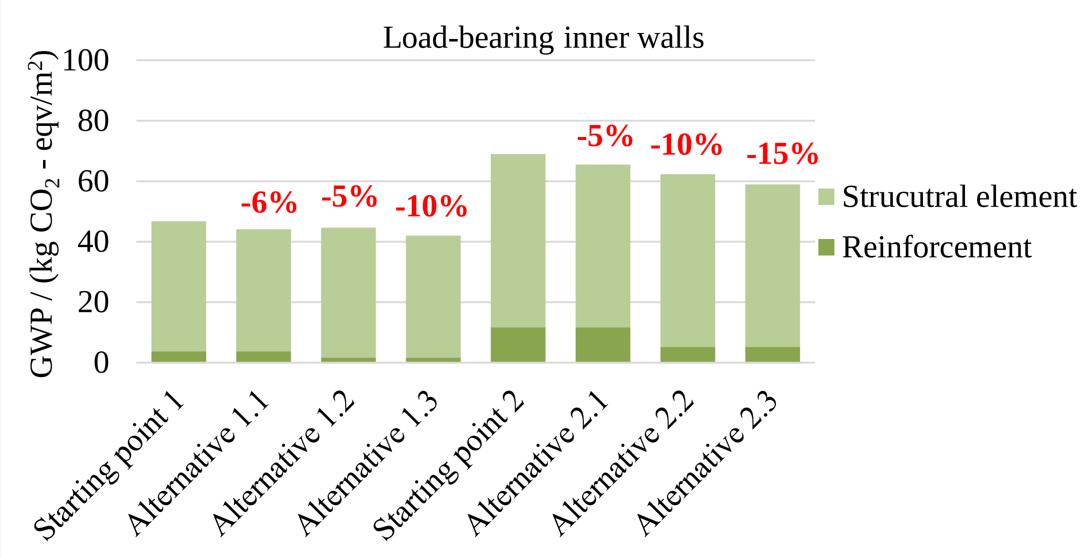


Figure 30. Sensitivity analysis of load-bearing inner walls, by different thicknesses and material combinations.

Windows
Due to limitations in window types in the simplified LCA tool no sensitivity analysis was conducted for different window types. Windows were instead included in the analysis of total LCA impact for each building type.

6.3.2 LCA for whole building

The Building Life-Cycle Impact Reduction in LEED v4 requires projects to demonstrate a reduced environmental impact of materials through an LCA. This should be demonstrated in a Whole Building Life-Cycle Assessment, where a Baseline Building is compared to a final Proposed Building design. The Baseline Building is called starting point where's the Proposed Building design is called best case. The best case results found during the sensitivity analysis is combined into a whole building design and called best case. The only fixed parameter regards the window type, which was limited in the dataset of the chosen LCA tool.

The total LCA of the two building designs are presented in two diagrams, one regarding a sandwich concrete element and the other a single-element concrete wall. The results are divided into two wall construction types based on assumptions made for the exterior concrete prefabricated wall. The best-case solution for the Linnea building shape is presented in Figure 31 and Figure 32. The results show that both exterior walls constructions achieve the benchmark reduction of 10 % compared to the starting point. However the single-element concrete wall achieves a higher reduction compared to the sandwich concrete element.

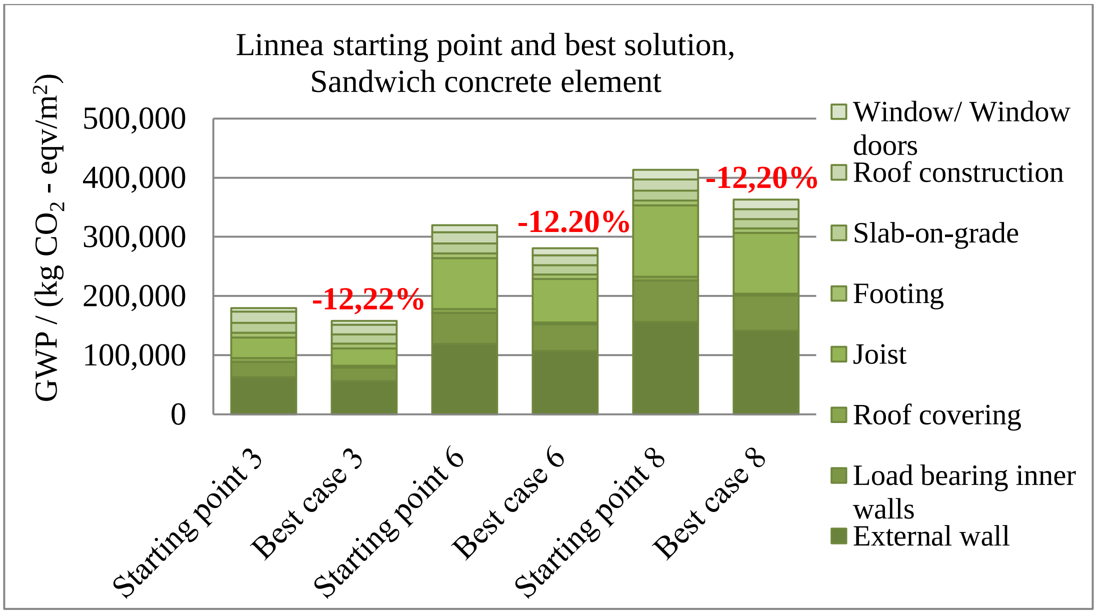


Figure 31. Starting point building design compared to best case building design. With a sandwich concrete element representing the exterior wall. Results from the sensitivity analysis are combined into a whole building best case for 3, 6 and 8 stories.

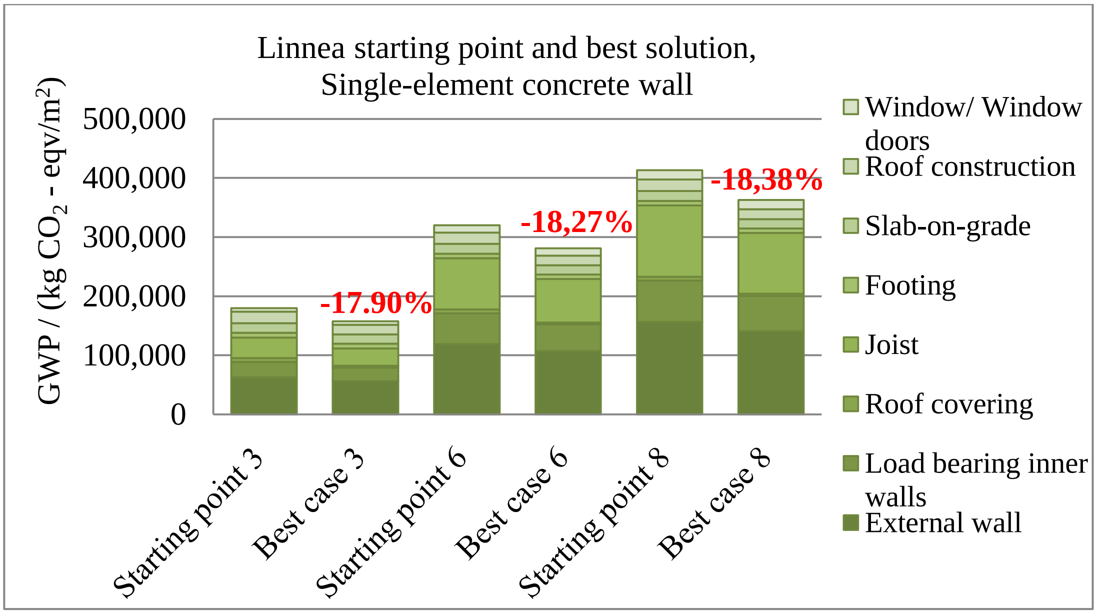


Figure 32. Starting point building design compared to best case building design. With a single-element concrete wall representing the exterior wall. Results from the sensitivity analysis are combined into a whole building best case for 3, 6 and 8 stories.

When assessing the building design of Frida similar results were found. The only difference between both studies regards the total areas of the building components. Nevertheless both building shape indicate that the single-element concrete wall allow a higher reduction of the global warming potential (CO_2-eqv.).

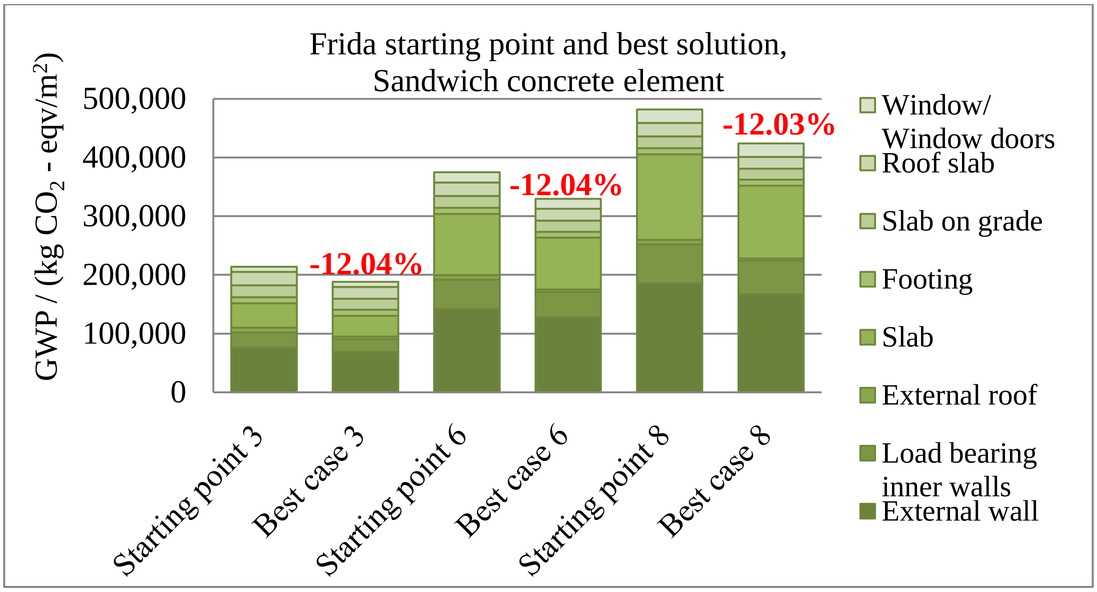


Figure 33. Starting point building design compared to best case building design. With a sandwich concrete element representing the exterior wall. Results from the

sensitivity analysis are combined into a whole building best case for 3, 6 and 8 stories.

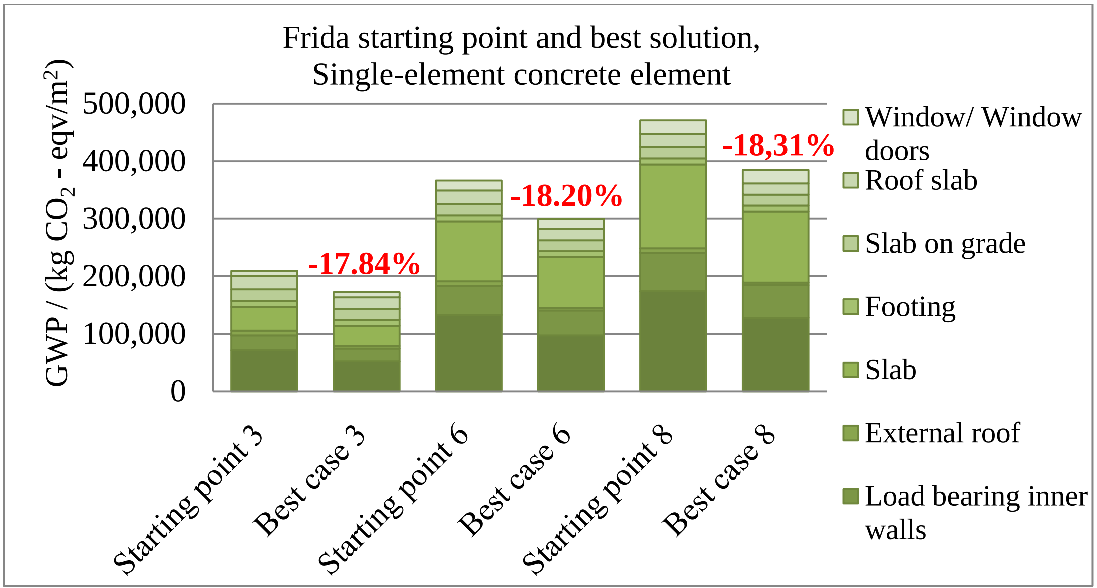


Figure 34. Starting point building design compared to best case building design. With a single-element concrete wall representing the exterior wall. Results from the sensitivity analysis are combined into a whole building best case for 3, 6 and 8 stories.

7 Discussion

LEED v4

The new version of LEED, LEED v4 introduces a more detailed LCA compared to the 2009 version. This was discovered from our study were we compared the old and new version of the Material and Resources category. The analyzed credit, Building Life-Cycle Impact Reduction, is included for the first time in LEED v4. The credit is intended to reduce environmental impacts caused by buildings by rewarding projects that study different design choices. The design choices are varied in an early design phase through LCA studies with a system boundary that covers cradle-to-grave. Furthermore there are other credits that rewards sustainable thinking both within the Material and Resources category, as well in other LEED categories. We think that this new mindset in LEED is a result of a deeper analysis of the global environmental problems. Instead of only analyzing the environmental impacts caused by one material or one building component, the whole building is analyzed as one product for its entire life-cycle, from raw material to demolition.

We think the inclusion of an early LCA study of different design alternatives is a good way to start. However the use of a reference model for each project creates some difficulties. The major difficulties lay in the choice of staring point, in other words the choice of ingoing materials for the Baseline Building. From our own experience, when creating a Baseline Building according to the stated requirements in LEED v4. We discovered that there are a lot of simplifications made regarding the choice of material inputs and datasets for the baseline model. LEED v4 specifies clearly which building components that should be assed, when comparing a Baseline Building to the proposed design. However project teams are allowed to choose their own material inputs and material datasets for the Baseline Building, as long the datasets and LCA tools comply with ISO standards. There is an absence of clear information regarding which materials are reasonable to use for the Baseline Building. This allows projects to make their own assumption of common construction and material types. Meaning projects could assume a concrete structure even though their first idea is to design a wooden structure. This would result in a clear impact reduction and would make the credit easier to attain. It is also possible to switch the Baseline Building design with the Proposed Building design if this accomplishes the desired impact reduction. This can be done because the relative reduction that needs to be presented for each impact category is dependent on the Baseline Building. Meaning that if the Baseline Building were assumed to use high impact materials from the start, the Proposed Building design would much easier reach the requirement of the credit. LEED v4 states requirements for developing a Baseline Building, although many of these regards energy and geometry of the Baseline Building and Proposed Building design. None of the requirements state which materials, products or data is appropriate to use in the Baseline Building. Because of this the material choice is left for each project to decide, allowing a worse material to be selected for the Baseline Building. Additionally there are other requirements that need to be fulfilled, for example local building regulations which might limit possible material choices for the project.

Nevertheless it is important to acknowledge that the EA prerequisite Minimum Energy Performance still needs to be fulfilled. Furthermore it is up to the GBCI to approve the changes for the proposed building, meaning that no extreme changes might be approved. Conclusions from this is that the credit is still quite unspecific and undeveloped regarding which materials and products are appropriate to use as a starting point, and which changes that are allowed to make. In these regards it seems, as the LCA credit for whole building assessment in LEED v4, is intended to introduce a LCA mindset to LEED users. Where project teams should learn how to perform an LCA, to understand which improvement that improves the outcome of the LCA.

The credit could also be made unspecific on purpose. If the credit lacks in details, then it is up to the users of the system to come up with improvements, since the users should be the ones that know the most about how to improve the certification system. We think that in the next version of LEED there will be a much more detailed credit or prerequisite for LCA, that will cover the whole building, not only climate envelope and structural parts. In this improved version, there should also be more information in what is appropriate to use as a starting point for the Baseline Building.

ASHRAE and regional building standards

Another problem that occurs when assessing a certification through LEED is the fact that is based on American standards. This makes the certification process in other countries more difficult, since they have their own standards to follow. In our case, which applies for any building constructed in Sweden, we had to use U-values for each material from the American standard 90. This complicates the certification process since the Swedish standard BBR refers to a mean U-value for the whole building envelope. ASHRAE states specific U-values for different building components used in the building envelope. The BBR U-value requirement is stricter compared to the American standard, because of this there will probably not be any problems for a Swedish project to be within the U-value limits. In our opinion, the American standard has a peculiar approach, to allow material to have a higher U-value, based on the fact that it is harder to reach a lower U-value if this material is used.

LCA

Even though LEED v4 refers to performance requirements of the building envelope in ASHRAE, the choice of different materials fulfilling the same performance would result in different outcome in the LCA results. One solution to reduce the flexibility of material selection could be to introduce manuals, rules or information of reasonable Baseline Building materials. For example by specifying the cement mixtures of concrete structures, by specifying reasonable input data for different materials or if generic material datasets should be used or specific manufacturer etc.

The database used in the simplified LCA tool, resembles the more advanced ECO_2 program. The simplified tool was used due to lack of time and experience in the ECO_2 program. Since the simplified tool was used, the possibility of different analysis was reduced. The dataset only included a mean generic value for each material. Nevertheless it should be noticed that the credit in LEED v4 allows project to compare EPD between different manufactures, which could improve the outcome of the LCA. This alternative requires a LCA tool that allows for modifications to the datasets and calculation factors, which could only be done by LCA experts. However in one case we were able to investigate the importance of specific dataset from a manufacturer compared to generic data for the same material. In our case we could compare a specific reinforcement manufacturer to the generic data. However the possibility of comparing different façade alternatives, window types, concrete mixtures (flash, ground granulated blast furnace slag, etc.) were not possible due to limited datasets. One possibility for further studies could be to include more variations of materials alternatives and how they would affect the final results. In addition, impacts from equal materials but manufactured by different producers were excluded. This could also be investigated further in a future study to determine the positive effects by choosing a specific manufacturer compared to generic value of materials.

Some of the questions, which could be included in future studies, include:

- What manufacturer should be chosen for the Baseline Building input materials?
- Is it better to choose a local manufacturer compared to one with a more environmental friendly material?
- Could generic datasets for each material be used for the Baseline Building, while specific manufacturer data is used for the Proposed Building design?
- This would lower the environmental effect caused by the built in materials, but would the GBCI approve this alternative? (We assume that they would since no project could in an early design stage decide one manufacturer.)

Another limitation in the LCA study was the exclusion of the A4 module group, transportation to site. This was excluded since the no assumption for location of the construction site or manufacturing location for the materials was made. This could have affected the LCA result if there were huge differences between two manufacturing locations, if the CO_2-eqv had been the same for two materials.

Statistical review

The analyzed SCB surveys were missing clear definitions regarding the manufacturing method of the structural material. Because of this we had to make assumption regarding the definition of the three manufacturing methods. We think that the two alternatives completely prefabricated and partly prefabricated could have been widely interpreted by the participants. All survey participants that used any type of ready-to-install structural materials that was delivered to the site, could have assumed this to be either completely prefabricated or partly prefabricated. In these thesis two alternatives to the most common manufacturing method was investigated.

The final LCA results indicated a clear difference between the two assumed construction types. This is because each construction type uses different insulation materials. Different insulation materials are suitable for different constructions, meaning the choice of construction type will affect the possible material alternatives. An alternative would be to assess different construction types and material assemblies for each building component. This way the sensitivity analysis would present more alternatives for reducing each impact category.

The choice of manufacturing method affects the LCA in regards to the material transportation to site, module group A4. A completely prefabricated exterior wall would increase the number of transportations needed to the construction site compared to built-on-site. Built-on-site would lower the number of transport due to the fact that the concrete is fluent, however this will mean more waste at the construction site compared to completely prefabricated elements. On the other hand the waste is not included in the credit Building Life-Cycle Impact Reduction, since group module A5 is not included in the LCA.

Future surveys conducted by SCB could incorporate definitions of the manufacturing alternatives regarding the structural materials. This would allow more transparency of the results and could present a more representative picture of the manufacturing method. In addition SCB surveys could include information regarding the structural elements this could be used as a reference point for the Baseline Buildings constructed in Sweden. The surveys would guide and lead project team in their material choice for the Baseline Building.

8 Conclusion

When creating a reference building, a so-called Baseline Building, there are some specific requirements to follow. The Building Life-Cycle Impact Reduction credit stats that a whole building LCA should be carried out for the structural elements and building envelope materials. In addition to this the Baseline Building and the Proposed Building have to be out of comparable size, have the same function and be built at the same location with the same orientation. These requirements are based on the fact that there cannot be any advantages for changing the circumstances of the project. When analyzing the LCA of the Baseline Building and the Proposed Building they have to be analyzed by the same system boundary, cradle-to-grave.

The following products should be included:

- Footing and foundations
- Structural pillars, columns etc.
- Structural wall assembly (from cladding to interior finishes)
- Structural floors and ceilings (not including finishes)
- Roof assemblies
- Parking structures, exclude parking lots
- Stair constructions

To be able to compare the Baseline Building with the Proposed Building they must:

- Be of comparable size
- Have the same function
- Have the same gross area
- Have the same orientation
- Have the same system boundary, a cradle-to-grave analysis. All life-cycle stages regarding the building structure and enclosure should be analyzed, according to the definition in ISO 21930, following sections A1 - A4, B1 - B7 and C1 - C4. Parameters that are not defined may be changed across the baseline and proposed building
- Have the same operating energy performance, which is defined in EA prerequisite Minimum Energy Performance
- Have the same service life at least 60 years, to include products maintenance and replacement cycle
- Use the same software tool and datasets when conducting a life-cycle assessment, chosen datasets must be compliant with ISO 14 044 (U.S. Green Building Council, 2013)

One of the main questions in this thesis was whether it is possible to define a general reference building applicable to Swedish conditions. In our investigations of the

Swedish building stock we could conclude that some building shapes and material were more common than others. However there still exist a lot to additional information regarding the material choice and construction type. For example no information regarding typical window types, where included in the surveys. Because of this necessary assumptions were made, to include windows in the investigated Baseline Building case. This leads to a large variation of the impact caused by window and doors in the Baseline Building design. Another large impact could be the choice of construction type in the Baseline Building design. This since there exist large variations of construction types, it is not possible to define a general construction that applies to all projects. Nevertheless from our investigations of the Swedish building stock, we were able to state that two building shapes, Apartment Block and Building Block were the most common building designs for multi-family dwellings. Further on the most common material for the structural component, roof covering and façade material were used as inputs in the conducted LCA. These where used for the assumed construction for the selected building shapes, Apartment Block and Building Block.

The structural concrete elements of both building shapes indicated to stand for the majority of the total impact. This was effectively reduced by changing the concrete quality and reinforcement steel supplier. On the contrary varying the concrete quality is not always a suitable options, the structural engineer should always determine the choice of concrete quality. However alternative concrete mixtures containing fly ash, ground granulated blast furnace slag or other concrete mixtures could be reasonable to assess in the early design phase. The choice of reinforcement steel supplier also affected the total results due to the high amount of material.

In conclusion project pursuing the credit Building Life-Cycle Impact Reduction, whole building LCA, option 4, should concentrate their improvement on the structural elements. Especially if concrete is used as the structural element. Results show that only varying the concrete quality and the manufacturer of reinforcement steel would lead to a reduction beyond the 10 % improvement stated by LEED.

9 References

ANSI/ASHRAE/IES Standard 90.1-2010, 2010. *Energy Standard for Building Except Low-Rise Residential Buildings.* SI Edition ed. s.l.:ANSI/ASHRAE/IES Standard 90.1-2010.

ANSI/ASHRAE/IES Standard 90.1-2010, 2011. *90.1 User's Manual.* s.l.:ANSI/ASHRAE/IES Standard 90.1-2010.

Bayer et al, .., 2010. *AIA Guide to Building Life Cycle Assessment in Practice,* New York: The American Institute of Architects.

Boverket, 071025. *Instruktioner och definitionertill besiktningsprotokoll Flerbostadshus,* s.l.: Boverket.

Boverket, 2009. *Så mår våra hus.* [Online]
Available at: http://www.boverket.se/sv/byggande/uppdrag/avslutade-uppdrag/sa-mar-vara-hus/om-undersokningen/
[Accessed 15 April 2015].

Boverket, 2014. *Boverket.* [Online]
Available at: http://www.boverket.se/sv/lag--ratt/forfattningssamling/processen-for-boverkets-regelskrivning/
[Accessed 13 March 2015].

Boverket, 2014. *Byggregler - en historisk överblick.* [Online]
Available at:
http://www.boverket.se/contentassets/ba75fc25915f4a79bad02ff6e9a5eb02/aldre-byggregler-2014-09-29.pdf
[Accessed 13 March 2015].

Boverket, 2015. *BBR 22.* [Online]
Available at:
http://www.boverket.se/contentassets/a9a584aa0e564c8998d079d752f6b76d/bbr-bfs-2011-6-tom-bfs-2015-3-konsoliderad.pdf
[Accessed 13 March 2015].

Carlson et al., 2011. *Livscykelanalys - ringar på vattnet.* 2nd ed. Göteborg: SIS Förlag.

ISO, n.d. *ISO 14000 - Environmental management.* [Online]
Available at: http://www.iso.org/iso/home/standards/management-standards/iso14000.htm
[Accessed 25 05 2015].

IVL, 2013. *About IVL Swedish Environmental Research Institute.* [Online]
Available at:
http://www.ivl.se/english/startpage/about.4.4a08c3cb1291c3aa80e80001436.html
[Accessed 29 05 2015].

Owens, B., 2013. *LEED v4, Impact category and point allocation development process,* Washington, DC: U.S. Green Building Council.

Rydh et al., 2002. *Livscykelanalys - En metod för miljöbedömning av produkter och tjänster.* 1st ed. Lund: Studentlitteratur.

Sandin, K., 2010. *Praktisk Byggnadsfysik.* Upplaga 1:1 ed. Lund: Studentlitteratur AB, Lund.

SCB, 2014. *Om SCB.* [Online]
Available at: http://www.scb.se/sv_/Om-SCB/
[Accessed 17 April 2015].

Strängbetong, 2014. *Sandwich- och VI-väggar.* [Online]
Available at: http://www.strangbetong.se/koncept-komponenter/komponenter/fasader/sandwichvaggar/
[Accessed 30 05 2015].

Svensk Betong, n.d. *Dimensionering av håldäck.* [Online]
Available at: http://svenskbetong.se/statik/haldaeck-hdf/dimensionering-av-haldaeck.html
[Accessed 28 May 2015].

Svensk Betong, n.d. *Dimensionering av väggelement.* [Online]
Available at: http://svenskbetong.se/statik/vaeggelement-homogenvaegg-v-och-sandwichvaegg-w/dimensionering-av-vaeggelement.html
[Accessed 28 May 2015].

Swedish Standards Institute, 2006. *Svensk Standard SS-EN ISO 14040:2006,* Stockholm: SIS Förlag AB.

Swedish Standards Institute, 2013. *SS-EN 15804:2012+A1:2013*, Stockholm: SIS Förlag AB.

The Statistical Services Centre, 2001. *Approaches to the analysis of survey data.* [Online]
Available at:
http://www.ilri.org/biometrics/TrainingResources/Documents/University%20of%20

Reading/Guides/Guides%20on%20Analysis/ApprochAnalysis.pdf
[Accessed 12 April 2015].

U.S. Green Building Council, 2009. *LEED 2009 for new construction and major renovations,* Washington, DC: U.S. Green Building Council.

U.S. Green Building Council, 2012-2015. *Country Market Brief: Sweden.* [Online]
Available at: http://www.usgbc.org/advocacy/country-market-brief
[Accessed 29 05 2015].

U.S. Green Building Council, 2013. *LEED, reference guide for building design and construction v4.,* Washington, DC: U.S. Green Building Council.

U.S. Green Building Council, 2014. *LEED v4, User guide,* Washington, DC: U.S. Green Building Council.

U.S. Green Building Council, 2015. *Guide to LEED Certification: Commercial.* [Online]
Available at: http://www.usgbc.org/cert-guide/commercial
[Accessed 21 May 2015].

Wikells Sektionsfakta, 2015. *Wikells Byggberäkningar AB.* [Online]
Available at: http://wikells.se/kalkylprogram.aspx
[Accessed 29 05 2015].

Appendix A. U-value calculation

$$U_m = \frac{(\sum_{i=1}^{n} U_i A_i + \sum_{k=1}^{m} l_k \Psi_k + \sum_{j=1}^{p} \chi_j)}{A_{om}} (W/(m^2 \cdot K))$$

Where:

U_i	Is the heat transfer coefficient stated in $W/(m^2{\cdot}K)$, for each building component
A_i	The area of the building component is calculated from the inside of a heated space (m^2). For windows and doors the area should include the frame dimensions
Ψ_k	The heat transfer coefficient is stated in W/(m·K), for linear thermal bridge
l_k	The length of indoor air in contact with the thermal bridge (m)
X_j	Is the heat transfer coefficient stated in W/K of a point shaped thermal bridge
A_{om}	The total envelope area which shelters the heated inside spaces from the outside (m^2). The building envelope includes all building components that separate the outside from inside, including separating heated spaces from semi-heated

U_i calculation

Compilation of each building component was calculated for exterior walls, roof and slab-on-grade and compared to typical U-value derived from BETSI. The input materials, thicknesses and heat transfer of each material are included in the table calculation:

The assumed λ-value for the used materials was set to (according to EN 12524):

- Insulation, 0,038 W/(m·K)
- Concrete, 1,7 W/(m·K)
- Plaster, 1,0 W/(m·K)

U-value calculation

$$U_{value} = \frac{1}{R_{tot}}$$

R-value calculation

$$R_{tot} = \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \cdots + \frac{d_n}{\lambda_n}$$

Table 35. U-value calculation for Single-element concrete wall

Exterior wall, (Single-element concrete wall)				Calculated U-value/ W/(m^2·K)	BETSI mean U-value/ W/(m^2·K)
Material layer	Thickness/ m	λ/ (W/(m·K))	R-value/ (m^2·K/W)		
Outside	-	-	0.04	0.18	0.2
Plaster	0.01	1.00	0.01		
Insulation	0.20	0.038	5.26		
Concrete	0.15	1.70	0.09		
Inside	-	-	0.13		
Total	0.36	2.74	5.53		

Table 36. U-value calculation for Sandwich wall element

Exterior wall (Sandwich wall element)				Calculated U-value/ (W/(m^2·K))	BETSI mean U-value/ (W/(m^2·K))
Material layer	Thickness/ m	λ / (W/(m·K))	R-value/ (m^2·K/W)		
Outside	-	-	0.04	0.18	0.2
Plaster	0.01	1	0.01		
Concrete	0.07	1.7	0.04		
Insulation	0.2	0.038	5.26		
Concrete	0.15	1.7	0.09		
Inside	-	-	0.13		
Total	0.43	4.44	5.57		

Table 37. U-value calculation for Roof construction

Roof construction				Calculated U-value/ (W/(m^2·K))	BETSI mean U-value/ (W/(m^2·K))
Material layer	Thickness/ m	λ/ (W/(m·K))	R-value/ (m^2·K/W)		
Outside	-	-	0.04	0.12	0.13
Insulation	0.30	0.038	7.89		
Concrete	0.2	1.7	0.12		
Inside	-	-	0.10		
Total	0.50	1.74	8.15		

Table 38. U-value calculation for Slab-on-grade

Slab-on-grade				Calculated U-value/ (W/(m²·K))	BETSI U_m-value/ (W/(m²·K))
Material layer	Thickness/ m	λ/ (W/(m·K))	R-value/ (m^2·K/W)		
Outside	-	-	0.04	0.12	?
Insulation	0.30	0.038	7.89		
Concrete	0.1	1.7	0.06		
Inside	-	-	0.17		
Total	0.40	1.74	8.16		

U-value for windows is set to 1.05 W/(m^2·K), according to gathered information from window suppliers (Elitfönster and Svenska fönster).
Results of U-value calculation:

- Exterior walls (Single-element and sandwich wall element): 0.18 W/(m^2·K)
- Roof construction: 0.12 W/(m^2·K)
- Slab-on-grade construction: 0.12 W/(m^2·K)

A_i calculation

Exterior walls
W = Width of building
D = Depth: of building
S_h = Story height
S_n = Number of stories
W_t = Exterior wall thickness

$$A_i = \left(\left(\left(W - (W_t \cdot 2)\right) \cdot (S_h \cdot S_n)\right) \cdot 2\right) + \left(\left(\left(D - (W_t \cdot 2)\right) \cdot (S_h \cdot S_n)\right) \cdot 2\right)$$

Results of Linnea building (sandwich wall element):

- 3 stories – 532.73 m^2 (528.31 m^2)
- 6 stories – 1065.47 m^2 (1056.63 m^2)
- 8 stories – 1420.62 m^2 (1408.84 m^2)

Results of Frida building (sandwich wall element):

- 3 stories – 706.00 m^2 (701.58 m^2)
- 6 stories – 1411.99 m^2 (1403.16 m^2)
- 8 stories – 1882.66 m^2 (1870.88 m^2)

Roof and slab-on-grade construction
W = Width of building
D = Depth: of building
W_t = Exterior wall thickness

$$A_i = \left(\left(W - (W_t \cdot 2)\right) \cdot \left(D - (W_t \cdot 2)\right)\right)$$

Results of Linnea building:

- Single-element concrete wall – 284.84 m^2

- Sandwich wall element – 280.14 m^2

Results of Frida building:

- Single-element concrete wall – 340.39 m^2
- Sandwich wall element – 334.15 m^2

Windows and doors

The total window area is calculated from architectural drawings, see appendix B, including frames.

Descriptions of abbreviations:

- W = Window type
- BD = Balcony door (glazed)
- EW = Entrance window
- ED = Entrance door (glazed)

Results of Linnea building:

- 3 stories – 155.1 m^2
- 6 stories – 313.2 m^2
- 8 stories – 418.5 m^2

Results of Frida building:

- 3 stories – 228.9 m^2
- 6 stories – 449.4 m^2
- 8 stories – 596.5 m^2

A_{om} calculation

Total building envelope enclosure was calculated by adding all Ai areas (enclosure component areas).

$$A_{om} = A_{i,wall}(including\ windows) + A_{i,roof} + A_{i,slab\ on\ grade}$$

Table 39. A_{om} for the two buildings

A_{om}/m^2 for Building shape	Components	3	6	8
Linnea (Building Block)	Single-element concrete wall	1102.41	1635.15	1990.30
	Sandwich wall element	1261.86	1616.91	1969.12
Frida (Apartment Block)	Single-element concrete wall	1386.78	2092.77	2563.44
	Sandwich wall element	1369.88	2071.46	2539.18

U_m calculation

The specific thermal resistance and area of each component was multiplied and added for calculating the U_m value. With thermal bridges excluded.

The exterior wall area included windows, these were first excluded for the exterior wall areas:

$$A_{i,wall_r} = A_{i,wall} - A_{i,windows}$$

Results of Linnea building (sandwich wall element):

- 3 stories – 377.63 m^2 (373.21 m^2)
- 6 stories – 752.27 m^2 (743,43 m^2)
- 8 stories – 1002.12 m^2 (990,34 m^2)

Results of Frida building (sandwich wall element):

- 3 stories – 477.1 m^2 (472.68 m^2)
- 6 stories – 962.59 m^2 (953.76 m^2)
- 8 stories – 1286.16 m^2 (1274.38 m^2)

The following formula for calculating the U_m value was:

$$U_m = \frac{\sum U_i \cdot A_i}{A_{om}}$$

Table 40. U_m for the Linnea building with a sandwich wall

Nr. of stories	Quantity	Unit	Sandwich wall element	Roof construction	Slab-on-grade	Window
3	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	373.20	280.10	280.10	155.10
	A_{om}	m^2	1261.90			
	U_m	**$W/(m^2 \cdot K)$**	**0.24**			
6	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	743.40	280.10	280.10	313.20
	A_{om}	m^2	1616.90			
	U_m	**$W/(m^2 \cdot K)$**	**0.33**			
8	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	990.30	280.10	280.10	418.50
	A_{om}	m^2	1969.10			
	U_m	**$W/(m^2 \cdot K)$**	**0.35**			

Table 41. U_m for the Linnea building with a single-wall element

Nr. of stories	Quantity	Unit	Single-element wall	Roof construction	Slab-on-grade	Window
3	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	377.60	284.80	284.80	155.10
	A_{om}	m^2	1102.40			
	U_m	**$W/(m^2 \cdot K)$**	**0.27**			
6	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	752.30	284.80	284,80	313.20
	A_{om}	m^2	1635.2			
	U_m	**$W/(m^2 \cdot K)$**	**0.33**			
8	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	1002.10	284.80	284.80	418.50
	A_{om}	m^2	1990.3			
	U_m	**$W/(m^2 \cdot K)$**	**0.35**			

Table 42. U_m for the Frida building with a sandwich wall

Nr. of stories	Quantity	Unit	Sandwich wall element	Roof construction	Slab-on-grade	Window
3	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	472.70	334.20	334.20	228.90
	A_{om}	m^2	1369.90			
	U_m	**$W/(m^2 \cdot K)$**	**0.30**			
6	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.050
	A_i	m^2	953.80	334.20	334.20	449.40
	A_{om}	m^2	2071.50			
	U_m	**$W/(m^2 \cdot K)$**	**0.35**			
8	U_i	$W/(m^2 \cdot K)$	0.18	0.12	0.12	1.05
	A_i	m^2	1274.40	334.20	334.20	596.50
	A_{om}	m^2	2539.20			
	U_m	**$W/(m^2 \cdot K)$**	**0.37**			

Table 43. U_m for the Frida building with a single-wall element

Nr. of stories	Quantity	Unit	Single-element wall	Roof construction	Slab-on-grade	Window
3	U_i	$W/(m^2·K)$	0.18	0.12	0.12	1.05
	A_i	m^2	477.10	340.40	340.40	228.90
	A_{om}	m^2	1386.8			
	U_m	**$W/(m^2·K)$**	**0.29**			
6	U_i	$W/(m^2·K)$	0.18	0.12	0.12	1.05
	A_i	m^2	962.60	340.40	340.40	449.40
	A_{om}	m^2	2092.8			
	U_m	**$W/(m^2·K)$**	**0.35**			
8	U_i	$W/(m^2·K)$	0.18	0.12	0.12	1.05
	A_i	m^2	1286.20	340.40	340.40	596.50
	A_{om}	m^2	2563.4			
	U_m	**$W/(m^2·K)$**	**0.37**			

Appendix B. Fenestrations

Table 44. Number of windows for each facade, Linnea

Facade openings, Linnea							
Number of windows	W1.0	W1.1	W1.2	W1.3	W1.4	WD1.0	WD1.1
South	3	1	2	1	0	2	0
South, entrance floor	3	1	2	1	0	2	0
North	6	1	0	0	0	0	0
North, entrance floor	5	0	0	0	1	0	1
West	5	0	2	0	0	1	0
West, entrance floor	3	0	0	1	0	1	0
East	4	0	2	0	0	1	0
East, entrance floor	4	0	2	0	0	1	0

Table 45. Number of windows for each facade, Frida

Facade openings, Frida						
Number of windows	W2.0	W2.1	W2.2	W2.3	W2.4	W2.5
South	4	4	2	0	0	0
South, entrance floor	4	4	2	0	0	0
North	0	2	4	0	0	2
North, entrance floor	0	2	3	0	0	3
West	0	0	0	1	2	0
West, entrance floor	0	0	0	1	2	0
East	0	0	0	1	2	0
East, entrance floor	0	0	0	1	2	0

Table 46. Number of windows for each facade, Frida

Facade openings, Frida			
Number of windows	WD2.0	WD2.1	WD2.2
South	4	0	0
South, entrance floor	4	0	0
North	0	2	0
North, entrance floor	0	2	2
West	0	0	0
West, entrance floor	0	0	0
East	0	0	0
East, entrance floor	0	0	0

Table 47. Window and door sizes, Linnea

Window and door dimensions, Linnea			
	Width / m	Height / m	Area / m^2
W1.0	1.00	1.40	**1.40**
W1.1	1.60	0.60	**0.96**
W1.2	1.10	1.80	**1.98**
W1.3	1.40	1.80	**2.52**
W1.4	0.85	2.23	**1.89**
WD1.0	1.00	2.20	**2.20**
WD1.1	1.05	2.23	**2.34**

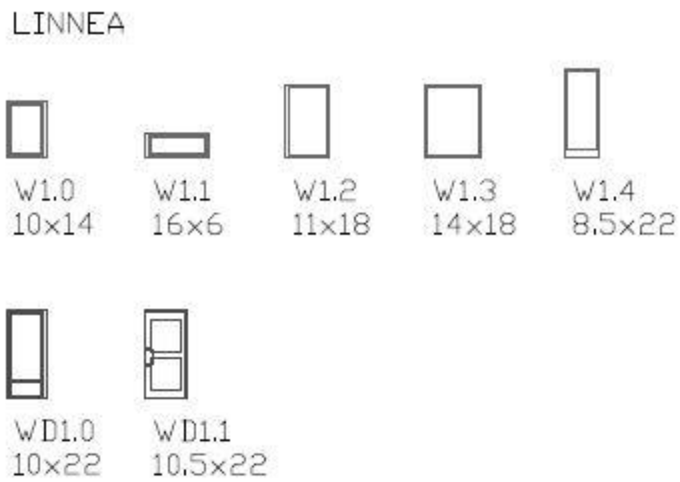


Figure 35. Windows in Linnea

Table 48. Window and door sizes, Frida

Windows and door dimensions, Frida			
	Width / m	Height / m	Area / m^2
W2.0	2.1	1.9	**3.99**
W2.1	2.1	1.4	**2.94**
W2.2	1.4	1.4	**1.96**
W2.3	1.6	0.6	**0.96**
W2.4	0.7	1.4	**0.98**
W2.5	2.0	2.5	**5.00**
WD2.0	1.0	2.2	**2.20**
WD2.1	0.8	2.2	**1.76**
WD2.2	1.05	2.5	**2.625**

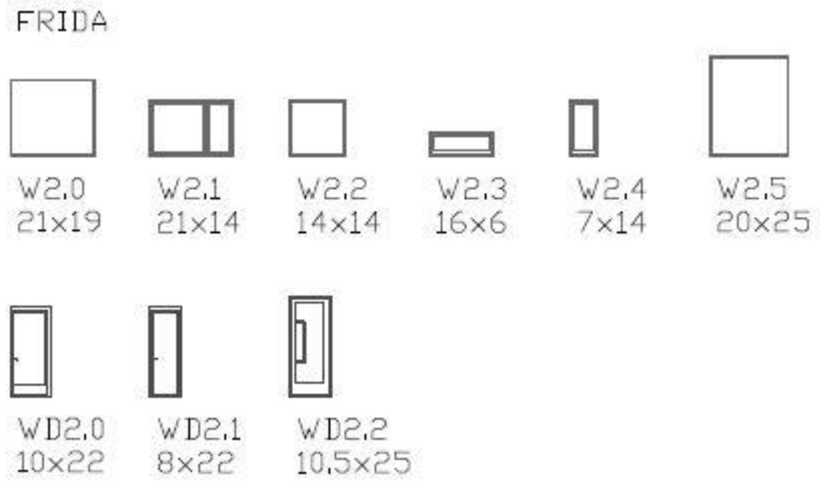


Figure 36. Windows in Frida

Appendix C. Architectural drawings

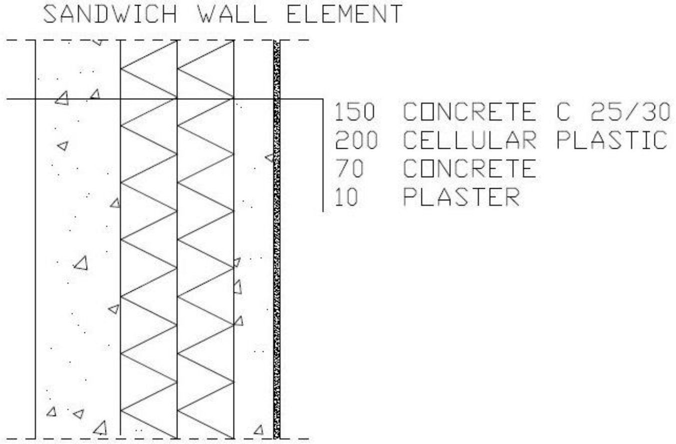


Figure 37. Sandwich wall element construction

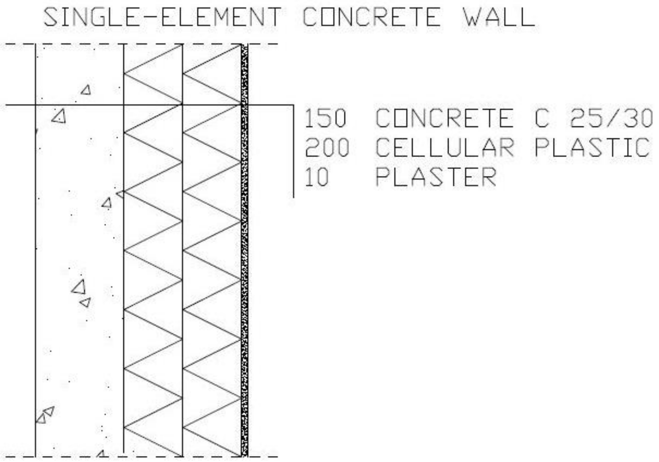


Figure 38. Single-element concrete wall construction

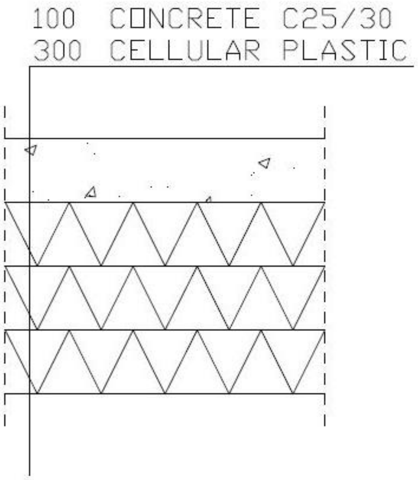


Figure 39. Slab-on-grade construction

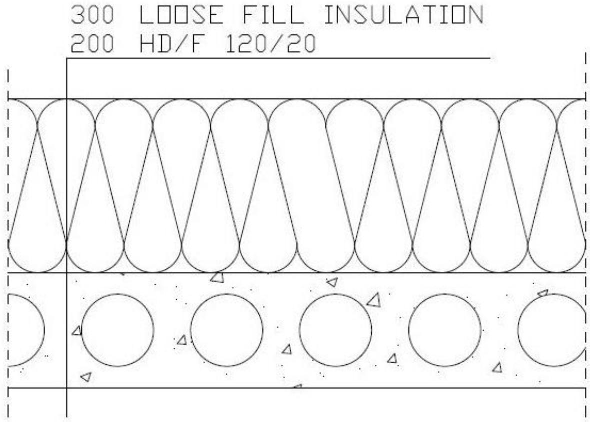


Figure 40. Roof joist construction

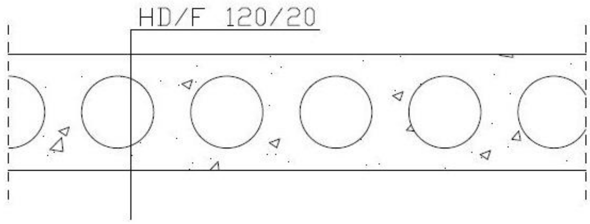


Figure 41. joist construction

Appendix D. LCA Building components

Table 49, Starting point for partly prefabricated 2, Sandwich wall element with alternatives

Partly prefabricated 1, Sandwich wall element	**Quantity**	**Unit**	**Material GWP / $kgCO_2$-eqv**	**Total building component GWP / $kgCO_2$-eqv**
Plaster	1.00	m²	6.60	
70 Concrete C25/30	1.00	m²	20.00	
Reinforcement B500BT ø12 (0,89 kg/m)	0.50	kg	0.41	
Reinforcement B500BT ø10 (0,62 kg/m)	3.30	kg	2.72	
200 EPS	1.00	m²	15.09	
150 Concrete C25/30	1.00	m²	43.00	
Reinforcement B500BT ø12 (0,89 kg/m)	1.00	kg	0.82	
Reinforcement B500BT ø10 (0,62 kg/m)	6.60	kg	5.44	94.09
Alternative 1				
Plaster	1.00	m²	6.60	
70 Concrete C25/30	1.00	m²	20.00	
Reinforcement B500BT ø12 (0,89 kg/m)	0.50	kg	0.41	
Reinforcement B500BT ø10 (0,62 kg/m)	3.30	kg	2.72	
200 Mineral wool	32.88	kg	22.72	
150 Concrete C25/30	1.00	m²	43.00	
Reinforcement B500BT ø12 (0,89 kg/m)	1.00	kg	0.82	
Reinforcement B500BT ø10 (0,62 kg/m)	6.60	kg	5.44	101.71

Alternative 2				
Plaster	1.00	m²	6.60	
70 Concrete C25/30	1.00	m²	20.00	
Reinforcement B500BT ø12 (0,89 kg/m)	0.50	kg	0.41	
Reinforcement B500BT ø10 (0,62 kg/m)	3.30	kg	2.72	
200 Rockwool insulation	30.00	kg	35.61	
150 Concrete C25/30	1.00	m²	43.00	
Reinforcement B500BT ø12 (0,89 kg/m)	1.00	kg	0.82	
Reinforcement B500BT ø10 (0,62 kg/m)	6.60	kg	5.44	114.60
Alternative 3				
Plaster	1.00	m²	6.60	
70 Concrete C20/25	1.00	m²	19.00	
Reinforcement B500BT ø12 (0,89 kg/m)	0.50	kg	0.41	
Reinforcement B500BT ø10 (0,62 kg/m)	3.30	kg	2.72	
200 EPS	1.00	m²	15.09	
150 Concrete C20/25	1.00	m²	40.00	
Reinforcement B500BT ø12 (0,89 kg/m)	1.00	kg	0.82	
Reinforcement B500BT ø10 (0,62 kg/m)	6.60	kg	5.44	90.09
Alternative 4				
Plaster	1.00	m²	6.60	
70 Concrete C25/30	1.00	m²	20.00	
Reinforcement [Norway] B500BT ø12 (0,89 kg/m)	0.50	kg	0.18	
Reinforcement [Norway] B500BT ø10 (0,62 kg/m)	3.30	kg	1.19	
200 EPS	1.00	m²	15.09	
150 Concrete C25/30	1.00	m²	43.00	
Reinforcement [Norway] B500BT ø12 (0,89 kg/m)	1.00	kg	0.36	
Reinforcement [Norway] B500BT ø10 (0,62 kg/m)	6.60	kg	2.38	88.80

Table 50, Starting point for partly prefabricated 2, Single-element concrete wall with alternatives

Partly prefabricated 2, Single-element concrete wall	**Quantity**	**Unit**	**Material GWP / $kgCO_2$-eqv**	**Total building component GWP / $kgCO_2$-eqv**
Plaster	1.00	m²	6.60	
200 Mineral wool	1.00	m²	32.60	
150 Concrete C25/30	1.00	m²	42.95	
Reinforcement B500BT ø12 (0,89 kg/m)	1.00	kg	0.82	
Reinforcement B500BT ø10 (0,62 kg/m)	6.60	kg	5.44	88.41
Alternative 1				
Plaster	1.00	m²	6.60	
200 EPS	1.00	m²	15.09	
150 Concrete C25/30	1.00	m²	42.95	
Reinforcement B500BT ø12 (0,89 kg/m)	1.00	kg	0.82	
Reinforcement B500BT ø10 (0,62 kg/m)	6.60	kg	5.44	70.90
Alternative 2				
Plaster	1.00	m²	6.60	
200 rockwool insulation	1.00	m²	35.61	
150 Concrete C25/30	1.00	m²	42.95	
Reinforcement B500BT ø12 (0,89 kg/m)	1.00	kg	0.82	
Reinforcement B500BT ø10 (0,62 kg/m)	6.60	kg	5.44	91.42
Alternative 3				
Plaster	1.00	m²	.60	
200 Mineral wool	1.00	m²	32.60	
150 Concrete C20/25	1.00	m²	40.37	
Reinforcement B500BT ø12 (0,89 kg/m)	1.00	kg	0.82	
Reinforcement B500BT ø10 (0,62 kg/m)	6.60	kg	5.44	85.83

Alternative 4				
Plaster	1.00	m²	6.60	
200 Mineral wool	1.00	m²	32.60	
150 Concrete C25/30	1.00	m²	42.95	
Reinforcement [Norway] B500BT ø12 (0,89 kg/m)	1.00	kg	0.36	
Reinforcement [Norway] B500BT ø10 (0,62 kg/m)	6.60	kg	2.38	84.88

Table 51, Starting point for 150 load bearing inner walls with alternatives

150 Concrete wall	**Quantity**	**Unit**	**Material GWP / kgCO_2-eqv**	**Total building component GWP / kgCO_2-eqv**
150 Concrete C25/30	1.00	m²	42.95	
Reinforcement B500BT ø12 (0,89 kg/m)	1.00	kg	0.82	
Reinforcement B500BT ø10 (0,62 kg/m)	3.60	kg	2.97	46.74
Alternative 1				
150 Concrete C20/25	1.00	m²	40.37	
Reinforcement B500BT ø12 (0,89 kg/m)	1.00	kg	0.82	
Reinforcement B500BT ø10 (0,62 kg/m)	3.60	kg	2.97	44.16
Alternative 2				
150 Concrete C25/30	1.00	m²	42.95	
Reinforcement [Norway] B500BT ø12 (0,89 kg/m)	1.00	kg	0.36	
Reinforcement [Norway] B500BT ø10 (0,62 kg/m)	3.60	kg	1.30	44.60

Table 52, Starting point for 200 load bearing inner walls with alternatives

200 Concrete wall	**Quantity**	**Unit**	**Material GWP / kgCO_2-eqv**	**Total building component GWP / kgCO_2-eqv**
200 Concrete C25/30	1.00	m²	57.26	
Reinforcement B500BT ø12 (0,89 kg/m)	1.00	kg	0.82	
Reinforcement B500BT ø10 (0,62 kg/m)	13.20	kg	10.88	68.96

Alternative 1				
200 Concrete C20/25	1.00	m²	53.82	
Reinforcement B500BT ø12 (0,89 kg/m)	1.00	kg	0.82	
Reinforcement B500BT ø10 (0,62 kg/m)	13.20	kg	10.88	65.52
Alternative 2				
200 Concrete C25/30	1.00	m²	57.26	
Reinforcement [Norway] B500BT ø12 (0,89 kg/m)	1.00	kg	0.36	
Reinforcement [Norway] B500BT ø10 (0,62 kg/m)	13.20	kg	4.75	62.37

Table 53, Starting point for roofing with alternatives

Sheet metal roofing	**Quantity**	**Unit**	**Material GWP / $kgCO_2$-eqv**	**Total building component GWP / $kgCO_2$-eqv**
Sheet metal	1.00	m²	13.16	
Paperboard VU typ 112	1.00	m²	3.98	
22 Tongue and groove panel	1.00	m²	1.11	
45x145 roof ridge-C14 c 1200	1.20	m	0.33	
45x95 roof ridge-C14 c 1600	0.70	m	0.21	
Nail-plate 60x240x2,0	2.20	pcs	0.58	
Brackets, nails	0.75	pcs	0.73	20.10
Alternative 1				
Alu-zink roofing	1.00	m²	11.24	
Paperboard VU typ 112	1.00	m²	3.98	
22 Tongue and groove panel	1.00	m²	1.11	
45x145 roof ridge-C14 c 1200	1.20	m	0.33	
45x95 roof ridge-C14 c 1600	0.70	m	0.21	
Nail-plate 60x240x2,0	2.20	pcs	0.58	
Brackets, nails	0.75	pcs	0.73	18.17

Alternative 2				
Concrete roof tiles	1.00	m²	4.93	
25x38 Battens	3.00	m	0.05	
25x25 Battens	2.00	m	0.03	
Paperboard	1.00	m²	3.98	
22 Tongue and groove panel	1.00	m²	1.11	
45x145 roof ridge-C14 c 1200	1.20	m	0.33	
45x95 roof ridge-C14 c 1600	0.70	m	0.21	
Nail-plate 60x240x2,0	2.20	pcs	0.58	
Brackets, nails	0.75	pcs	0.73	11.95
Alternative 3				
Roofing felt	1.00	m²	3.98	
Paperboard	1.00	m²	3.98	
22 Tongue and groove panel	1.00	m²	1.11	
45x145 roof ridge-C14 c 1200	1.20	m	0.33	
45x95 roof ridge-C14 c 1600	0.70	m	0.21	
Nail-plate 60x240x2,0	2.20	pcs	0.58	
Brackets, nails	0.75	pcs	0.73	10.92

Table 54, Starting point for roof joist with alternatives

200 Concrete joist HD/F	**Quantity**	**Unit**	**Material GWP / kgCO$_2$-eqv**	**Total building component GWP / kgCO$_2$-eqv**
300 loose wool fill	1.00	m²	6.22	
HD/F 200 Concrete C25/30	1.00	m²	45.81	
Reinforcement B500BT ø10 (0,62 kg/m)	12.00	kg	9.89	61.92
Alternative 1				
300 loose wool fill	1.00	m²	6.22	
HD/F 200 Concrete C25/30	1.00	m²	45.81	
Reinforcement [Norway] B500BT ø10 (0,62 kg/m)	12.00	kg	4.32	56.35

Alternative 2				
300 loose wool fill	1.00	m²	6.22	
HD/F 200 Concrete C20/25	1.00	m²	43.06	
Reinforcement B500BT ø10 (0,62 kg/m)	12.00	kg	9.89	59.16
Alternative 3				
300 rock wool fill	1.00	m²	10.68	
HD/F 200 Concrete C25/30	1.00	m²	45.81	
Reinforcement B500BT ø10 (0,62 kg/m)	12.00	kg	9.89	66.38
Alternative 4				
300 loose wool fill	1.00	m²	6.22	
200 Concrete C25/30	1.00	m²	57.26	
Reinforcement B500BT ø10 (0,62 kg/m)	18.00	kg	14.83	78.31
Alternative 5				
300 loose wool fill	1.00	m²	6.22	
200 Concrete C20/25	1.00	m²	53.82	
Reinforcement B500BT ø10 (0,62 kg/m)	12.00	kg	9.89	69.93

Table 55, Starting point for joist with alternatives

200 Concrete joist HD/F	Quantity	Unit	Material GWP / $kgCO_2$-eqv	Total building component GWP / $kgCO_2$-eqv
HD/F 200 Concrete C25/30	1.00	m²	45.81	
Reinforcement B500BT ø10 (0,62 kg/m)	12.00	kg	9.89	55.70
Alternative 1				
HD/F 200 Concrete C25/30	1.00	m²	45.81	
Reinforcement [Norway] B500BT ø10 (0,62 kg/m)	12.00	kg	4.32	50.13
Alternative 2				
HD/F 200 Concrete C20/25	1.00	m²	43.06	
Reinforcement B500BT ø10 (0,62 kg/m)	12.00	kg	9.89	52.94
Alternative 3				

160 Concrete C25/30	1.00	m²	45.81	
Reinforcement B500BT ø10 (0,62 kg/m)	3.00	kg	2.47	
40 "Plattbärlag" C25/30	1.00	m²	11.45	
Reinforcement, slab	24.00	kg	19.78	79.51
Alternative 4				
60 concrete C25/30	1.00	m²	17.18	
Reinforcement mesh 5150	1.20	m²	1.75	
Concrete TT-joist H=400	1.00	m²	32.21	51.13
Alternative 5				
HD/F 200 Concrete C20/25	1.00	m²	43.06	
Reinforcement [Norway] B500BT ø10 (0,62 kg/m)	12.00	kg	4.32	47.38

Table 56, Starting point for footing with alternatives

Siroc U-element U600 S200 H=600	**Quantity**	**Unit**	**Material GWP / kgCO$_2$-eqv**	**Total building component GWP / kgCO$_2$-eqv**
Siroc U-element U600 S200	1.00	m	81.00	
Reinforcement B500BT ø12 (0,89 kg/m)	4.00	kg	3.30	
Reinforcement B500BT ø6 (0,22 kg/m)	0.70	kg	0.58	
Concrete C25/30	0.10	m³	29.00	113.87
Alternative 1				
Sundolitt U+ S200MX H=400	1.00	m	31.69	
Reinforcement B500BT ø12 (0,89 kg/m)	4.00	kg	3.30	
Reinforcement B500BT ø6 (0,22 kg/m)	0.70	kg	0.58	
Concrete C25/30	0.08	m³	23.00	58.57
Alternative 2				
Siroc U-element U600 S200	1.00	m	81.00	
Reinforcement B500BT ø12 (0,89 kg/m)	4.00	kg	3.30	
Reinforcement B500BT ø6 (0,22 kg/m)	0.70	kg	0.58	
Concrete C20/25	0.10	m³	27.00	111.87

Alternative 3				
Siroc U-element U600 S200	1.00	m	81.00	
Reinforcement [Norway] B500BT ø12 (0,89 kg/m)	4.00	kg	1.44	
Reinforcement [Norway] B500BT ø6 (0,22 kg/m)	0.70	kg	0.25	
Concrete C25/30	0.10	m³	29.00	111.69

Table 57, Starting point for slab-on-grade with alternatives

100 concrete slab + 300 cellular plastic	**Quantity**	**Unit**	**Material GWP / kgCO_2-eqv**	**Total building component GWP / kgCO_2-eqv**
100 Concrete C25/30	1.00	m²	28.63	
Reinforcement mesh 6150	1.20	m²	2.51	
100 Cellular plastic	1.00	m²	7.55	
100 Cellular plastic	1.00	m²	7.55	
100 Cellular plastic	1.00	m²	7.55	53.78
Alternative 1				
100 Concrete C20/25	1.00	m²	26.91	
Reinforcement mesh 6150	1.20	m²	2.51	
100 Cellular plastic	1.00	m²	7.55	
100 Cellular plastic	1.00	m²	7.55	
100 Cellular plastic	1.00	m²	7.55	52.06
Alternative 2				
100 Concrete C25/30	1.00	m²	28.63	
Reinforcement mesh 6150	1.20	m²	1.10	
100 Cellular plastic	1.00	m²	7.55	
100 Cellular plastic	1.00	m²	7.55	
100 Cellular plastic	1.00	m²	7.55	52.37
Alternative 3				
100 Concrete C20/25	1.00	m²	26.91	
Reinforcement [Norge] mesh 6150	1.20	m²	1.10	
100 Cellular plastic	1.00	m²	7.55	
100 Cellular plastic	1.00	m²	7.55	
100 Cellular plastic	1.00	m²	7.55	50.65

LUND UNIVERSITY

Dept of Architecture and Built Environment: Division of Energy and Building Design
Dept of Building and Environmental Technology: Divisions of Building Physics and Building Services