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Life cycle global warming potential and costs of an apartment building

Thesis submitted in a partial fulfilment of the requirements for the degree of Master of Science in Building Technology

Helsinki 12.11.2018
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Abstract of master's thesis

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Abstract

The build environment produces significant part of the global greenhouse gas emissions, in Finland about one-third. Sustainable development and minimising the negative environmental impact are a common global goal, but it will not be conducted without the observation of costs.

The research forms from two parts: literature review and a case study. The study has three goals: to find a cost-efficient way to reduce the total greenhouse gas emissions of a building, to test that Skanska's early stage BEBE provides reliable data for life cycle costs and greenhouse gas emissions and to present a definition and information on how to calculate life cycle costs and emissions.

The literature review describes the current use and the background of the evaluation methods. The case study determines the emissions and costs of the building materials of a project including two apartment buildings. The emissions are considered from cradle to gate and the costs until the end of the construction. In addition, the maintenance for the first 25 years of the use is included in both.

Early stage BEBE operates well on the estimation of global warming potential. The costs and the emissions from the use stage form 1% and 6% from the total respectively. For the life cycle emissions, there is no need to study the maintaining of the materials. The best way to lower total emissions and costs is with material selection in the planning stage.

Keywords Global Warming Potential, Life Cycle Cost, Life Cycle Analysis, apartment building

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Diplomityön tiivistelmä

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Tiivistelmä

Rakennettu ympäristö tuottaa huomattavan osan globaaleista kasvihuonekaasupäästöistä, Suomessa noin kolmanneksen. Kestäväkehitys ja negatiivisten ympäristövaikutusten minimointi ovat yhteinen globaalitavoite, mutta sitä ei tehdä ilman kustannusten tarkkailua.

Tutkimus koostuu kahdesta osasta: kirjallisuuskatsauksesta ja tapaustutkimuksesta. Tutkimuksella on kolme tavoitetta. Se pyrkii löytämään kustannustehokkaan tavan pienentää rakennuksen kasvihuonekaasupäästöjä, testaamaan tuottaako Skanskan Pika-ROA luotettavaa tietoa elinkaaren päästöjen ja kustannusten määrittämisen ja esittämään tavan laskea elinkaarikustannukset ja -päästöt.

Kirjallisuuskatsaus kuvaa tarkasteltujen laskentatapojen taustaa ja käyttöä. Tapaustutkimuksessa määritettään kahdesta kerrostalosta muodostuvan hankkeen rakennusmateriaalien kustannukset ja kasvihuonekaasupäästöt. Tuotteiden päästöt käsitellään kehdosta portille ja kustannukset rakennuksen valmistumiseen asti. Rakennuksien käytön ajasta otetaan huomioon ensimmäisen 25 vuoden aikaiset päästöt ja kustannukset rakennusmateriaalien huollosta ja kunnossapidosta.

Pika-ROA toimii hyvin ilmastonlämpenemispotentiaalin arvioinnissa. Rakennuksen huoltoa ja kunnossapito tuottaa noin 1 % päästöistä ja 6 % kustannuksista. Elinkaaren päästöjä tarkasteltaessa, ei kunnossapidon päästöjen sisällyttäminen ole välttämätöntä. Paras tapa pienentää päästöjä ja kustannuksia on materiaalivalinnoilla suunnitteluvaiheessa.

Avainsanat ilmastonlämpenemispotentiaali, elinkaarikustannus, elinkaarianalyysi, kerrostalo,

Preface

This master's thesis was completed between May and October 2018. The subject was selected with the consideration of Skanska's needs and my personal interests. The aim of the thesis was to find ways to determine the life cycle greenhouse gas emissions and costs of an apartment building.

I want to thank Skanska for the interesting subject and funding of my work. I am thankful to everyone at Skanska who have helped with the thesis and given support through the thesis process. Special thanks to my advisor Mia Andelin for listening and guiding during the work. I am grateful of the time I could solely focus on the thesis writing process and want to thank my boss Elina Ikäläinen for giving the time to me. I also want to thank my supervisor Jarek Kurnitski for giving new point of view during the writing process.

Finally, I am thankful to all support outside work, family and friends. You kept me sane during the whole university journey. Thank you all for that.

Helsinki 12.11.2018
Maaria Koskinen

Table of Contents

1 Introduction

This section is divided into three sub-sections. The first section explains the background of the thesis, the importance of the research subject and to what are the used methods based on. The second sub section presents the research subject and its outline. The third section introduces the connection between this study, building rating systems and suggested ways of calculating the studied factors. The thesis does not include all the parts of the life cycle of a building and the sections explain the reasoning for the narrowing of the subject.

1.1 Background

World Commission on Environment and Development (WCED) described sustainable development in Our common future -report in the following way: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (WCED, Bruntland Commission, 1987.) This is one of the most used ways to define sustainable development and it remains globally as an important focus point. Currently, United Nations (UN) has 17 sustainable development goals, from which the following four are related to the subject of the thesis:

- Goal 9: Industry, Innovation and Infrastructure promotes sustainable industrialization and foster innovation emphasises the importance of technical progress as a base for achieving the set environmental objectives.
- Goal 11: Sustainable Cities and Communities emphasises the ability of cities to have an effect to all aspects of sustainability: environmental, economic and social.
- Goal 12: Responsible Consumption and Production promotes resource and energy efficiency besides other factors.
- Goal 13: Climate Action also takes into account that climate change should be minimized in an economically sustainable way. (United Nations, 2018.)

The environmental impact, caused by different industries, has increased considerably since the end of the Second World War. The scale of the problem was acknowledged rather late, at the end of the 1960s. The interest in the environment and the impact that human activity has on it has grown for decades. This concern has resulted in multiple national and international agreements and guidelines besides The Brundtland report, such as the Rio declaration and The Kyoto protocol. (Borg, 2001) According to the European Council, the main international climate action agreement is the United Nations Framework Convention on Climate Change (UNFCCC). The objective of UNFCCC is to prevent dangerous human impact on the environment by stabilising the greenhouse gas concentrations in the atmosphere. (Council of EU, 2018.)

Global warming is the consequence of greenhouse gases (GHG), such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), and their long-term build-up in the upper atmosphere. GHG emissions need to be reduced to stabilise their global concentrations. (Khasreen, et al., 2009.) Getting control over global warming is an important international goal.

At the beginning of this millennium, the built environment accounted for up to 50% of global CO_2 emissions making it the largest contributor of GHG emissions from all industries. In the EU, the building sector is responsible for approximately 40% of the overall environmental load. In Finland, approximately one-third of the GHG emissions and 40% of energy use occur from buildings and construction. (Khasreen, et al., 2009) (Kuittinen & le Roux, 2017). The global cumulative impact on the environment from buildings has increased due to the large number of current construction projects. Most of the environmental impacts from the built environment are caused by the operation and maintenance phases of the buildings. Better energy efficiency lowers the amount of emissions coming from the use stage. By using improved materials and building technologies, the construction sector may contribute significantly to better the environmental life-cycle of its products and the sustainability of construction. (Mateus & Bragança, 2011.)

In 2016, the National Energy and Climate Strategy of Finland set the goal of lowering the carbon footprint of buildings and other construction products (Kuittinen & le Roux, 2017). According to Statistics Finland, emissions in CO_2 equivalents (CO_2eq) have decreased already 22% from 1990 to 2015. Currently, life cycle emissions calculations for buildings are voluntary and the overall emissions through the life cycle of a building are not regulated. Commercial building rating systems, such as LEED and BREEAM, encourage on evaluating and minimizing the carbon footprint of a building proactively. The goal is that strategy guidelines created for Finland will lead to low carbon solutions for buildings. (Bionova Oy, 2017.)

One of the possibilities to assess the life cycle emissions is life cycle analysis (LCA). In the 1960s, LCA was used to assess energy demand for chemical processes and industrial production systems. At the beginning of the 1990s, the interest in LCA started to broaden also other purposes. This development resulted in the methodology going in two directions: existing methods were refined, and new, simplified tools were created for applicants within the company, such as product design. In addition, in 1990, standardization process for LCA was initiated and leading to the ISO 14040 + 44 series, Environmental management, Life cycle assessment, Principles and framework. (Borg, 2001) (Hoogmartens, et al., 2014). European standards EN 15804, Sustainability of construction works, Environmental product declarations, Core rules for the product category of construction products, and EN 15978, Sustainability of construction works, Assessment of environmental performance of buildings, Calculation method, explain the module division between the life cycle and how to calculate the carbon footprint in CO_2 equivalents (Kuittinen & le Roux, 2017).

When LCA was developed, it mainly focused on products with a short lifespan or just a part of a whole system and therefore it has not yet been optimised for the building sector. LCA usually studies the total environmental impact of a product or material from ‘cradle to gate’ or ‘cradle to grave’. (Borg, 2001) In cradle to gate, LCA is performed for the production process, whereas cradle to grave includes also the transportation to the site, construction process, operation and maintenance processes and demolition and waste treatment processes (Mateus & Bragança, 2011).

LCA is seen mainly as a tool for delivering more eco-efficient life cycles (Khasreen, et al., 2009). To get even more sustainable solutions, it is beneficial to also consider the economic side. Life-cycle costing (LCC) is one of the multiple methodologies, that can support and account for a more inclusive view of costs. In the 1960s, LCC as such was first used by the US Department of Defence for the acquisition of high-cost military equipment such as planes and tanks. (Hoogmartens, et al., 2014.) In the 1970s, comparative benefits of alternative energy design options in buildings were assessed and compared by using LCC (Cole & Sterner, 2000).

Focusing only to the initial costs should not be the main interest as better and often more expensive solutions reduce the total costs of a building during its lifespan. It is recommended therefore that the focus on life cycle costs, including repairs, maintenance needs and the ability to change. (Schade, 2007) (Kuittinen & le Roux, 2017).

1.2 Research problem and outline

This master thesis focuses on two factors in an apartment building: its global warming potential and its costs, both during the life cycle of a building. Both are considered through a fixed period, referred to as the life cycle in this research. A multi-storey apartment building was selected as the research subject because it is a standard product of Skanska and development actions were made on the chosen standard solutions. In addition, about two thirds of all building permits, given between 1/2015 and 3/2018, to build individual apartments are for apartment buildings according to the Statistics Finland.

As a goal, the thesis has following aims.

- To find a cost-efficient way to reduce the total greenhouse gas emissions of a building
- To test that simplified building element-based estimation (Early stage BEBE) provides reliable data for life cycle costs and GHG emissions
- To present a definition and information on how to calculate life cycle costs and the environmental impact of buildings, when environmental impact refers to the global warming potential.

In the thesis, the environmental impact and costs are considered element based. The element division is based on building element based estimation of Skanska (BEBE, fin. rakennusosa-arvio, ROA) which is based on Building 80 (Talo 80). Building 80 is a Finnish Building Classification System published by Building Information Ltd. The system is created for new building construction production and its planning. It divides the construction phase to following main classes:

0. Costs for developer
1. Groundworks
2. Foundations and external structures
3. Structural frame and roof construction
4. Supplementary structures
5. Surface structures
6. Appliances, fittings and fixtures
7. Mechanical works
8. Operating costs of the site
9. Overall costs of the site.

In this thesis, environmental impact refers to global warming potential (GWP). According to UNFCC, GWP is a metric for weighting the climatic impact of emissions of different greenhouse gases. It is not beneficial to separately consider every GHG when calculating their effect on the climate change (Kuittinen & le Roux, 2017). The global warming potential of different gases is calculated with the corresponding amount of CO_2 in CO_2-equivalents. The embodied carbon, for example in wood products, is not included in the study.

The focus on the evaluation of costs and environmental aspects is in materials, their production, construction and usage phase. The use phase includes maintenance, alterations and renewals. In either, LCA or LCC, the calculations are not done from cradle to grave.

Repayment periods of upgraded construction solution are wanted to be less than the life time of the building. According to the Act on the Taxation of Business Profits of Income from Professional Activity, paragraph 34, subsection 2, 360/1968, it is said that the write-off of one tax year is maximum 4% from the acquisition cost, without write-offs. This means that the building value, considering to taxes, equals zero after 25 years at the earliest. It is reasonable to assume that the life cycle costs should have been equalized during that time, even though more expensive materials were used in the building phase.

In the thesis, the studied life cycle phases for costs are the construction process, maintenance, repair, replacements and refurbishments, according to Figure 1 stages A 4-5 and B 2-5, including also material purchasing. Emissions are calculated from cradle to gate, in Figure 1 A 1-3, and from maintenance and renewals, B 2-5. As previously stated, the use stage includes the first 25 years of use. It is assumed, that demolition does not occur during the studied period, which leaves the end of the life stage wholly out from the thesis.

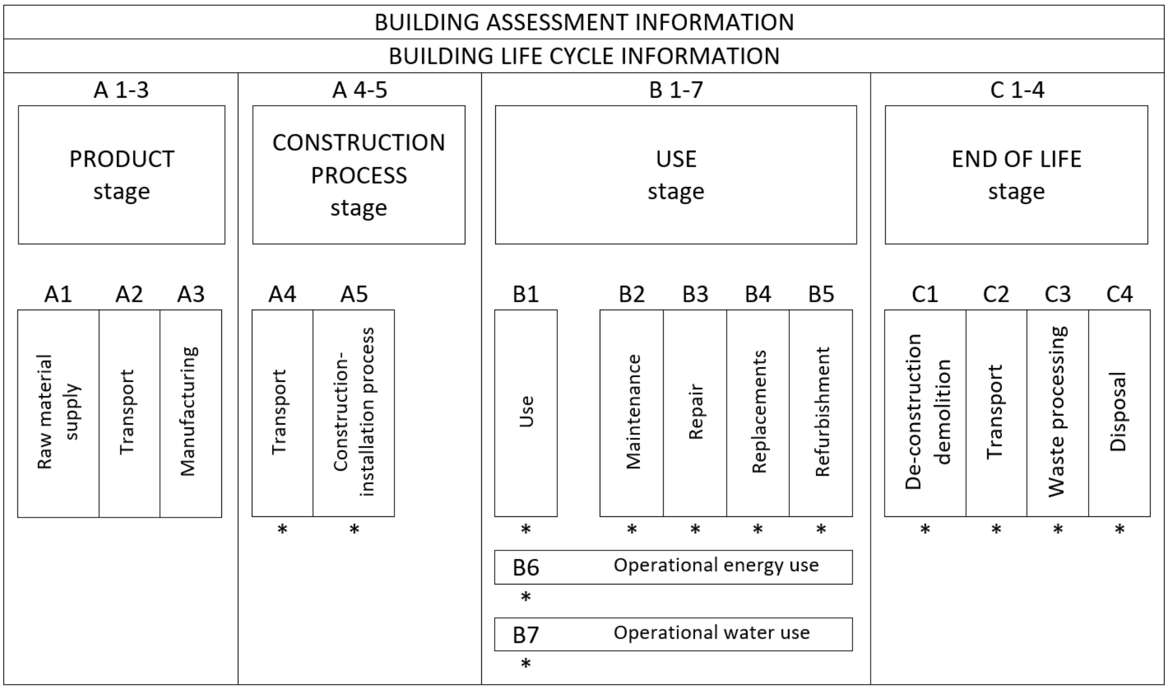


*Figure 1 Division of Building life cycle information *scenarios (EN 15978:2012)*

During the use phase, costs and emissions are calculated to the actions the housing corporation is responsible for, such as maintenance and renewals. Residents' use of electricity, heating and water are not considered, but the maintenance and renewal of those systems are. (Kuittinen & le Roux, 2017.)

To obtain more comparable results between different building projects, costs and environmental impact of land acquisition, rent and groundworks are not considered in this study. It is not beneficial to take into account the costs from land acquisition or rent as these are unique to every project (Kuittinen & le Roux, 2017). In addition, because of uncertainties, costs and emissions coming from possible defects liability repairs are not considered in the study. The goal is to produce a building with no immediate need of repair, which makes it impossible to predict the needs.

1.3 Connection to other projects

The subject of the thesis has connections to current international and national projects and possible future guidelines. The evaluations made are also linked to some commercial rating systems. Few of the most important current projects and their connections to the thesis are presented next.

Currently there are multiple ecological and sustainable development indicators for buildings. Results from different indicators are challenging to compare, which may mislead and confuse consumers and investors. European commission has developed Level(s) indicators to unify the field. (Ministry of the Environment, 2018.) Level(s) forms from six macro-objectives, which are divided further to basic and advanced core indicators. The macro-objectives are:
'Life cycle environmental performance' macro-objectives for buildings
1. Greenhouse Gas emissions from building life cycle energy use
2. Resource efficient material life cycles
3. Efficient use of water resources.

'Quality, performance and value' macro-objectives for buildings
4. Indoor air quality
5. Resilience to climate change
6. Optimised life cycle cost and value.

Macro-objectives include similar indicators as what are calculated in the thesis. Life cycle GWP and LCC are part of Level(s), the first as an advanced and the second as basic core indicator. The first macro-objective includes subsection 1.2 Life cycle Global Warming Potential, where the operational and embodied GWP is calculated in kg CO_2eq/m2. As a part of 6.1 and as advanced indicator there is acquisition and maintenance costs in €/a/m^2. In Level(s), the suggested LCC time span is 50 years for apartment buildings. Additionally, the service life of building and its components in years is section 2.2 Building service life planning. (Dodd, et al., 2016.) The instruction on how to calculate these core indicators, is close to the way they are calculated in this study. Some differences are found on how many parts of the life cycle are included in the calculations. The reasoning, on not including all aspects of the life cycle in this study, is explained later in the thesis.

Green Building Council Finland (GBC Finland) aims to bring the sustainability aspect to a natural part of the actions of the building industry. In 2011, they started a project to develop the industry indicators to evaluate ecological and energy efficiency. As a result, GBC Finland published life cycle indicators and a guide how to calculate them. The indicators for the project stage are arithmetic total energy use (Fin. energiatehokkuusluku), life cycle carbon footprint, life cycle cost, indoor environment class. (GBC Finland, 2013.)

The most considerable difference between carbon emission calculations, done in the thesis and how GBC Finland suggests doing it, is taking to account the ground elements. GBC Finland suggest to consider soil and rock material, ground reinforcements, pavements on the plot and large entities on the yard, such as playground and park (GBC Finland, 2013). In this study, these are not considered, because the focus is building elements and materials. The aboveground structure more comparable than, for example, the foundations. The ground may alternate largely between different projects and the used methods cannot be standardized.

GBC Finland guides to calculate costs in a similar manner as the carbon footprint, including all the same parts. In this study, as stated in 1.2, only part of the whole life cycle of the building is examined and life cycle is considered in different ways for emissions and costs. The whole life cycle is not studied, so that the results can be compared to other similar projects. Including, for example, transportation to the site would lower the possibility to analyse differences between material emissions and costs in different projects.

According to GBC Finland, the most used green building certifications in Finland are international BREEAM (Building Research Establishment's Environmental Assessment Method), LEED (Leadership in Energy and Environmental Design) and Finnish RTS Ympäristöluokitus. In Finland, it is more common for commercial buildings to have green building certificates than residential buildings (USGBC, 2018) (GreenBookLive, 2018). Currently, 188 buildings have BREEAM certification in Finland and only one of them is a residential building (BRE Global Ltd, 2018). There are 246 buildings, which have a LEED certification but there are no information available about how many of them are residential.

The national legislation related to environmental politics has developed according to the international agreements and the obligations from EU legislation (Ministry of the Environment, 2015). Finland set a goal to lower the emissions 16% on the sectors outside emission trading from 1990's level by 2020. This lowering is part of the goal set on national environmental act (609/2015), which ensures that the amount of GHG emissions are monitored and reduces. The long-term goal is to cutback the emission level 80% from 1990 level before 2050. It is important to know that in EU construction, heating of buildings and residency are part of the sectors who cannot take part into emission trading. They have to reduce their emissions directly by concrete actions if any rules or regulations refer to that.

2 Methods

The thesis forms from two main research parts: literature review and case study. This section presents the methods used to study these parts. Interviews were conducted to support the findings.

Different parts of the life cycle are studied for environmental impact and costs in this research. The emissions are studied for the materials from cradle to gate. The life cycle phases included in the cost studies are construction costs and material purchasing. In addition, the maintenance and renewals are analysed for the studied elements for the first 25 years of the use stage on both emissions and costs. Figure 2 shows what is commonly considered as a life cycle of a building also showing its parts. The full life cycle of a building or a material is not considered in the thesis. The variation in length of the life cycle is explained in chapter 1.2.

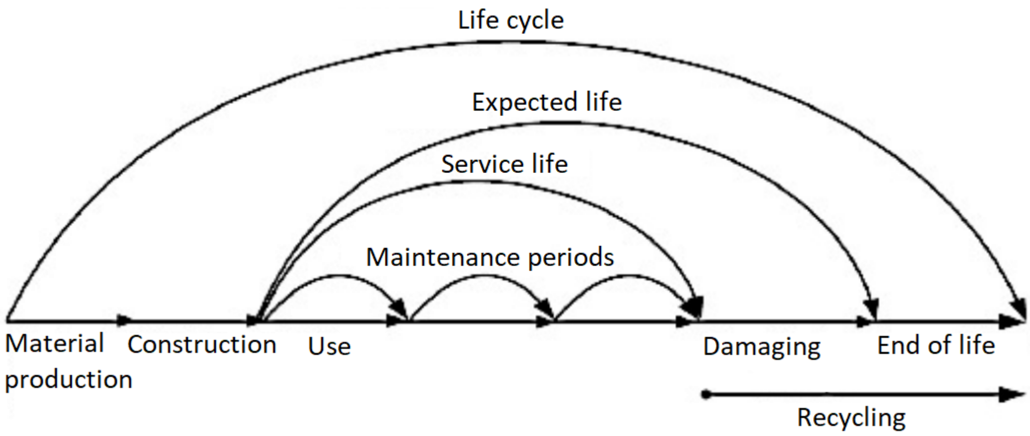


Figure 2 Life cycle of a building (Myyryläinen, 2008)

The data for the research was gathered from several sources. Literature and previous researches perform as the base for this study. When selecting references, it was preferred that the publication occurred after 2000. Some exceptions to the publication time restrictions can be found from subjects that have not changed significantly during the years, such as the basics of the methods, the history of LCA and LCC. The most recent versions of laws and regulations were used. Selected references are published either in English or in Finnish. Finnish sources have been particularly used to obtain country specific information, because especially for LCA inventory analysis, the data nationality is considered important when choosing data sources (Khasreen, et al., 2009). The reliability of all used data was carefully studied. For numerical data used for case studies calculations, the selected publications were selected so that they were published mainly after 2010 to ensure as up to date information.

To support both parts, few interviews have been conducted. Interviewees were all experts from Skanska. Interviews supported the gathered knowledge from literature and ensured that the company specific data is reliable and accurate.

2.1 Literature review

Literature review is divided into five parts: Environmental assessment and Life Cycle Analysis of buildings, 3.2Global warming potential of building industry, Life cycle costs and cost analysis for buildings,
Combining assessment of environmental impact and costs of a building and Global warming potential of building industry. The titles were selected to cover the whole research subject and were used to create outline and the base for finding the sources.

Most of the used articles were found by using Google Scholar. Article search was done in both English and Finnish, but the focus has been in English except when country specific information was searched. When researching previous case studies, the focus has been on residential buildings and cases in Nordic countries with similar climate as Finland. Search words, such as, construction, building, life cycle analysis, life cycle cost, global warming potential and their abbreviations, were used to find relevant sources.

Publications were evaluated according to which journal or website where they were published. The reliability of the journals was ensured with the ratings in Publication Forum. Publication Forum is created by Finnish scientific community and it classifies publication channels for their quality assessment. Journals are classified with a four level system from zero to three. (Julkaisufoorumi, 2018.) Most of the journals used in the thesis were in leading level 2 and none of them was under the basic level 1. Used website sources were considered reliable when the owner of the page is not biased and well known at least nationally, such as ministries. When, for example, a new product was introduced in the website of a company finding it, partiality can be assumed. Still, websites were used because they might have been only data source about the subject.

Books have been used as a support to the other sources. Book search was based on the mentions of books on electrical sources and articles. In addition, search was conducted to find publication from a few to selected writers who have researched at least partly the thesis topic, such as Arto Saari and Leevi Myyryläinen. Books have been searched from the databases of The Harald Herlin Learning Centre of Aalto University and Helmet library. The goal was to find a broad view of publications to increase the reliability of this study.

2.2 Case study

In this thesis case study was made to research one multi-storey apartment building and its environmental impacts and costs through selected parts of its life cycle. It is divided into six parts: Background, Conducting the case study, Life cycle assessment and Global Warming Potential, Life cycle costs, Maintenance and renewals and
Optional structures. The way case study is performed, is explained in the chapters, besides the first one, according to their titles.

Case study enables reaching on a practical level and answering the set research questions. The case forms a base for the study narrowing it and enabling the possibility to gain more detailed view about the research subject. This part of the thesis was made as an instrumental case study. Meaning that the case project was selected to research selected subject and to help on answering research questions, not because of the interest of that particular project. (Stake, 1995.)

In this thesis, specific phenomenon is studied, which allows the use of only a single case. One case was considered enough to find answers to the research questions without losing the trustworthiness of the results. By having only one case, the research subject can be studied more deeply and in a versatile way.

3 Literature review

In this section, the previous study on the research subject is presented. At the beginning, the environmental impact of buildings is studied, first considering LCA and then GWP in separate sub-sections. Thereafter, the costs and their analysis in previous studies is presented. As the goal of the thesis, costs and emissions are combined and the possibilities and challenges of this combination are presented in the fourth sub-section. Lastly, review was made about the life cycle maintenance needs and renovation.

3.1 Environmental assessment and Life Cycle Analysis of buildings

Building sector is a crucial and a great contributor to the environmental loads generated by society (Borg, 2001). Study conducted in 2010 by Kiinteistömaailma, shows that the end customer is interested in the energy efficiency and the environmental impact of the apartment. Still, ecological building materials aspect is one of the least valued aspects of a building. (Kiinteistömaailma, 2010.)

According to standard EN 15978, Sustainability of construction works, Assessment of environmental performance of buildings, Calculation method, environmental impact is a “change to the environment, whether adverse or beneficial, wholly or partially, resulting from environmental aspects”. The standard describes environmental aspect as an “aspect of construction works, part of works, processes or services related to their life cycle that can cause to the environment”.

Assessment tools focusing on one environmental aspect, such as the carbon footprint, differ from LCA because of its comprehensive environmental scope. LCA includes multiple factors, such as, greenhouse gases, natural resources and water emissions. (Hoogmartens, et al., 2014.) The best fit for the analysis would be a level of single product or material. Still, it is generally accepted to be used for construction products and a whole building. Building life cycle is considered long, decades, and the design is rather complex. This makes the use of LCA-tools challenging and they are not widely used in building design. In addition, building rating systems are not comprehensive or consistently LCA-based. (Mateus & Bragança, 2011.)

There is no one right method of performing LCA, according to the standard ISO 14040, but guidelines can be found. Standard makes a base for the assessment and does not cover any field specifically. The organization implementing the study can decide how research is performed to get the solution in wanted form. Because there is no standard specifying how to calculate LCA for a building, the results may vary between different inspections, which emphasises the decisions made in the investigative company. The lack of specific standards on LCA in building industry often leads to non-comparable results (Ochsendorf, et al., 2011).

LCA is a powerful assessment tool on determining environmental impacts. Still, it is important to know that LCA is not a decision-making tool nor does it solve dilemmas. (Motuziene, et al., 2016.) Comparing different projects with different details may lead to misunderstandings: a smaller building in most cases has a lower environmental impact that a bigger construction. For example, skyscraper and 4-storey apartment building cannot be compared by their LCA results, even when emissions are divided with area, because they are built for different use and need different types of structures. To be able to compare the results, the analysis needs to be done to plans designed for the same purpose, location and use.

The most traditional way of conducting LCA is process LCA. In this method, material quantities and energy are converted into CO_2 emissions. Process data forms the base for the inspection which makes the method accurate. The emissions of every process are analysed separately thought the life cycle of the product based on the boundary definitions. To get total life cycle emissions, process emissions are added together. The process LCA can be used to compare similar products, because processes are analysed separately with appropriate data. (Säynäjoki, et al., 2012.)

Part of LCA is life cycle inventory (LCI), which is a methodology for making the needed estimations of, for example, material properties that are included in the LCA study (Rebitzer, et al., 2004). LCI environmental impact data can be challenging to find. For quantified information, Environmental Product Declarations (EPD) are a good source. EPD is a document about the life cycle environmental impact providing transparent and comparable information. EPD is referred to in ISO 14025, Environmental labels and declarations, Type III environmental declarations, Principles and procedures, which makes it an international way of providing the life cycle data of products. (EPD International AB, 2018.) Currently only 24 Finnish products have an EPD. From these, nine are paints, four insulations and three asphalt concrete. This shows that only few producers have wanted to get the EPD for their products. (Rakennustietosäätiö RTS, 2018.)

For life cycle efficiency, it is reasonable to invest in even in solutions, which produce high amount of emissions, if this leads to a larger decrease of emissions in the use stage. In the use stage, it is also important to produce the energy with as low emissions as possible. The earlier the emission efficiency is taken as a part of the planning and the goals of the project the less it costs and the easier it is to achieve the set goal. Still, when great improvements are wanted to make, large entireties need to be considered, as shown in Figure 3.

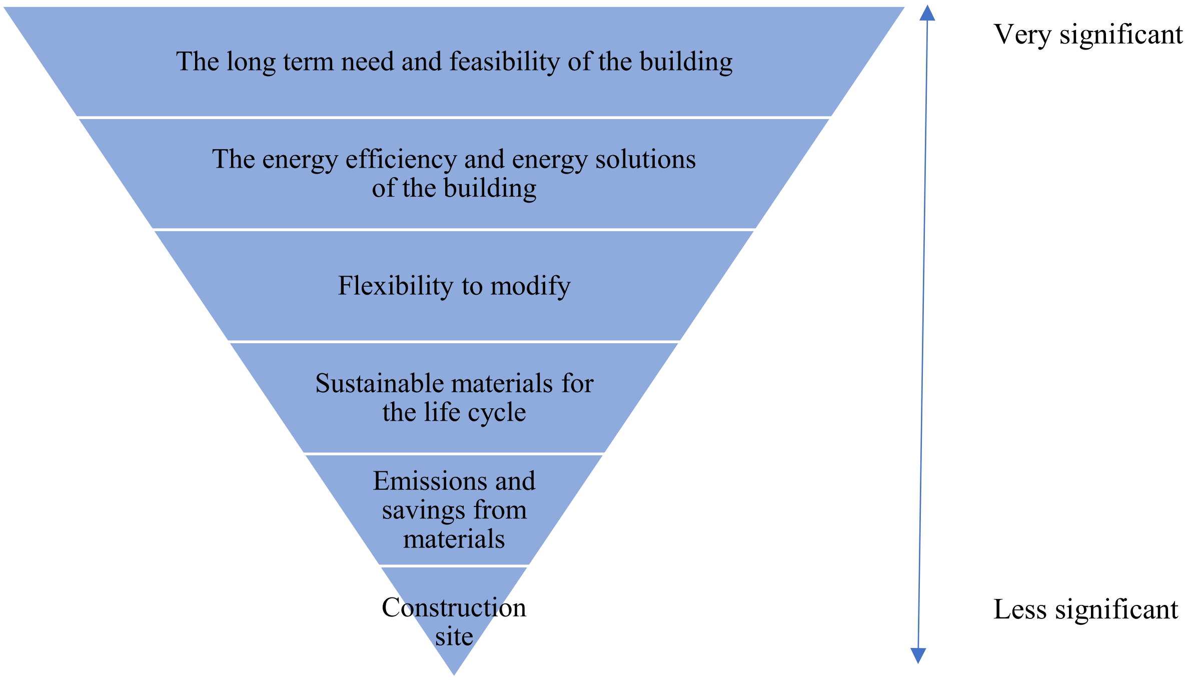


Figure 3 The division of the emissions of an apartment building for 100 years with different energy classes and solutions (Pasanen, et al., 2012)

LCA for constructions products is very complex, because of large number materials, actors and processes. Construction processes have a wide life cycle span, leading to the need for multiple assumptions. Still, LCA is regarded as the best method available for assessing the environmental performance of a product. (Mateus & Bragança, 2011.)

3.2 Global warming potential of building industry

In Finland, the construction material related emissions are 100-1000 kgCO_2eq/m^2. This includes all factors from building types to variations in production of materials and their origin. Construction of new buildings creates roughly 3 million tons of GHG. Renovation materials produce 0.5-1.2 million tons of GHG emissions, when the amount of waste is assumed to be replaced with new materials. The materials are considered having a low number of materials with low emissions, such as wood, but to mostly be materials with high emission intensity, such as concrete. The emissions from the use of buildings, heating the service water and electricity use produces approximately 15 million tons of CO_2eq. This means that all together energy use of the building, new construction and renovations create about 35% of the GHG emissions in Finland. According to the Statistic Finland, the total GHG emissions of 2016 was 58.8 million tons of CO_2eq. (Häkkinen & Vares, 2018.)

Global warming potential is used as a metric for weighting the climatic impact of the emissions of different greenhouse gases within the Kyoto Protocol (Shine, et al., 2005). The unit of GWP, CO_2eq, is described as “a metric measure used to compare emissions from various greenhouse gases on the basis of their global warming potential” according to the European Environment Agency (European Environment Agency (EEA), 2001). According to the standard ISO 14064-1:2006, Greenhouse gases, Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals, there is a great variation in the GWP for different gases, as shown in Table 1.

Table 1 GHG global warming potentials, based on ISO 14064-1

Gas	**Global Warming Potential**
Carbon dioxide	1
Methane	21
Nitrous oxide	310
Hydrofluorocarbons (HFCs)	140 - 11 700
Hydrofluoroethers (HFEs)	100 - 500
Perfluorocarbons (PFCs)	7 000 - 23 900

GWP is popular, because its design and application are simple, and it is rather transparent. Its definition is rather simple, in calculation, only a few input parameters are required, and the calculation process is relatively easy when compared with some of the alternatives, such as energy balance climate model. (Shine, et al., 2005.)

To achieve a sustainable building, the goal should be low embodied carbon content and low emissions from the operation phase. A large part of life cycle impact of a building comes from its material related and their GHG emissions, which should always play part of the LCA studies when construction products are researched. (Ruuska & Häkkinen, 2015.)

The construction phase creates a clear carbon spike to the life cycle of a building. This high amount of GHG emissions in a short time creates a question, if they contribute profitably the GHG goals of the near future, even though the building under construction would be the elite of energy efficient buildings. The emissions might cause advancing of the climate change to an undesired course. Because energy efficiency has its profitable affects to climate not immediately but during many years, the severe affects from construction might exceed the long-term benefits. (Säynäjoki, et al., 2012.)

Emissions can be reduced with different solutions in planning, but the decreasing potential is higher in product development. Product development can enable the use of low carbon materials or materials produced with minimum amount of fossil fuels. (Häkkinen & Vares, 2018.) For example, concrete production creates great amount of CO_2 emissions. In the construction of a single-family house, it can be responsible up to 99% of the total CO_2 emissions. Most of the emissions come from its production process especially from cement. (Khasreen, et al., 2009.)

During the life span of a building, most of the emissions come from the energy use, as seen from Figure 4. While the energy efficiency of buildings is increasing, the importance of the focus on other parts of the life cycle grows. The second largest phase creating emissions is the production of the materials which is known to have great opportunities on improvements (Häkkinen & Vares, 2018). To gain development rapidly, the focus should be on the emission rich processes and finding cost efficient ways on decreasing their emissions.

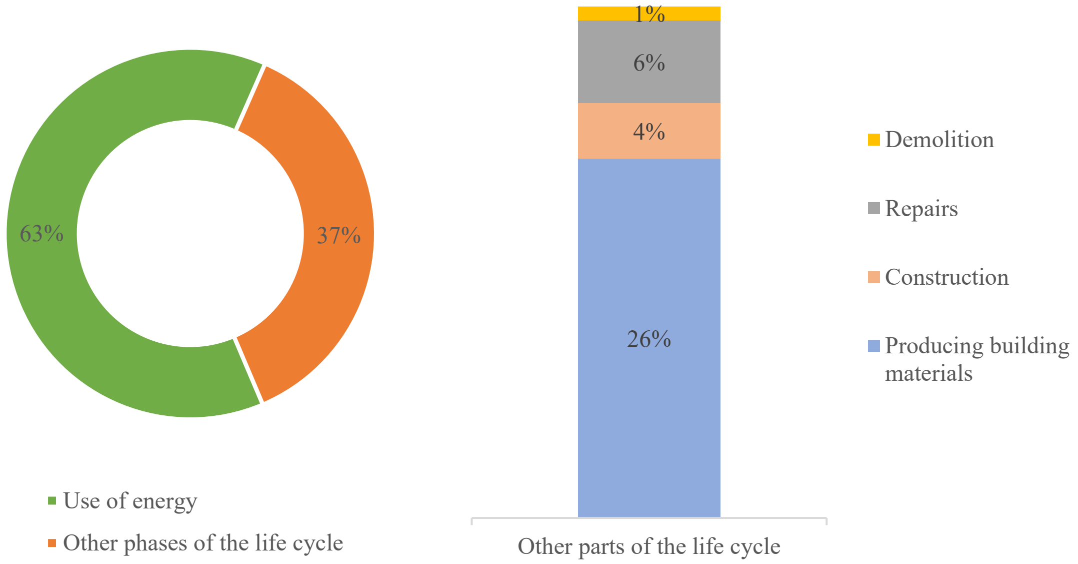


Figure 4 Formation of average apartment building's carbon footprint (Ruuska & Häkkinen, 2013)

Life cycle CO_2eq emissions are suitable for measuring the environmental effectiveness of a building, because it allows the combination of construction and use stage. It also correlates positively with other environmental impacts thus, it guides to the right direction on broader environmental impacts. (Pasanen, et al., 2012.) Carbon footprint is a widely known term and it often refers to the CO_2 equivalent emissions. Because the term can be seen, in for example media, it is familiar to the end customer. Providing reference data and the carbon footprint of the building, the information can be used in the marketing of apartments and be considered encouraging the sales. (Wiedmann & Minx, 2008.)

3.3 Life cycle costs and cost analysis for buildings

Life cycle costing is defined in standard 15686-5, Buildings and Construction Assets, Service-life Planning, Part 5: Life-cycle Costing. It is described as an "economic assessment considering all agreed projected significant and relevant cost flows over a period of analysis expressed in monetary value. The projected costs are those needed to achieve defined levels of performance, including reliability, safety and availability." Typically, LCC analyses are established purchasing, operating and end-of-life. All parts of the phase are considered, such as in purchasing the delivery, installation and insurance. (Perera, et al., 2009.)

It is common to aim to minimize the costs of the construction and in the design decision-making process the initial capital cost is still the main factor affecting the decision. This does not inevitably improve the performance of a building during its lifespan. Higher production costs may decrease the total life cycle cost (LCC). Therefore, it is valuable to show the relation between design choices and lifetime cots to the construction client. It is desirable to all to find the most cost-efficient solution. For example, during 25-year time, an office building will consume about three times its initial investment. (Schade, 2007.)

The lifetime quality, its improvements, and cost effectiveness of the building are, or should be, a shared interest for the constructor, the owner and the end user. LCC often gets a low priority from the construction clients because they are not aware of its benefits. Initial costs can be estimated rather easily and reliably, which makes it the main base for decision-making. Maintenance and operational costs are not as predictable as they continue to the future and depend on multiple factors. This creates challenges on LCC evaluation. (Schade, 2007.)

Even though it might seem reasonable, that customer should be willing to pay more from energy efficient building or apartment, it is not always reality. The reasoning behind higher prices, compared with other options on the market, needs to be clarified. When the customer is ready to invest in energy efficiency to get faster returns, the visibility of the investment is valued high. For example, the customer often prefers upgraded windows to attic insulation, even if the later one has higher energy saving potential. A study conducted in the US also states that if building has, for example, LEED certification, the selling prizes of the building increase. There are not many studies showing how willing European, or in detail Finnish, citizens are to pay more for energy efficiency. (Popescu, et al., 2012.)

Evaluating LCC should be a transparent process to be able to replicate the calculation process for the future projects. Within one company, the calculations should be done the same way every time and the information sources clearly stated for later examination. To be able to compare different design choices, there should be a clear cost breakdown structure. Gathering data for LCC can be rather difficult because of its limited availability. Data can be collected from, for example, manufacturers, suppliers, contactors and testing specialists. Life cycle data is usually an estimate, because data is complicated to measure. (Schade, 2007.)

Values got from life cycle costs analysis (LCCA) studies are stated in monetary units and might not provide the most environmentally effective solution. However, LCCA often indicates environmentally desirable solutions. For example, energy efficiency lowers the environmental impact of a building simultaneously saving money. LCCA may also reveal that additional costs from improvements done to lower environmental impact of a building cause only minimal additional costs over time. (Davis, et al., 2005.)

It is important to consider how LCC is used as a tool to help selecting design solutions or as an asset. The familiarity of the currency unit may create a false sense of certainty about the data (Swarr, et al., 2011).

When performing LCC far to the future, it is important to conduct a sensitivity analysis. Sensitivity analysis is used to clarify how responsive the end result is to changing the initial data. It can be use, for example, to show how the profitability order can change. (Saari, 2001.)

In the design phase, it would be important to understand what occurs through the whole life cycle of a building. People working within the operational phase claim that in design and development phase there is not enough knowledge on how much life cycle operational maintenance costs are (Ristimäki & Junnila, 2015). Building cannot be used in a more efficient way than it is designed and build. The efficiency and the length of the life cycle of a building is mainly decided in project design. (Myyryläinen, 2008.)

Table 2 presents the division of the costs in an example project. In the example, the life cycle was considered to be 50 years and the interest 3%. It can be seen, that the construction costs make a significant part of the total life cycle costs. In the planning phase, the focus is often on construction costs. In the early phases of the planning, there is the most potential to have an effect to the final costs. In addition, the selections made for construction directly affect to the use and end stage of the building.

Table 2 Example of life cycle cost (Vainio, et al., 2012)

Present value	**Residential apartment building**	
	[€/floor-m^2]	**Share**
Plot acquisition	200	7%
Construction costs	1200	44%
Costs from building care	790	29%
Maintenance costs	540	20%
Disposal	20	1%
Total (VAT 0%)	2750	100%

3.4 Combining assessment of environmental impact and costs of a building

LCA and LCC studies produce information that supports planning in the long term and helps setting priorities. Regular assessments may also help in controlling business performance. Tools can analyse, for example, the economic and ecological success. LCA and LCC have the same aim: raising awareness and intending some sort of behavioural control. (Bierer, et al., 2015.) Ways have been found to combine these methods. LCA and LCC have several ways how they may be applied to achieve sustainability: economical, environmental and societal. (Hoogmartens, et al., 2014.)

Traditional LCC does not consider environmental impact. ISO 14040 standard for LCA methodology, does not either address the integration of cost analysis with LCA. The methods share similar goal and scope definition and limited integration of them has occurred. They differ from each other in purpose and approach. Even though LCC and LCA are done to provide answers to different questions, finding a way to combine them, would be beneficial. For example, LCC is seen as a valuable aspect of sustainability assessment, because finances are often important part of the decision making (Norris, 2001) (Swarr, et al., 2011).

In the building industry, the constructors are often selected based on their offers, with the focus on the initial costs. Applying lifecycle assessment major saving might be achieved in the long run. (Ristimäki & Junnila, 2015.) This has reflected as problems and has not promoted the development of the industry. It is possible that there have been restrictions on who has been invited to offer. It is important that construction industry proceed from only competitive bidding.

There is a high interest wanting to demonstrate the connection between life cycle cost-efficient solutions and lower carbon emissions. Combining LCA and LCC would lead to a higher value for both tools and their results. (Perera, et al., 2009.) Assessments, such as environmental, should not be limited to one phase of the lifespan of the building. These restrictions can lead to poorly informed conclusions and actions. (Ochsendorf, et al., 2011.) Building goes through multiple phases and it should be stated clearly, which have been studied and why some are left out from the research, especially in life cycle evaluations.

The difficulty in life cycle evaluating is that when no one is responsible for doing them, which does not encourage on performing it. The obligation should be on the responsibility of the property investors and owners to demand or do the life cycle evaluation. The profit from improvements is often desired to gain quickly. Longer payback times are seen as unprofitable in most business models, which would like a continuous profit. (Ristimäki & Junnila, 2015.)

Combining ecological and economic dimensions may produce savings, which can be significant compared with the initial investment, if life cycle thinking comes a basic part of construction development. Improvements in structures to improve energy efficiency will in the eventually lower also the running costs. Even small design changes may lead to large carbon reduction with insignificant effect to costs. (Ristimäki, et al., 2013.)

One difficulty on combining environmental impact and LCC is the difference in units. LCC denominates monetary units whereas greenhouse gases are measured with carbon dioxide equivalents. In addition, LCA and LCC often use different time frame. LCA usually covers the whole life cycle of a product from cradle to gate or grave whereas in LCC the economic lifetime can matter more. This means that costs do not include, for example, the final stages of the building, such as demolition. (Hoogmartens, et al., 2014.)

It is important to find ways to combine counting environmental impacts and costs. The definition of the term, LCA or LCC, and the way elements are considered needs to stay the same throughout the process. The results of both evaluation the costs data can give a false sense of certainty, which can make it more sensitive data and its errors need to be well explained. (Swarr, et al., 2011.)

It is recommended to consider the environmental impact of building materials in the planning phase. By calculating, for example, the carbon footprint, the most cost-efficient way to decrease it can be found. The plans should be put into practice when the build starts. (Kuittinen & le Roux, 2017.) After the construction is completed, the details of the changes should be corrected to plans to re-evaluate the calculations for the use phase. In addition, this helps on improving the calculation for future projects and determining the accuracy of used calculation methods.

In Table 3, comparison of LCA and LCC is shown. It can be seen, that they have a lot of differences, which emphasises the importance of clarifying both of their outline before doing any calculations attempting to find a relation between them.

Table 3 Differences between LCA and LCC in purpose and approach (Norris, 2001)

Tool/Method	**LCA**	**LCC**
Purpose	Compare relative environmental performance of alternative products systems for meeting the same end-use function, from a broad, societal perspective	Determine cost-effectiveness of alternative investments and business decisions, from the perspective of an economic decision maker such as a manufacturing firm or a consumer
Activities which are considered part of the 'Life Cycle'	All processes causally connected to the physical life cycle of the product; including the entire pre-usage supply chain; use and the processes supplying use; end-of-life and the processes supplying end-of-life steps	Activities causing direct costs or benefits to the decision maker during the economic life of the investment, as a result of the investment
Flows considered	Pollutants, resources, and inter-process flows of materials and energy	Cost and benefit monetary flows directly impacting decision maker
Units for tracking flows	Primarily mass and energy; occasionally volume, other physical units	Monetary units (e.g. dollars, euro)
Time treatment and scope	The timing of processes and their release or consumption flows is traditionally ignored; impact assessment may address a fixed time window of impacts (e.g., 100-year time horizon for assessing global warming potentials) but future impacts are generally not discounted	Timing is critical. Present valuing (discounting) of costs and benefits. Specific time horizon scope is adopted, and any costs or benefits occurring outside that scope are ignored

The goal of planning should aim for overall life cycle economy. Construction is done to defined purpose affordably and with high quality. The building and building parts should be made in a way that they are durable and their useful life is as long as possible. (Myyryläinen, 2012.) Buildings are complex systems, which is why the best solution is achieved with experts from multiple fields.

3.5 Life cycle maintenance and renewals

Building should be designed for a long life span to ensure effective material use. Flexible design that is easy to maintain and fix, might cause extra initial costs but support effective material use. Good maintenance can extend the life span of technical systems and building parts during the usage phase. In addition, they may prevent moisture and mould problems. (Peuranen & Hakaste, 2014.)

Maintenance elongates the use stage of a building. Maintaining the building forms from different types of actions with alternative effects to the life span length, as seen from Figure 5. The functionality of an element lowers in a linear fashion between different maintenance actions. Maintenance needs to be scheduled in a cost efficient way. Even with regular maintenance the useful life of an element has an end point. The evaluation between the renewal time and different types of maintenance affect to the actual costs and emissions created during the life cycle of the element. (Myyryläinen, 2008.)

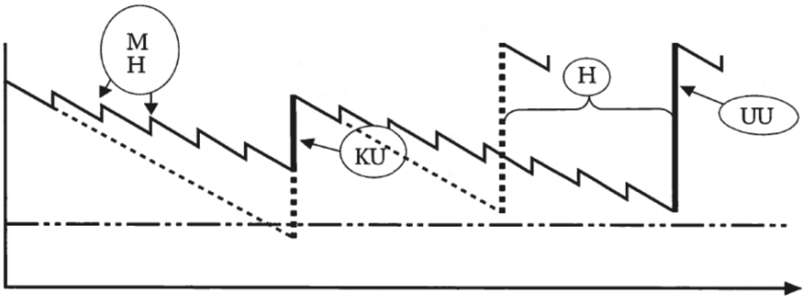


Figure 5 The effect from maintenance and renewals to the length of a life cycle of a building element (Myyryläinen, 2008)

The lowering trend of the functionality of the building elements without regular maintenance
The lowest functionality level accepted by the customer
MH = Regular maintenance enables the constant functionality of a building, lowers the maintenance need and elongates the life cycle of building elements
KU = With maintenance building elements are maintained, building elements which quickly wear out are renewed and elongated the life cycle of building elements
UU = Renewing a building element
H = Elongating the life cycle of a building element with regular maintenance and timing right the maintenance methods

All the costs coming from up keeping a building are covered with, for example, the maintenance charges of the apartments in the same apartment building and other compensations of the use. Real estate management includes heating, electricity, cleaning, property managing, drinking and foul water, waste management, insurances and real estate tax. Maintenance and renewals keep building and its parts in working order when they are done regularly. (Saari, 2001.) According to the law, stakeholder has to take care of the inside of their apartment, Limited Liability Housing Companies Act (LLHC) chapter 7, paragraph 3§, subsection 1. The board of housing corporation need to ensure that the buildings in the property are maintained, LLHC chapter 7, paragraph 2§, subsection 1. Property manager takes care of keeping the building, LLHC chapter 7, paragraph 17§, subsection 1. In addition, the housing corporation hires a maintenance company to take care of the routine maintenance work. The distribution of work between property manager and the maintenance company varies between housing corporations according to their agreements. (Realia Isännöinti, 2017.)

According to the Limited Liability Housing Companies Act, the board of the housing corporation is demanded to make a plan for the future maintenance to present to the stakeholders’ meeting. It can be professionally made as a long-term plan, which includes a common plan for the future 5-10 years. The plan includes a timeline where the future maintenance needs are set, so that the annual maintenance and their cost are clearly stated.

Building might undergo multiple changes in its form and function during its life span. These changes can be as, or even more, significant, than the original product. (Khasreen, et al., 2009.) Even though the changes might have major effect, they cannot be predicted. Energy use, maintenance and emissions from products are the predominant contributors to environmental loads of the usage phase. Often materials and components are not considered as a part of usage phase assessments. (Borg, 2001.)

4 Case study

This section forms from six sub-sections. Firstly, the studied building project is presented. The project is visualized with pictures of, for example, the facades. The second sub-section presents the materials and tools used to perform the case study. The studied aspects are presented separately at the end of the section.

4.1 Background

The case project As. Oy Helsingin Venny forms from two four-storey buildings and total of 59 apartments and is designed and build by Skanska. The single stair building has staircase A and the slab block staircases B and C as shown in Picture 1. Apartments vary from studios to four room apartments. Buildings are located in Kuninkaantammi, northern Helsinki. All apartments have balconies or terraces, except one, which has a balconette. There is one sauna and a laundry with a drying room for the common use of the residents. The housing corporation has an underground garage, which is excluded from this study. The building was finalized and taken into use in June 2018. (Skanska Kodit, 2018.)

Picture 1 As. Oy Helsingin Venny site plan (Skanska Kodit, 2018)

The facades of the buildings are shown in pictures below. The façade of the single stair building is partly brick masonry, which can be seen as a darker surface than other facades. Picture 7 shows the ready buildings from the yard.

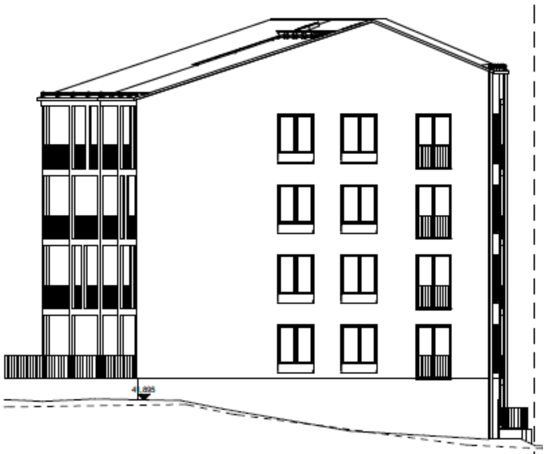
The base floors are partly ground supported floor slab and partly hollow core slab elements. External walls are mainly ferroconcrete elements or insulated render ferroconcrete elements. The exterior of the building with staircase A is partly brick masonry as previously stated. The loadbearing walls between the apartments are 200 mm thick concrete walls. Partition walls are steel frame plasterboard walls. Both intermediate floor and roof structures are hollow core slab elements. Buildings have ridge roofs covered with concrete tiles. Balconies are concrete balcony slab elements, either cantilever balconies or supported with concrete jamb wall elements. (Skanska Kodit, 2016.)

Picture 2 Facades from southwest

Picture 3 Facades from northeast

Picture 4 Facades from northwest

Picture 5 Facade of the single stair building from southeast



Picture 6 Facade of the slab block from south east

Picture 7 Picture from the yard of Venny, on left the single stair building and on right the slab block (Skanska Kodit, 2018)

Apartments have mechanical supply and exhaust ventilation with heat recovery. The buildings are heated with district heating. All apartments have radiators. Bathrooms, saunas and toilets have electrical floor heating for comfort. Solar panels are installed to the roof of the slab block. The electricity produced by the panels is used for common spaces. (Skanska Kodit, 2016.)

The floor area efficiency, net area over gross area, may also affect the emissions and costs over the area. The efficiency of the single stair building is 0.71 the slab block is 0.68. The division of gross area from the total in housing corporation divided into the different buildings is presented in Figure 6.

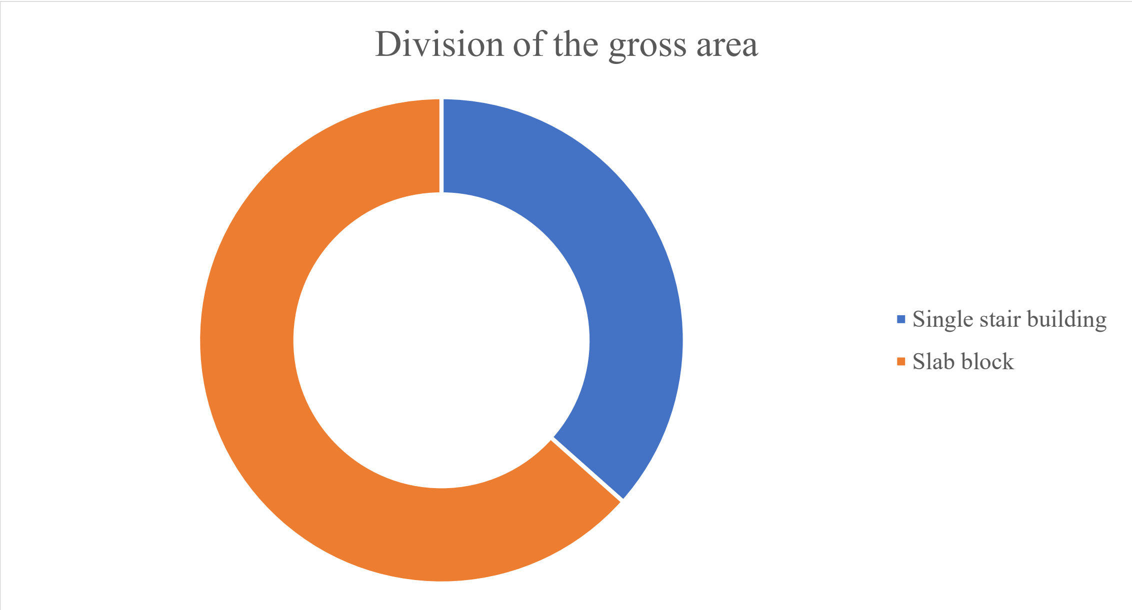


Figure 6 Division of the gross area between different building types

Early stage BEBE is the first cost estimation tool used in a building project. The tool has integrated GWP calculator for building components in classes 2. Foundations and external structures, 3. Structural frame and roof construction, 4. Supplementary structures and 5. Surface structures. Costs are calculated to all elements considered in early stage BEBE. Calculating tool makes a lot of estimations. The tool is made in a way that only major structures and areas need to be known, which can make it good in helping on aiming at low emissions in the project. The used values are based on past projects and their averages.

4.2 Conducting the case study

Data about the case project Venny was gathered from project documents, such as building element-based estimations (BEBE), and with interviews. The actual design choices of Venny were compared with other alternatives to see if different solutions would have led to lower environmental impact. The research was done in a way that the results support the decision making of the future projects and help on life cycle thinking. These large concrete structures would distort the environmental impact calculations why the parking hall under the buildings is not included in the research.

The early stage BEBE is a preliminary estimate for the costs of the construction. In addition, it calculates an estimation of cradle to gate CO_2eq amount from foundations, frame, roof, complementary and surface structures. Not all elements within these classes are studied, ones with small effect on total emissions have been excluded. The carbon emission calculations were re-evaluated to ensure its coverage and that the used values on carbon emissions and densities of materials are correct magnitude. Costs and emissions from maintenance and repair were separately calculated and added to the results. In the end, all results are explained per area unit to be able to compare between projects. The results were compared with previous research and calculations done with more detailed quantities to ensure that the early stage BEBE can be used in life cycle cost and environmental impact assessment in future projects.

In this thesis, LCA as GWP and LCC are evaluated in a parallel manner, meaning that they are conducted separately but in a similar way. Each of them has their own goal and scope definition, life cycle length concept and databases. Because LCA is studied for fewer materials, not all values from LCC can be connected to it. Elements studied in LCA are separated from LCC study for the merge. If no connection between LCA and LCC is not considered, it lowers the decision-making possibilities based on the results (Bierer, et al., 2015).

The study is based on estimations and no exact actualized values of the project. The accuracy of the GWP results is analysed by comparing them with values from the detailed quantity list. This shows the importance of the accuracy of the initial data. The accuracy of costs in BEBE has been studied before and is not analysed in detail. In the early stage of planning there are multiple factors to decide about. Because the opportunities are broad, the environmental aspects should be considered besides the costs.

Maintenance needs for the building components has been evaluated and their environmental impacts and costs calculated. Maintenance and renewals are done when needed, which emphasises that the used values are estimations on how the life cycle could go.

Optional solutions for the elements with high GWP or costs have been compared with the real structure. Selected elements have clear options that could have been used in the project. Emissions and costs have been calculated the same way to the optional solutions as to the real structure. Optional structures have been selected according to the standard solutions of Skanska. The structural analysis of the options was not studied.

The elements, inspected in early stage BEBE, are compared between the single stair building and the slab block. Emissions were compared in classes 2-5 and costs in classes 2-7. Class 1 ground works was not included because the buildings are on the same plot and estimations on what belongs to which building was not beneficial to be made. Classes 8-9 operating and overall costs of the site form differently for the project with two buildings than to project with only one building. By removing them from cost evaluation, for example, supervision of the site is not calculated twice. In addition, the civil defence shelter was not considered because it is situated only in the single stair building. If the buildings were not in the same housing corporation, both of them would have their own civil defence shelter. The biggest difference between the single stair building and the slab block, in addition to the floor area, is their façade materials. The first one is brick mortar and render, and the later one render and concrete elements.

Calculation data is not showed in detail in the study because of the confidential information they include. The main reference for the calculation data was books and regulations with the early stage BEBE. References in detail have been presented in the following chapters.

4.3 Life cycle assessment and Global Warming Potential

Life cycle assessment refers, in this study, to life cycle global warming potential. LCA was performed to building elements. All the used values were based on the database of Skanska or other reliable sources. The trustworthiness of the used values creates the base for the whole case study. The values do not include the project specific details, such as transportation. Demolition and recycling phases are not studied in detail because it is assumed they do not occur during the inspected life span.

LCA calculations are conducted in the study are done with similar outlines as ISO 14040:2006. ISO 14040-standard defines the principles and framework on how to execute life cycle assessment. LCA can be helpful in providing knowledge for the decision-making process. In addition, it can be beneficial in marketing. Assessment may differ greatly based on its depth of detail and time frame, which are based on the goal and scope definition. According to the ISO 14040 standard, LCA consists of four definite analytical steps:

1. goal and scope definition
2. creating the life cycle inventory
3. impact assessment
4. result interpretation.

LCA, and its second part, life cycle inventory (LCI), are done as an iterative process according to the standard. LCI studies consist of three parts:

1. defining the goal and scope
2. inventory analysis
3. interpretation.

LCI is an important part of this study. The existing database and its values needed to be re-evaluated to guarantee their trustworthiness. In addition, the interpretation and finding relations between LCA and LCC studies is part of the thesis.

All the major decisions about the design are made in the early stage of planning, which is why it is important to make LCA studies also early in the design phase. Often the main parts of the physical construction are known at the early stage, which makes predicting their environmental impact easier and the results can be reliable. However, emissions on future operation and maintenance need are often solely determined by assumptions.

Early stage BEBE determines cradle to gate estimation of GWP of building elements in a construction project. Values used to calculate GWP were originally mostly based on Skanska's own database and partly collected from miscellaneous sources. To guarantee the reliability of the sources and the values, early stage BEBE was analysed and the density and emission data was compared with three different sources: one from Finnish Environment Institute (SYKE) and Pöyry Building Services and two from VTT Technical Research Centre of Finland. The guidance on how to calculate the carbon footprint of a building, by SYKE and Pöyry, lists the specific weights and GHG emissions of different building materials cradle to gate (Nissinen & Rintala, 2010). The background report for the environmental impact of building materials from VTT lists several construction materials and their specific weights and emissions. The emissions in that report include the sourcing of the raw material, manufacturing the material, transport to the site and waste at worksite (Ruuska & Häkkinen, 2013). When comparing the emissions with others, it has been considered that the values include more aspects evaluated than cradle to gate. ECO2 data for materials and products from VTT lists different building materials and their carbon footprints. The data does not only include Finnish materials like the previous ones. (Ruuska, 2013.) Materials that were stated to be from other countries in Europe, or just European, were used with care. All the values were compared with each other and the values currently in early stage BEBE to determine what should be used.

The GWP from maintenance is calculated with the use of the same emission data as in early stage BEBE. If the GWP of building element has not been evaluated in the construction phase, its emissions are not considered in the maintenance phase either. The emissions were considered only for those renovated or renewed building elements or part of them that need maintenance or renewal. Inspections were assumed to cause no emissions. Maintenance and renewal intervals are based on a publication by Rakennustieto – Building Information and a book about the technical life cycles of building elements.

4.4 Life cycle costs

In this study, LCC includes the costs occurring to the housing corporation during the first 25 years of use phase and the construction and material costs. The selection of the time frame is based on the Act on the Taxation of Business Profits of Income from Professional Activity.

Costs occurring during the construction and purchasing of the materials are determined with early stage BEBE and the maintenance and renewal costs are separately calculated. Maintenance company does many inspections during the usage phase. It is assumed that not all the inspections cause extra costs, but they are part of the contract between the maintenance company and the housing corporation. For the use phase, the same elements are studied for both LCA and LCC.

Life cycle cost analysis (LCCA) can be helpful when studying compromise between low initial costs and long-term savings and conclude how long the repayment period of an incremental cost of a specific system is. It is not practical to create a comprehensive life cycle cost estimate for each potential building element. This would take a lot of time an effort making it an expensive process. It is more reasonable to focus on systems and features which most probably have an impact to long-term costs. (Davis, et al., 2005.) Because in this study, the assessment period is short, can most of the maintenance and renewal needs be considered.

4.5 Maintenance and renewals

Some elements need to be maintained or renewed within 25 years of use. Because a long-term maintenance plan was not available, the information was collected in multiple sources. When the time interval was given for maintenance or renewal interval, the average has been used. It is probable that more maintenance needs will occur during the studied time, but they cannot all be predicted. For a housing corporation, planning future expenses and maintenance is important. The orderliness, effectiveness and prediction is promoted with clear future plans. A strategy is beneficial when defining how the housing corporation is maintained, developed and managed. According to law, every housing corporation must have a plan for future and maintenance (LLHC 10 chapter 5-7§). The task of the board of the housing corporation and property manager, if there is one, is to manage the building according to the rules and regulations, such as law and goals set by the stakeholders' meeting. (The Finnish Real Estate Federation, et al., 2017.) The board of the housing corporation gives guides and regulations to the property manager. Property manager looks after the property and the building and also manages the daily administration of the housing corporation (LLHC 7 chapter 17§). The maintenance company takes care of the everyday maintenance needs.

The used expenses correspond to the 2018 January level without VAT. The costs do not include all of the costs or all project based expenses. To get the total costs, lacking parts should be assessed, such as planning and site costs, the sales margins of the contractors and the risk reservations. The amount of material and work the cost estimates are based Ratu-files and the information given by the material producers. The hourly wages were from average payments per hour in salary statistics. In the metropolitan area, the construction work expenses can be proportioned to the higher costs with an area coefficient. The most significant differences between the used values and reality, may be caused by the current economic situation, the size of purchases and the got discounts. (Lindberg, et al., 2018.) In the thesis, the values were used as they are, no additions were made.

The used average operational lifespan, maintenance and inspections periods are based on previous building information files, researches, reports and practical experiences, such as building surveys. The values change according to the same reasons as the maintenance periods do. The used values, based on the RT 18-10922, do not take into account the aesthetic service life or construction errors.

Besides the listed maintenances and renewals, residents might want to renovate their apartments. The emissions and costs occurred from those are not taken into account. The quantity details for use stage costs and emissions are based on BEBE and cost estimation. These have more detailed and accurate estimations compared with early stage BEBE.

Table 4 and Table 5 show the estimations of maintenance and renewal intervals. In reality, the maintaining of the building occurs when it is needed, which might be sooner or later than stated at the tables. The board of housing corporation decides with the help of experts decides the actual timing. The maintenance listing also presents, what type of maintenance the building element needs.

Table 4 Maintenance need of the building elements [1]RT 18-10922, [2] (Myyryläinen, 2008) [3]Act 663/1996 11§, [4] Act 506/2011 20§

Building element	**Maintenance need**	**Maintenance interval [a]**
Base[1]	Renewing the coating	20
Brick exterior[1]	Seam repair	25
Exterior plastering[1]	Painting	15
Concrete elements on façade[1]	Renewing the element seams	15
Wooden windows[1]	Painting from outside	10
Front door[1]	Painting	15
Balconies with concrete structure[1]	Painting	15
	Renewing the element seams	15
Balcony glazing[2]	Maintenance	First in 7 years, after that every 5 years
Staircases[2]	Painting	20
Rainwater gutters and pipes	Inspection	1
Heat distribution, pumps and vents[1]	Inspection	1
Ventilation, heat recovery, parts of ventilation machine[1]	Inspection	1
Water/drains, pumps, pressure rising station[1]	Inspection	1
Electricity system[2]	Periodical inspection	15
Information system[2]	Inspection	5
Elevators[3]	Scheduled inspection for first four years	4
	Inspections, after fourth year	2
Civil-defence shelter[4]	Inspection and maintenance	10

The renewals occur mostly on building service systems. The apartment owners might want to renew, for example, the kitchen during the studied period. Because the renewal is within the apartment and not considered mandatory but they are done for the want, they are not included in the study.

Table 5 Average technical life of building elements LÄHDE: [1]RT 18-10922, [2]Leevi Myyryläinen Kiinteistön teknisen huollon käsikirja

Building element	**Renewal interval [a]**
District heating, heat exchanger[1]	20
Heat distribution, pumps and vents[1]	22
Radiator vents[1]	17
Heat recovery, ventilation[1]	22
Water/drains, pumps[1]	22
Water/drains, heat exchangers, water heaters, cold water pumps[1]	20
Water/drains, pressure rising station[1]	25
Water/drains, water measuring in apartments[1]	9
Water/drains, taps and hydrants[1]	20
Ventilation equipment[1]	22
Common sauna[2]	20

4.6 Optional structures

Skanska has created a standardized base for the planning for their apartment buildings. It is based on standardized use of building elements and methods. Standardized solutions in operations and production methods ease the planning, procurement and implementation, shorten the lead-time of the project and improve the profitability. (Skanska Oy, 2018) The goal is to have a great base for the project without special needs. It can help on leading the selection towards cost-efficient and environmentally friendly buildings.

Optional solutions, presented in Table 6, were selected based on their possibly large effect to the costs and environmental impact. In addition, the structure needed to have at least one alternative option on standard Skanska selections. Most of the selected building elements participate greatly in the mass of the building, which makes them possible to change especially carbon emissions greatly.

The possible structural changes that would have occurred, if optional solutions were used, are not considered. The restrictions based on the plan according to, for example, façades are not included in the study. It is not ensured that optional solutions would have worked in the actual building.

The elements, which optional solutions are studied, were selected based on their large emissions. In addition, all of them have at least one commonly used optional solution.

Table 6 Optional solutions studied

Building element	Current solution	Optional solution
Roofing	Concrete tiles	Flat roof, felt roofing
		Felt roofing
		Tin roofing
Roof	Hollow core slab	In-situ casting
Intermediate floor	Hollow core slab	In-situ casting
		Thinner hollow core slab
Base floor	Ground supported floor slab	In-situ casting, loadbearing
		Thinner hollow core slab
		Thicker hollow core slab
Façade	Building 1: Plastering (75%), bricks (25%) Building 2: Concrete elements (50%), plastering (50%)	All plastering, fibre-reinforced render
		All plastering, thin coat render
		All bricks
		All concrete elements

Some of the optional structures need maintenance during the studied period. They were studied in the same way as the other maintenances, separately from the early stage BEBE. All maintenance needs are presented in Table 7. None of the studied optional structures needed renewals during the studied time.

Table 7 Maintenance needs of the optional structures

Building element	Optional solution	Needed maintenance	Maintenance interval [a]
Roofing	Flat roof, felt roofing	Maintenance	10
	Tin roofing	Painting	12
Façade	All plastering, fibre-reinforced render	Painting	15
	All plastering, thin coat render	Painting	15
	All bricks	Seam repair	25
	All concrete elements	Painting	15
		Elastic seam repair	15

5 Results

The results are divided in a similar manner as the case study, starting with its results of GWP and then examining LCC. The relation between emissions and costs is attempted to find. The studied case forms from two buildings: single stair building and slab block. The division between the buildings is presented in fourth sub-section. The project needs maintenance during the studied 25-year period. Section 5.5 explained the significance of the studied aspects during the use stage. Lastly, it is presented how the project could have produced less emissions with lower costs by different structures.

5.1 Global Warming Potential

The total emissions from the calculated materials in Venny, without maintenance or renewals, is 331 kg CO_2eq/gross-m^2. Only classes stated before are evaluated. Those that were not included in the research are not included to early stage BEBE and were considered to create only little emissions or to include too project specific data. In addition, a few building elements in classes 2.-5. are not included, such as snow guards and ladders to the roof, because of their minor effect. Even though groundworks, class 1, create considerable amount of emissions, they would make the results harder to compare between different projects. Appliances, fittings and fixtures, class 6, emissions are depending almost solely on the number of apartments. GWP of machines and the actual work, classes 7-8, are also project specific and no estimations were selected to be made. Figure 7 shows how emissions from material production divide between the studied Building 80 classes.

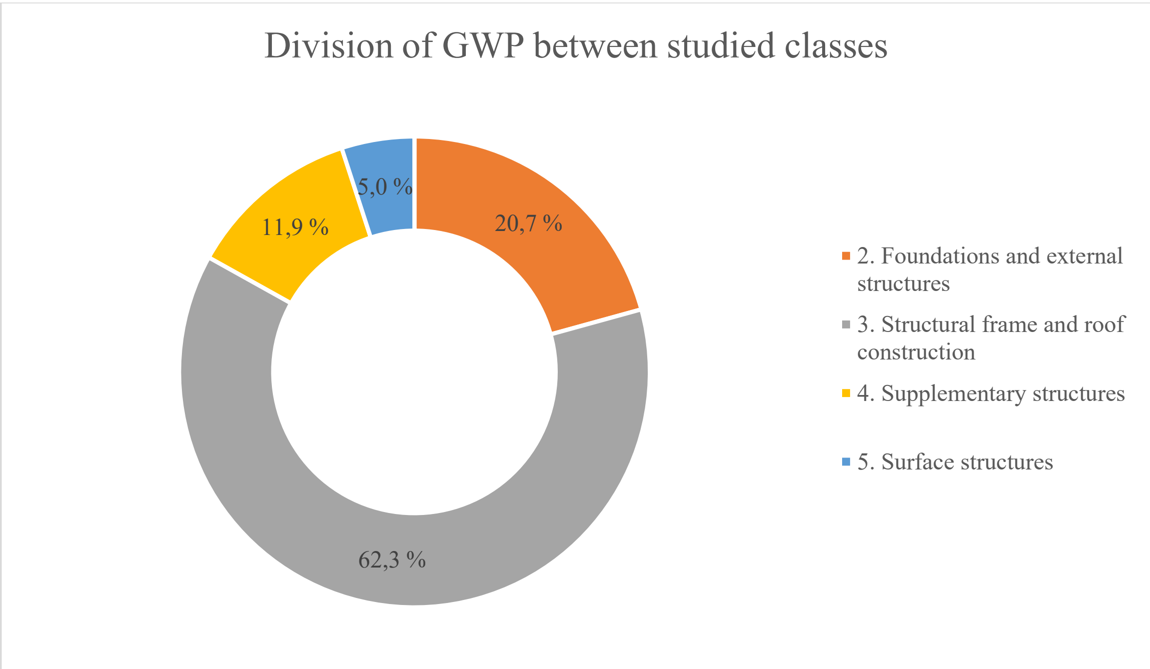


Figure 7 Percentages how GWP divides between studied classes, both buildings taken into account, no maintenance or renewals

The emissions were calculated separately to each of the studied building components in classes 2-5. From all studied building elements the top ten, producing the most GHG emissions, conduct 70.3% of all emissions. The top ten building elements, their classes and their percentages from all emissions are presented in the following list. Five of the elements in the list are mostly concrete. These elements in placements 1, 2, 4, 5 and 8 compose 45.3% of the total GHG emissions.

Building element (class), percentage from all emissions

1. Hollow core slab, intermediate floor (3), 18.0%
2. Loadbearing partition wall (3), 9.7%
3. Roof, no roof covering (3), 7.9%
4. Footing (2), 6.9%
5. Ground supported base floor (2), 6.4%
6. Plaster element, thin coat render, slab block (3), 4.7%
7. Concrete element, exterior painting, slab block (3), 4.5%
8. Hollow core slab, roof (3), 4.3%
9. Plaster element, two-coat fibre-reinforced render, single stair building (3), 4.0%
10. Wooden windows and doors (4), 3.9%.

5.2 Life Cycle Costs

All classes and building elements included in early stage BEBE have been studied to determine total cost estimation. Figure 8 presents the divisions of material and construction costs according to early stage BEBE by Building 80 classes. The social costs from classes 1-7 are 5.0%. Classes 8 and 9 are together were combined in early stage BEBE.

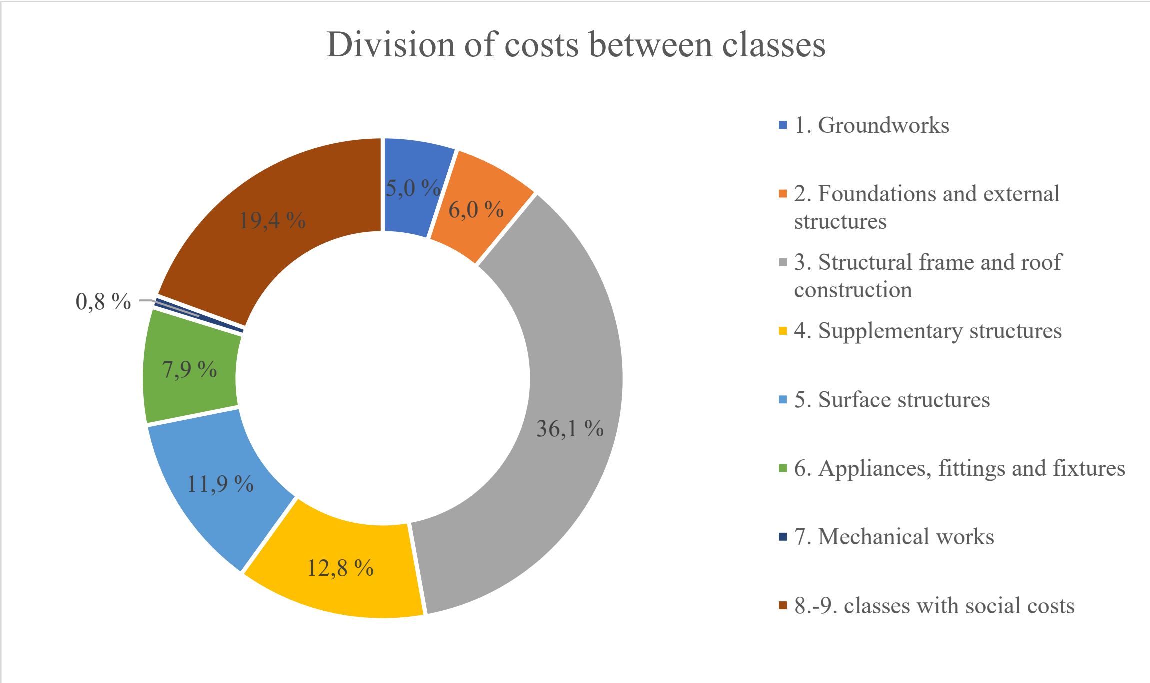


Figure 8 Percentages how costs divide between studied classes without maintenances or renewals

The costs are calculated separately to all elements within classes. The top ten from the costs of all building elements form 39.1% form all costs. Following listing presents the top ten and their classes.

Building element (class), percentage from total costs
1. Plaster element, thin coat render, slab block (3), 4.9%
2. Plaster element, two-coat fibre-reinforced render, single stair building (3), 4.4%
3. Supervision of work (8-9), 4.4%
4. Fixed furnishing (6), 4.3%
5. Concrete element, exterior painting, slab block (3), 3.9%
6. Wooden windows and doors (4), 3.8%
7. Hollow core slab, intermediate floor (3), 3.7%
8. Cranes and scaffolds (8-9), 3.6%
9. Loadbearing partition wall (3), 3.5%
10. Workers' social costs (8-9), 2.6%.

Because the materials are the main interest in the thesis costs were also compared with each other without the operating and overall costs of the site. The top ten building elements and their classes, when classes 8.-9. are not taken into account are presented in the following list and form 44.1% of the costs from classes 1-7.

Building element (class), percentage of the costs from classes 1-7
1. Plaster element, thin coat render, slab block (3), 6.1%
2. Plaster element, two-coat fibre-reinforced render, single stair building (3), 5.4%
3. Fixed furnishing (6), 5.3%
4. Concrete element, exterior painting, slab block (3), 4.9%
5. Wooden windows and doors (4), 4.8%
6. Hollow core slab, intermediate floor (3), 4.6%
7. Loadbearing partition wall (3), 4.4%
8. Elpotek duct element, (4), 3.2%
9. Painting and levelling, inside (5), 2.7%
10. Parquet / laminate (5), 2.7%.

The focus on decreasing costs was in the classes were emissions where also calculated, so that both aspects could be improved simultaneously.

5.3 Comparison of emissions and costs

Table 8 presents the top ten building components by their emission sources and costs and shows the placement of that component in the other listing. To have more connection between the studied aspects and to compare parts which emissions could have been estimated, classes 8-9 was not included in the costs side. Six of the building elements can be found from both top ten lists. The comparison table does not include maintenance or renewals.

Table 8 Comparison of top ten lists of emissions and costs without maintenance and renewals

Building element	Placement	
	Emissions	**Costs (without classes 8-9)**
Hollow core slab, intermediate floor	1	6
Loadbearing partition wall	2	7
Roof, no roofing	3	25
Footings	4	27
Ground supported base floor	5	52
Plaster element, thin coat render, slab block	6	1
Concrete element, exterior painting, slab block	7	4
Hollow core slab, roof	8	37
Plaster element, two-coat reinforced render, single stair building	9	2
Wooden windows and doors	10	5
Fixed furnishing	not studied	3
Elpotek-duct element	15	8
Painting and levelling, inside	not studied	9
Parquet / laminate	24	10

5.4 Single stair building vs. slab block

Venny forms from two buildings, which are different types: a single stair building and a slab block with two stairs. They were compared to observe, if the building type has an effect on the emission or cost effectiveness. From the whole project, the gross areas divide 37% single stair building and 63% slab block.

Figure 9 presents how emissions divide between the building types when they were studied separately. The total emissions of the single stair building are 361 $kgCO_2eq/gross\text{-}m^2$ and for slab block 333 $kgCO_2eq/gross\text{-}m^2$ when maintenance and renewals are not considered.

The division of costs between different building types, without maintenance or renewals, in Venny is displayed in Figure 10.

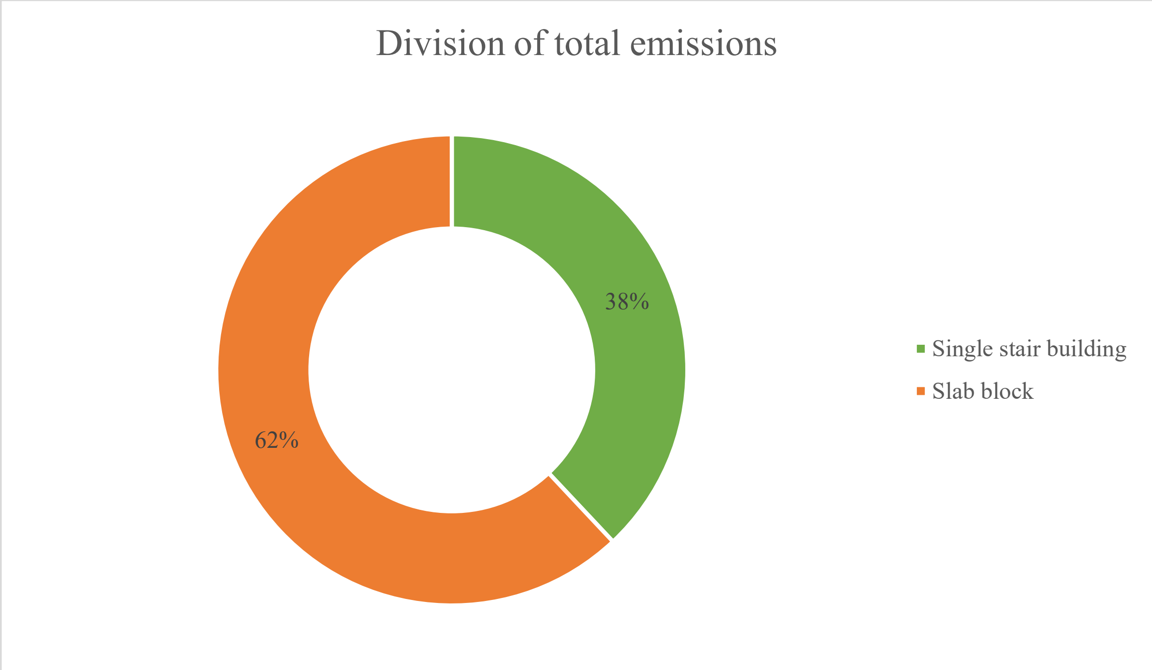


Figure 9 Total emission divided between different building types

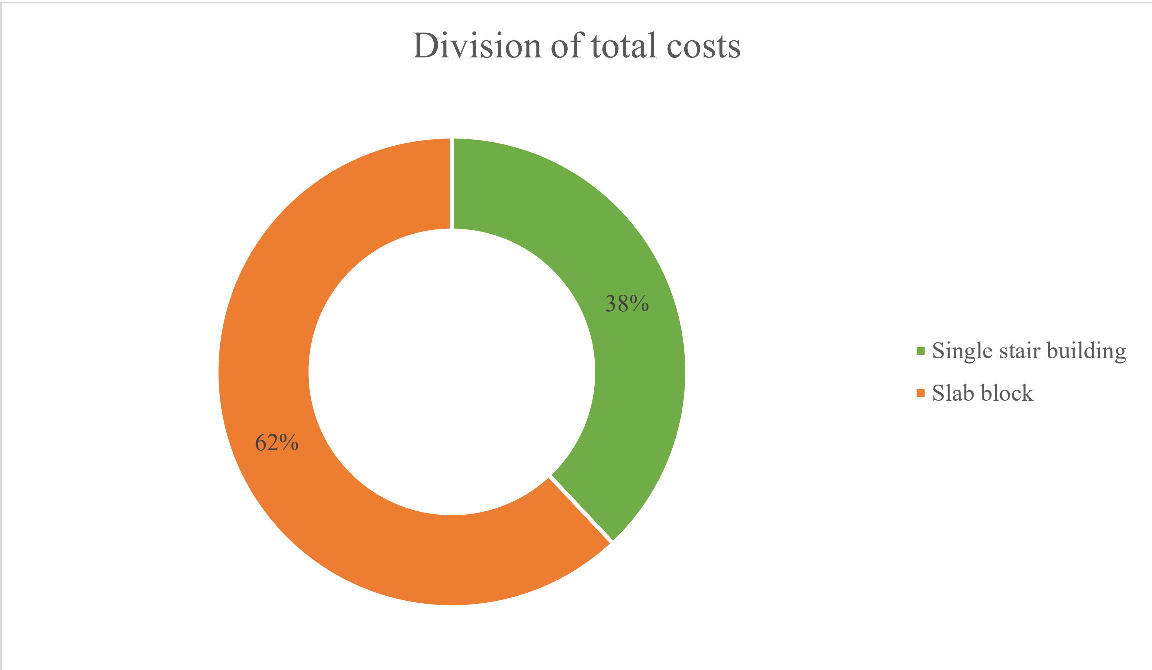


Figure 10 Total costs between different building types

The emissions and costs per gross area per studied class are compared in Figure 11 and Figure 12. Emissions were studied to classes 2-5, in a similar manner to the full results. Costs were evaluated only to the classes 2-7. Classes 1 and 8-9 were occluded due to their difficulty on dividing them between the buildings.

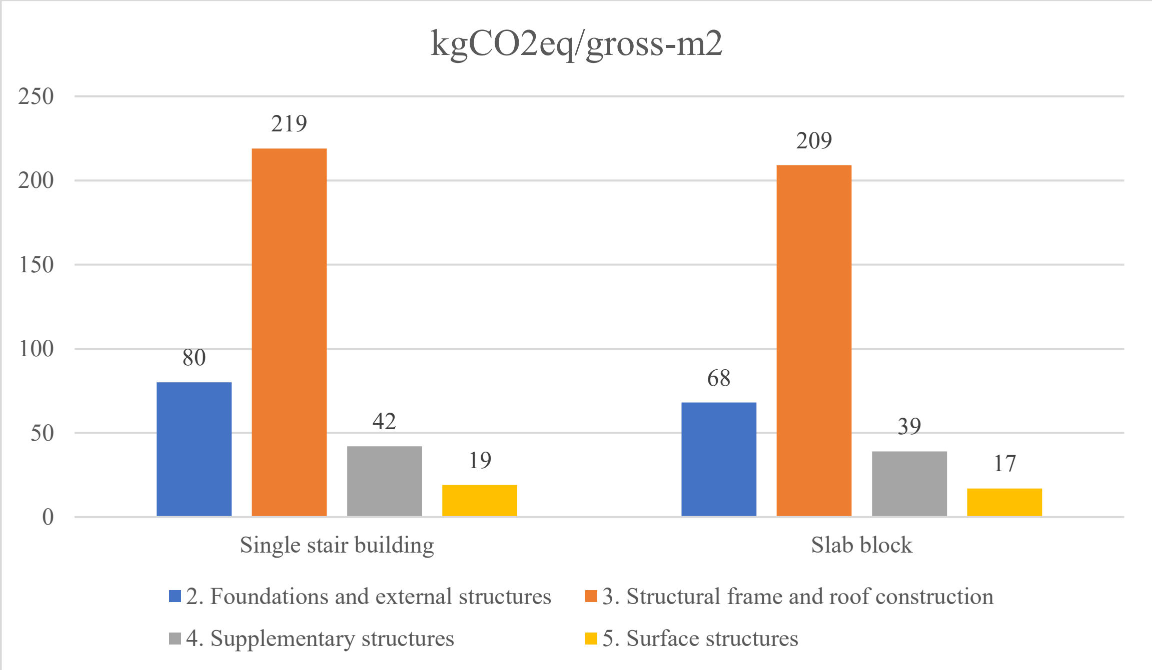


Figure 11 Division of emissions between classes

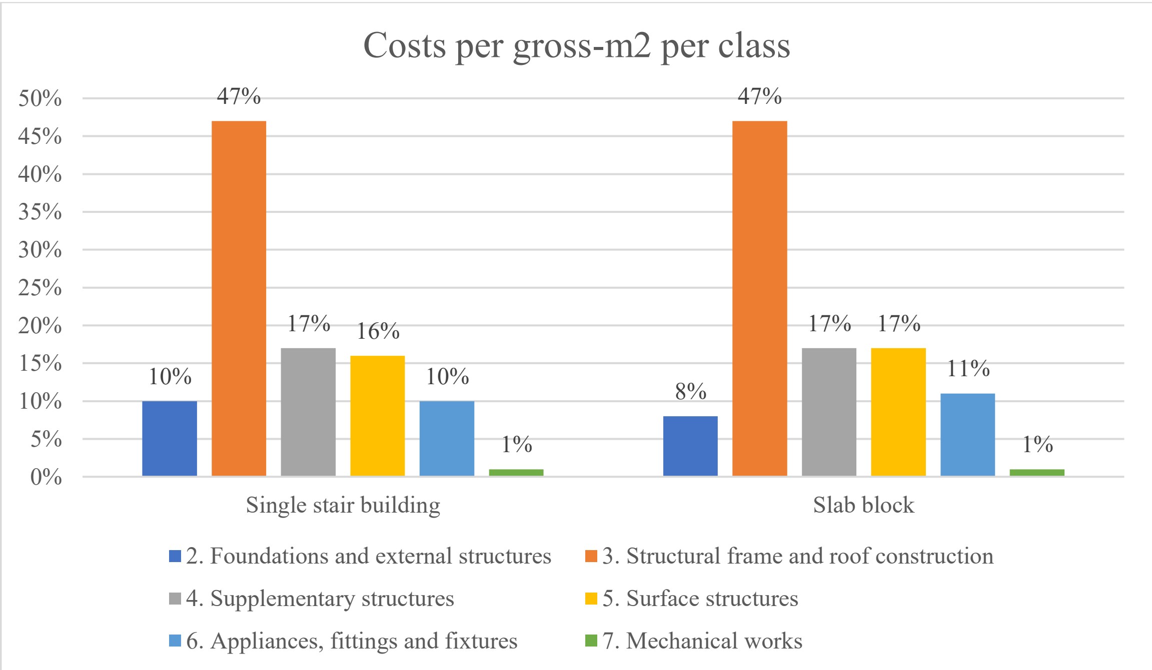


Figure 12 Cost division between classes

5.5 Maintenance and renewals

Total maintenance costs for the buildings and the evaluated building elements are about 6% of the costs before use stage. The considered maintenance actions create only 2.5 $kgCO_2eq/gross\text{-}m^2$. This means that these emissions are about 1% of the emissions coming from product stage. The emissions and costs from maintenance per building element, are presented in Table 9.

It was assumed that the maintenance company does all inspections that do not need a specialist. No emissions or costs were counted from them. It was estimated that the maintenance company hired by the housing corporation does the inspections as a part of the contract without extra costs.

Most of the maintenances occurring during the studied period are paintings. The emissions of HVAC are not considered in the construction phase and are either not considered in the maintenance and renewals.

*Table 9 Division of emissions and costs from all maintenance and renewals, *assumed to be done by the maintenance company*

Building element	**Division of emissions [%]**	**Division of costs [%]**
Base	17.1	7.0
Brick exterior	9.8	2.2
Exterior plastering	26.5	3.9
Concrete elements on façade	8.7	6.8
Wooden windows	2.8	27.6
Front doors	0.7	0.6
Balconies with concrete structure	18.7	3.6
Balcony glazing	-	0.8
Staircases	15.6	2.1
Rainwater gutters and pipes	*	*
District heating, heat exchanger	-	6.9
Heat distribution, pumps and vents	*	6.1
Radiator vents	-	5.6
Ventilation, heat recovery, parts of ventilation machine	-	4.8
Water/drains, pumps, pressure rising station, heat exchangers, heaters, cold water pumps, water measuring in apartments, taps and hydrants	-	13.0
Common sauna	-	1.3
Electricity system	-	*
Information system	-	*
Elevators	-	7.7
Civil-defence shelter	-	*

5.6 Optional structures

The emissions and costs of different solutions were compared with the used structure. The changes are presented in Table 10.

Table 10 Optional solutions compared to the real structure, including maintenance

Version		**Emission change to the original one**	**Costs change to the original one**
		[%]	[%]
Roofing	Felt	2.1	1.4
	Tin	1.4	0.8
Roof	In-situ casted roof	3.0	1.0
	Flat roof, felt	2.1	1.4
Intermediate floor	In-situ casting	2.4	1.8
	Thinner hollow core slab	-3.3	-0.2
Base floor	In-situ casting, loadbearing	4.2	1.1
	Thinner hollow core slab	2.7	2.0
	Thicker hollow core slab	4.2	2.2
Façade	Fibre-reinforced render	0.6	1.0
	Thin coat render	-0.3	-0.1
	Bricks	3.5	-1.1
	Concrete elements	-0.8	-0.4

According to the results, the most cost and emission effective solution is presented in Table 11. The roof structure was not considered, because of the inability of the early stage BEBE on creating different structures for sloped and flat roof. For the façade concrete elements were selected beyond brick masonry, because of the savings in both emissions and costs. If the optimal solutions were used, the total emissions would decrease to 313 $kgCO_2eq/gross\text{-}m^2$ when maintenance and renewals are not taken into account. The cost savings are 1.5%. The most cost efficient solution would have been to select brick façade, this would have had 1,6% savings in costs but, the emissions would be 328 $kgCO_2eq/gross\text{-}m^2$.

Table 11 The most cost efficient combination of solutions to minimize emissions from studied building parts

Structure	**Best solution**
Roofing	Concrete tiles
Intermediate floor	Thinner hollow core slab
Base floor	Ground supported floor slab
Façade	Concrete elements

6 Analysis and discussion

This section is divided into six sub-sections. The calculation results of GWP and LCC are analysed together. Different types of buildings are compared in the second sub-section. Optional structures are discussed with the optimal solutions. The got results are compared with other researches to ensure their reliability. In addition, the used amount in early stage BEBE are compared with more detailed values to evaluate the accuracy of the tool. Section 6.5 introduces suggestion on improving the emission effectiveness and costs of a building and what future studies could be conducted. In the end, the thesis process and the learning curve experienced during the study are presented.

6.1 Global Warming Potential and Life Cycle Costs

The top ten emission producing building elements create a considerable amount of the total emissions, in total 70.3%. The top 20 creates 89.5% from total emissions. When emissions are wanted to reduce, focus should be on the group, which produces most of the emissions. It helps on including also other aspects than environmental while improving the selection of elements when the amount of improvements is limited.

Costs are more evenly spread between different elements than the emissions. Excluding the classes 8.-9., the top ten forms 44.1% of the total and the top 20 61.7%, which is still less than the top ten of the emissions. Lowering costs requires focus on multiple aspects. Savings in one part may cause an increase of the costs in other, which emphasises considering the building and its elements as a whole, even more than when emissions are studied. Classes help on observing where the largest opportunities on savings can be found. Class 3 also makes the largest amount of costs from all classes. There is no single building component that has a significantly large effect on the costs. The top ten is within 2.3 percentage points when all classes are compared and 3.4 percentage points when class 8.-9. is not considered.

The difference on how much the top ten covers can be partly explained by the smaller number of studied elements in emissions. The amount of elements taken into account for costs is about 3.5 more than for emissions. If costs were calculated only from the same elements as emissions were, the top ten would make approximately 60% of the total costs on the limited selection. This difference also shows the risk of the reliability of the emission results. Classes studied in GHG emissions create 67% of total costs. When classes 8.-9. are not taken into account, 68.9% of all components included in the early stage BEBE have their GHG emissions calculated in the study.

Following six of the building elements are on both top ten lists:
- Hollow core slab, intermediate floor
- Loadbearing partition wall
- Plaster element, thin coat render, slab block
- Concrete element, exterior painting, slab block
- Plaster element, two-coat reinforced render, single stair building
- Wooden windows and doors.

The amount of all these elements is great in the buildings. When the costs and emissions are wanted to minimize together, the first focus should be on these six. It can be examined, that the façade has the most options on improvements.

The estimation of emissions and costs were done within Building 80 classes separately for each building elements. The building element based calculation on studied aspects has multiple benefits. It allows evaluating which components have the largest opportunity on reducing the studied aspects. When significant savings are wanted to have, the change cannot occur only on components having a minor effect. It may be simpler to make small changes but the change has more effect when it is done to elements with considerably large mass. It can often lead to great savings. The challenge is that these parts have limited amount of options and are structurally important restraining the options available for the researched project.

Over half of the emissions from Venny come from its structural frame and roof construction. From top ten of the building components producing the most GHG emissions nine are at least partly concrete. The listing covers well the building part with the highest mass. The hollow core slabs of intermediate floors are alone 18.0% from total emissions, making its effect larger that classes 4 and 5 combined.

Mostly concrete building components, that are part of the top ten listing, form almost half, 45.3%, of the total emissions. Alternative options to these components are also mostly concrete making the possible changes relatively small. This emphasises the relationship with concrete producing companies and encouraging them on the development of more environmentally friendly concrete in a cost efficient way. In addition, it is good to notice that the top ten on the most expensive building components, only two are mostly concrete and found also from top ten emissions. The amounts of these two, hollow core slab intermediate floor and loadbearing partition wall, are also on top ten list of material amount. The costs are explained with the amount, not the price per square meter of product. The study would benefit from a detailed investigation of the concrete used. Because concrete is mainly ordered ready, it is not known, for example, what kind of cement is used for it. This creates uncertainties to the biggest emission creator.

Not all Building 80 classes were studied in CO_2eq emission study, because of the limitations of early stage BEBE. In addition, the omitted classes are rather project specific challenging the desired comparison to other projects. Limitation also excludes the possibility to see whether improvements could or should be made on the classes left out from the research. For example, if significant differences were found between different fixed furnishing, they could be selected based on more features than money. All projects will have them, but in different amount. Expanding the knowledge to end customers is important, so that they can make better decisions. Already, some design options are emphasised as environmentally friendly for the end customers.

Class 3, Structural frame and roof construction, creates the biggest part of both, emissions and costs. It includes the largest number of components that are included in both of the studied aspects and most of the parts on the top ten lists. Class 2, Foundations and external structures are mostly concrete, which has high emissions from the product stage compared with many other materials. The class produces about fifth of the total emissions, when different types of footings that are considered in the emissions calculation are combined, but it has the fewest components. This emphasises well how much the emissions vary between different materials, and material volumes alter between elements and classes. No relation can be detected between the number of elements in each class and their emissions or costs, it is more dependent on the used materials.

If class 6, appliances, fittings and fixtures, was wanted to include in emission studies, it would be beneficial to focus on the energy efficiency of the appliances and the need for the maintenance of the fittings. For example, if the cabinet doors in bathrooms are likely to get moisture damage quickly, their renewals occur more often than it is assumed and the emissions from them increase. These changes would improve, besides LCA and LCC, the customer satisfaction.

The profit got from savings needs to be evaluated on multiple aspects before changes are made. For example, purchasing windows with lower costs and emissions may lead to lower customer satisfaction due to draught and the decrease of the energy efficiency of the building. All decisions affect more than one aspects and finding the balance between different options is important. Before decision making, the valued aspects should be listed, so that the end result is optimal.

It is important to handover the building to its end owners in good condition and when the project is ready. In ideal situation, the building does not have any construction defects, which could cause extra costs and emissions. As an improvement, it is crucial to follow the imperfection found in different projects during the defect's liability period. If a systematic error is found, the whole process or material should be reconsidered. This would also bring the estimation and the real case closer together.

Material produce GHG emissions the most in the early stages of their lifespan, before the building is ready. Maintenance emissions are relatively low when compared with the emissions from the material production stage. This emphasises the value of the decision made in the early stage and the minority of the maintenance emissions compared how much effort it takes to calculate them. Results might have changed if all HVAC systems were studied.

The studied time period for maintenance and renewals is relatively simple part of the life cycle of a building, when considered according to the number of elements needing maintenance. Still, the need for maintenance is surprisingly small. The actual maintenance periods may vary due to difference in use, the possible error in the installation and the set goals and demands. The use stage is solely based on estimations, hence it naturally has uncertainties.

Multiple elements and systems need inspections regularly. The goal of inspections is to lower the amount of major renovation or maintenance needs, so that all problems are noticed early. In this study, the inspections created a dilemma; inspections on themselves do not create emissions but small maintenances might occur simultaneously as a preventative action. It was assumed that the property manager or the maintenance company hired to the housing corporation takes care of them without extra costs.

Renewals occur mainly to the building service systems. It was expected that the renewals for the same system, that are scheduled within five years, are done simultaneously. The estimation was done mainly because of the challenge on finding reliable data on the renewal costs separately to different parts.

The study would not have gained a lot of reliability by including more classes to study in the use stage. Maintenance cannot be completely avoided and it increases the use life of building elements. It should always be considered with the benefits gained from it, not only focusing on minimizing costs and emissions. The goal is that buildings have a long use life to minimize the initial costs and emissions of construction a new building.

The inside finishes will most likely be renovated during the studied period. Apartment owners make the decision to renovate their apartment. The renovations during the studied period are impossible to estimate and are out of the study scope. If the renovations are assumed to be, for example refreshing walls or even changing the kitchen, the emissions would not be considerable amount compared with the overall product stage emissions. On the other hand, the cost affect may be noticeable if most of the apartments would do renovations.

The building systems, such as HVAC, are known to need both maintenance and renewals. Because of the thesis outline, their emissions are not studied. The difficulty on making emission estimations is the lack of knowledge in used materials and their amounts.

The actual price and emissions from life cycle upkeeping are difficult to estimate and the reliability of the estimation compared with what it will be uncertain. The results can be seen as a good guess and they give scale of the impact to total costs and emissions. Not many expensive or emission intensive aspects during the use stage were found. It might have been beneficial to attempt to find more detailed information on the maintenance and renewal needs.

The emissions from the maintenance and renewals of classes, that were not included in the study, would most likely not have an effect on the results. All studied maintenances created only about one percent of the total emissions. If lack of few maintenances would create significant amount of emissions, it is likely that there is also error in the studied parts. For the costs, the most uncertainties come from if the maintenance company charges the maintaining separately for each work. In addition, the buildings also need other type of maintaining than the materials, such as the cleaning of common areas and clearing the snow. These aspects may make the maintaining have a noticeable impact to especially to costs.

Considering both GHG emissions and, it would have been more beneficial to study other aspects than the maintenance and renewal of material, because of its small affect to the whole. Especially for the emissions, used energy to, for example, heating constitutes a large part of the total during the whole life cycle. The energy emissions appear to be well studied field. This enables the possibility to merge this study and the results from more aspects during the use phase to have even wider inclusion to the results. In addition, there was a thesis conducted in Skanska about the construction phase GHG emissions. Altogether, combining several results, from at least few studies besides this one, the results could be called whole life cycle emissions and costs.

6.2 Single stair building versus slab block

Two different building types, single stair building and slab block that form Venny, were compared. Emissions were analysed in a similar way as when researched in total but for costs only classes 2-7 were included to minimize some of the costs doubling from being taken in to account for both, even though they are in the same project.

Comparing the division of gross area, emissions and costs between single stair building and slab block, similar distribution can be noticed. The single stair building contributes to the total gross area with 37% of the total, 38% to both emissions and costs. It produces slightly more emissions and costs per gross area than the slab block.

The division of emissions between different classes follows similar trend in both building types. In all classes, the emissions from the single stair building are always greater, in classes 2-3 clearly and in classes 4-5 only a little.

Costs per studied classes are percentage vice alike each other in different building types. The greatest differences can be detected in second and third class. The visualization of the costs in percentages makes the costs seem close to each other.

The single stair building has a floor plan that enables more efficient façade to the gross area relation of the building than the slab block. This difference in efficiency can be seen as the difference in the amount of surface structures create costs.

On surface structures, it needs to be noticed that buildings have different façade materials. As mentioned earlier the brick facade has higher emission content than other options and only single stair building is partly brick façade. Secondly, the façade of the slab block is made from the two façade options creating the lowest amount of emissions from studied options. This may be the reason of the slight difference in division of gross area and emissions.

Some changes would have occurred if maintenance would have been considered when comparing the building types. Even though the brick façade is more emission intensive in the product stage, its emissions from maintenance are notably lower. Still, the maintenance was noted to create only little emissions compared with the product stage but the difference in costs might have made single stair building to seem slightly better.

Studies focusing on comparing the type of the building, meaning weather the building has one or multiple stairs, appeared to be hard to find. It would be beneficial to compare different types to be enabling to favour certain building type. For example, the current trend in Finland of building higher creates new structural demands, which may lead different costs and emissions per square meter than in a so-called traditional apartment building. Different height may change the most emission intensive or costly parts. This is why it cannot be said that the results got from this research can be compared as they are to similar type of results from a high rise.

6.3 Optional structures

Thirteen different options from five categories were studied to compare them with the used materials and to find the optimal solution.

The used concrete tiles have the lowest emissions from roofing options presented in the study. Besides having the lowest product stage emissions per gross square meter, it benefits from needing no maintenance during the studied period. In addition, the concrete tiles are the least expensive solution. In the product stage, the emission difference between tiles and tin is only 1 $kgCO_2eq/gross\text{-}m^2$. All roofing materials make rather much emissions compared on the amount that is needed. Even though the material need is low in comparison with many others, such as walls or intermediate floors, the change in emission can have 1.5%. The change is similar to what can be achieved with intermediate floors, which area is almost three times the roofing area and the mass is even greater.

Because of the error in early stage BEBE with the sloped roof structure, tin and tile roofs, seem to have lower emissions than a flat roof. It can be said, that the study does not provide information that would enable the comparison between sloped and flat roof. The studied roof structure, the hollow core slab, seems to be the best solution in both emissions and costs. Still, the solutions of the roof should be considered with care, because of possible extra errors. More in depth study about the roof structure and its assumption on the early stage BEBE should be made. The best solution of the roof structure was not evaluated because of previously presented problems.

In both intermediate and base floors, the used solution produced less emissions and was less expensive in comparison with in-situ casting. Overall, for the intermediate floor, it is better to use hollow core slabs for both emission and the cost point of view. Ground supported base floor has the least amount of material, and by all options being mainly concrete, making it no surprise, which one creates the least emissions. The benefits from the ground supported floor slab cannot be reached in every project, because the selection of the base floor is based on several factors. In the base floor, the emissions from in-situ casting are in the similar size as thicker hollow core slab but the hollow core slab is has a higher price. It would be beneficial to do the comparison on base floor selections in solutions that are structurally checked to work on selected plot type and do comparison on different ground types. This would show if this component high in the list of emissions, could be optimized in a cost-efficient way. In addition, according to the results, the base floor has the highest possibility to have an effect on both emissions and costs.

Most of the needed maintenances for the studied solutions were for façades. From the results, it can be seen that brick masonry is the worst solution on both emissions but the best one for costs when façade materials are being compared. The most cost efficient way to minimize the emissions would have been to use only painted concrete elements as the façade. Concrete elements are free from having restrictions on colour, similar to renders. Visually, the challenge of concrete elements is their high number of seams, which could be avoided with different solutions.

Façade options are not limited to the studied four and the difference between all, or at least the ones that are mostly used, should be considered. At minimum, they should be set to a list “from best to worst” when both costs and emissions are considered. Already from this study, it can be detected that thin coat render is better than fibre-reinforced render in both researched aspects. The façade is an aspect to which it is rather easy to have an effect on and the large amount of it enables high savings. The city and the master plan of the area might create some restrictions. If discussion with the city policy-makers can be had early in the progress, and there is prove that some solutions would be more environmentally friendly, might the design pass their judging.

To get more variation between optional solutions and the actual buildings, innovative solutions that are not included in usual projects should have been considered. Wooden structures were selected not to be studied. It could be ensured that if they were included, the optimal solution would have wooden structures. New, innovative structures might lower the emissions significantly, but the costs would probably rise massively. As stated before, the focus was set to the solutions already in use of Skanska.

The hunt for new more improved solutions should be the interest of all members of the planning of buildings. This encourages companies on developing new products for the market. Progress is inevitable when the old solutions are no more accepted. The consciousness stays but the want to be more environmentally friendly has been in rise for several years. It is old fashioned to think that the customer is only interested on the traditional three: money, time and quality. The discussion on what is wanted to have should be open between the material production and planning.

The challenge of the new solutions if that their useful life is often fully based on estimations. If the material has only been used in prototype building, it is not ready for the use of large construction company. The testing of the solution in the real life and seeing it work is mandatory before taking it as a part of the basic solutions of a company.

6.4 Comparison to other researches and detailed material quantities

Skanska has conducted a list of 60 past projects showing 20 building elements with the highest emissions for each project. Calculations were done with early stage BEBE and included only the material production. The ten building elements creating the highest amount of emissions in studied project Venny were compared with the top 20 lists. From all lists, roof, footings, wooden windows and doors and load bearing partition wall were found. 48% of the cases included the hollow core slab in roof and in intermediate floor. Different types of renderings were found in 47% of the project top 20 and ground supported base floor in 42%. It should be noted that not all projects have the same solutions, which might make some options looking rare.

Table 12 and Figure 13 present the comparison between Venny and other studies. All buildings in comparison are constructed in Finland. The carbon footprint of buildings studied in Nykänen, et al. research include the phases A1-A3, the product stage. The building A, has the most disadvantageous shape, making it use the highest material use of all wooden buildings in that study. In wooden apartment buildings, one material creating most of the emissions is concrete. The study conducted by Ruuska & Häkkinen, focuses on the GHG emissions created by the building materials and only the emissions from producing the materials are included in the comparison. In addition, the study shows that the mass of the same design may have a great variation. In the study, it was not considered if the optional solutions creating the minimum and maximum values are safe or would actually work. No simulations on the options were made. Besides the basic structure of the example building, the study also gives a range how emissions vary according to the building mass. In the third study, by Pasanen, et al., the goal was to produce environmentally friendly building still using concrete in conservative way. Emissions from materials are only considered here from Häkkinen & Vares research. Also, pile driving and soil are not considered. The basic structure, besides in the minimum case, has a concrete frame.

Table 12 Comparison of Venny to other projects, [1] (Nykänen, et al., 2017), [2] (Ruuska & Häkkinen, 2013), [3] (Pasanen, et al., 2012), [4] (Häkkinen & Vares, 2018)

Building type	**Emissions [kgCO_2eq/gross-m^2]**
Venny, according to this thesis	331
Venny, with optimal solutions	313
Wood or concrete hybrid structures, apartment building, A[1]	394
Wooden apartment building, B[1]	187
Two wooden apartment buildings, Cwood[1]	226
Two concrete apartment buildings, Cconcrete[1]	395
Concrete apartment building[2]	313 (173…414)
Concrete apartment building/sheltered housing[3]	238
“Basic” apartment building[4]	380
“Basic” apartment building, estimated minimum[4]	212
“Basic” apartment building, estimated maximum[4]	493

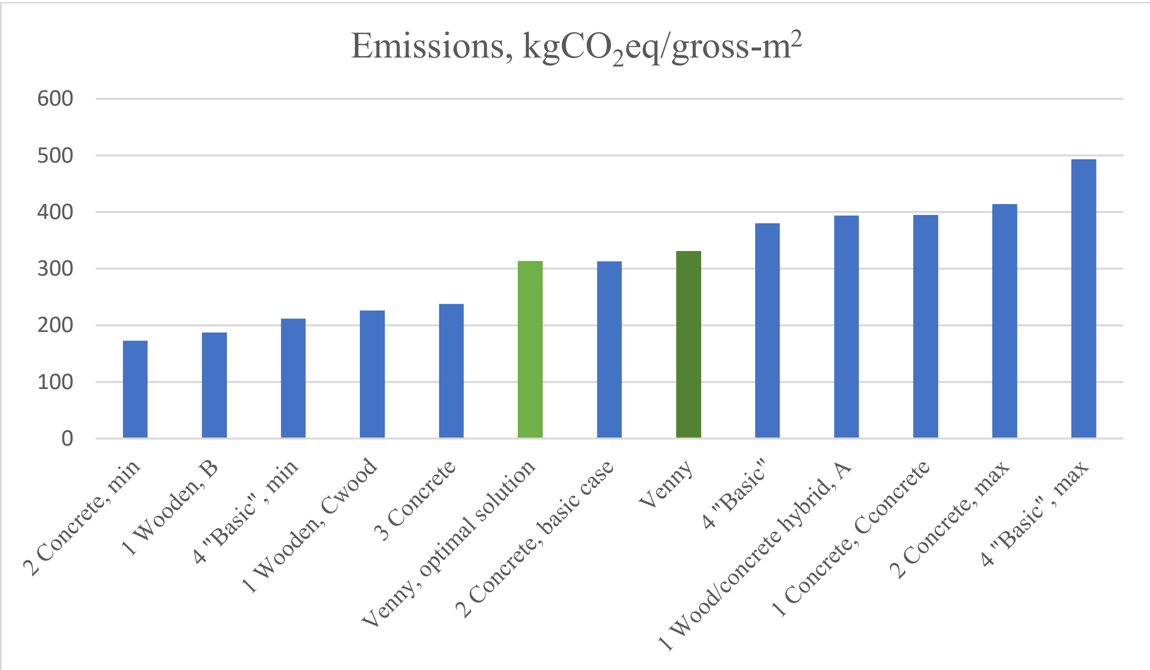


Figure 13 Comparison of GHG emissions in different projects from smallest to largest

Venny performs well, when compared with other concrete buildings that were not built to be especially environmentally friendly, as seen in Figure 13. Still, Venny is rather far away from buildings were the emissions have been focused on minimizing. Even the so-called optimal Venny produces 75 kgCO_2eq/gross-m^2 more emissions than the next option. The gap between the actual structure and the next largest solution is smaller size, 49

$kgCO_2eq/gross\text{-}m^2$. Overall, Venny seems to be a planned with good materials for a concrete apartment building when emissions are considered.

Venny was compared with other projects conducted in Skanska. The comparison was narrowed to include single stair buildings and slab blocks that have been calculated between 2008-2017. The comparison includes 23 single stair buildings and 13 slab blocks. When the project comprises from two buildings the one inserted into early stage BEBE first, names the project. Venny is included in as a single stair building.

The comparison of emissions per gross floor area is shown in Figure 14. The early stage BEBE that was used for the comparison, did not have the improvement that were made for this thesis. The value used for Venny is got with the same version as the rest of the results. The comparison confirms that Venny is neither really good nor very bad when its material emissions are considered. The emissions for the single stair building vary between 269 and 414 $kgCO_2eq/gross\text{-}m^2$ and for the slab block from 283 to 361 $kgCO_2eq/gross\text{-}m^2$. The average for both building types is 329 $kgCO_2eq/gross\text{-}m^2$.

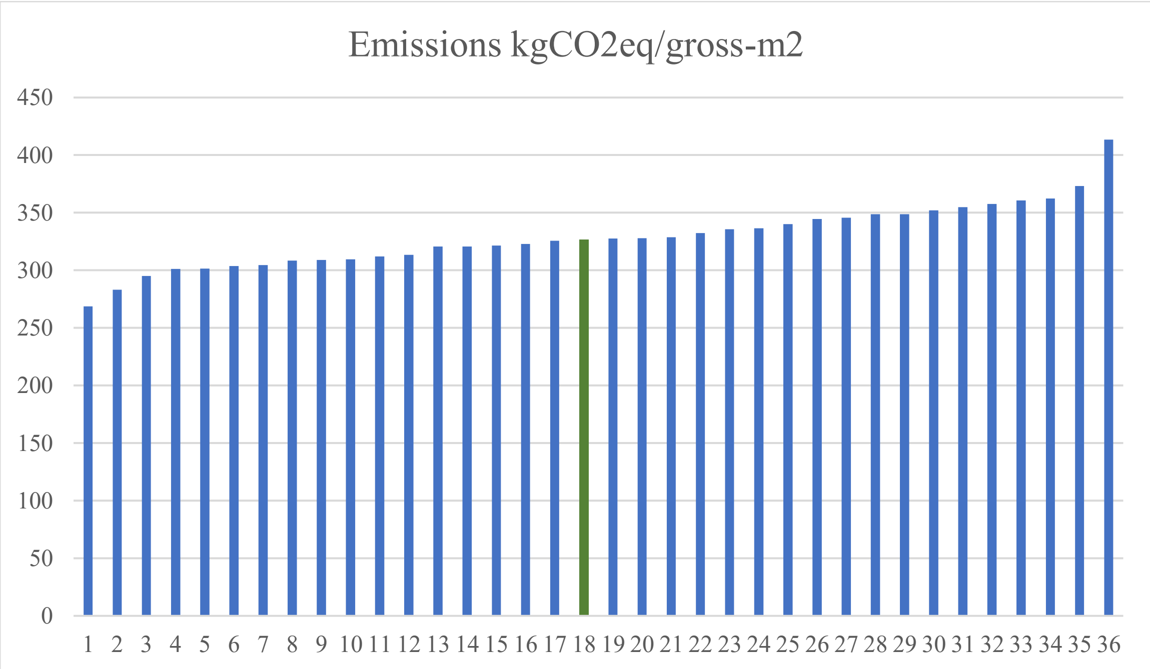


Figure 14 Comparison of GHG emission between Skanska projects, Venny no. 18 in green

The same selection of buildings was compared according to their costs per gross floor area. Venny performs better in the cost than in the emissions comparison as seen from Figure 15.

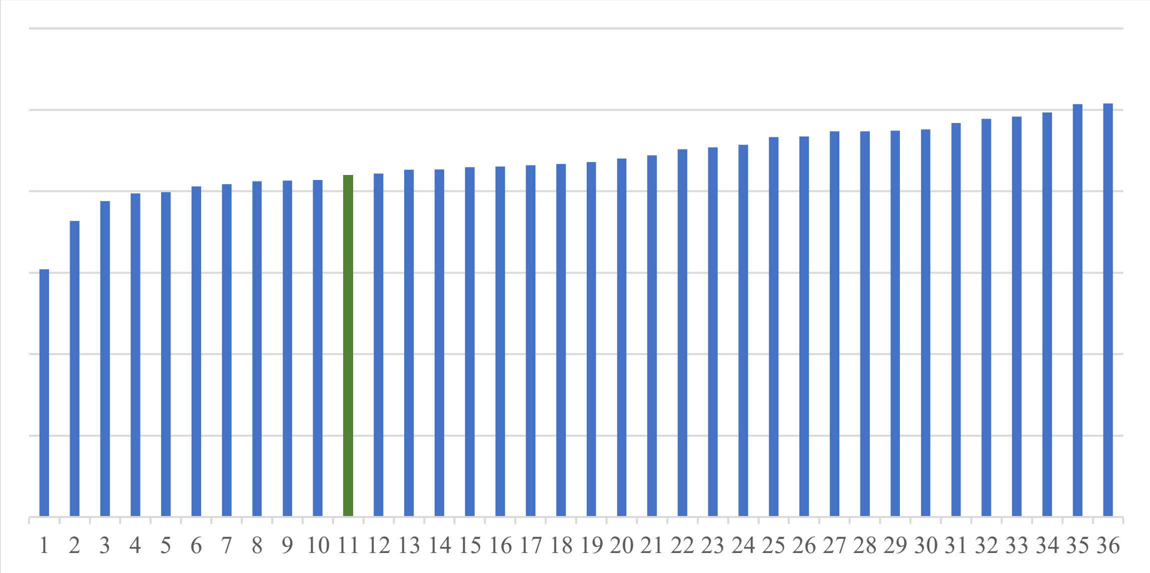


Figure 15 Comparison of costs between Skanska projects, Venny no. 11 in green

When Venny was selected as the case study subject, it was not known that the project is showing the average of the building emissions when compared with other projects from Skanska. Being in the middle of the emissions it provides good information on the easy ways on lowering the emissions. On the costs, Venny lies of the best third of the compared projects. Because lowering costs is still possible on the level Venny is, it encourages on finding more ways to get saving especially in more expensive projects, which do not have any special solutions leading to selected prise rise.

The material amount got estimation tool early stage BEBE was compared with the more detailed amounts from the detailed cost estimate. The top 15 of the most emission producing materials were in comparison. The amount equal to 81.7% of all emissions. Footings are clearly too large in the early stage BEBE. The tool estimates the footings area to be equal to the building areas. Other vice, the values in the early stage BEBE are close to the amounts in detailed cost estimate, mostly a bit over. In addition, differences between amount of façade types varies, but this is because of change in design. For example, in early stage BEBE the brick masonry was estimated 25% from the façade of the single stair building when later the amount has changed to 50%. In total the amount of façade area, is well estimated. The design changes mean that the actual emissions and costs are somewhat higher than estimated; the amount of “the worst” material has increased and “the best” has decreased.

6.5 Suggestions

It is important to acknowledge that overlooking one or more part from the life cycle of a building, results are incomplete and may lead to inadequate conclusions (Ochsendorf, et al., 2011). To improve the got results to be more accurately presenting the life cycle emissions, should there be more detailed research into the construction phase. Results from this study should be combined with previous research about the emissions of a construction of an apartment building. This would lead to wide view from the emissions, helping to make better, more sustainable choices in the future. The emissions and costs of construction are mostly different in every project, making the result more project based. Still, knowing what processes create major amount of emissions or costs are important to know, to be able to improve them.

The most emission intensive raw materials in concrete structure are its cement and reinforcement. Improved materials could have a great effect on total emissions. Manufacturing cement clinker causes 800 kgCO_2eq/t of clinker. In Finland, most of the concrete reinforcement has high content of recycled materials in structures where recycled steel can be used according to the building code. In Europe, the emission level of recycled steel is 470 kgCO_2eq/t of steel, which is under a fourth of steel with no recycled material. In an example case, the use of green concrete would lower the product stage emission from 830 tCO_2eq with 190 tCO_2eq. (Pasanen, et al., 2012.) The developer of green concrete, Rudus, states that the use of green concrete can lower the carbon emissions 20-50%. The cost effect of using green concrete is not known, but it can be assumed that it would increase the costs being a special material. (Rudus, 2018.) Plussementti has a higher additive concentration than so called normal cement. CO_2 emissions of Plussementti are claimed to be 10% less than normal cement making it an efficient way to lower the total emissions from concrete structures. The contractor and customer can suggest or demand the concrete to be made by using Plussementti. The costs the effect of Plussementti is not known. Because concrete is mostly ordered premade to the site, the change from asking to change one component of the recipe cannot be estimated.

Even though concrete is wanted to be the supporting structure, should the options for the non-carrying walls be considered. For example, the wall separating balconies from apartments could be made from wooden elements rather than from concrete. This rather small change could have a positive effect to the emissions without creating large changes on overall design or budget.

The actual emissions of the materials should be studied to ensure the reliability of this study. The accuracy of the used values could be ensured by asking more details about the amounts of the used materials from the manufacturer. The difficulty is that the created emissions are usually got through calculations. Still, if the base was, for example, a detailed concrete recipe, average distance from the factory to the site and the production process of the steer rebar, the solutions would gain more accuracy. It is not known if any noticeable change to the results would be gained with more detailed approach. Either, it cannot be guaranteed that the manufacturers are willing to give detailed information of their productions process claiming it to be a company secret.

When improvement on the material choice has been made and it leads to larger costs, some improvements that can be easily seen by the customers should also be made. As stated in 3.3, customers are more willing to pay from visible changes rather than in improvement of the materials. Other option is that the carbon footprint of the building is told and compared with other projects. For this, the accuracy of the given value needs to be known and more detailed data than the early stage BEBE used.

Comparing the studied project with other projects, a suggestion for a level of emissions that should be tried to accomplish in the planning phase was found. For the so-called normal projects, where the emissions are not emphasised, the GHG emissions should be under 350 kgCO_2eq/m^2 according to early stage BEBE. When the project wants to focus on the emissions, the level should be under 300 kgCO_2eq/m^2. The higher level has been exceeded by about 20% and the smaller one was achieved only by 8% of the projects included in section 6.4 to the comparison. Because the lower level may be challenging with current solutions, it should be reconsidered after trying to accomplish it in actual projects and evaluating the projects that achieved it. If a large error was found from the early stage BEBE or a change of material occurred, the values should be reconsidered.

6.6 Progress of the thesis

The goal of the thesis was to have a subject that can be studied deeply rather than widely. It felt that this kind of process taught more than a wide surface scratch. The deeper study also felt to improve the relevancy of the study to both Skanska and as a scientific research.

An the beginning of the research, it was thought that the environmental impact should be studied with LCA. Rather quickly, while making the literature review, it was noticed that LCA is too broad when also costs are wanted to study and subject studied in detail. The change from LCA to GWP enabled a clearer view of the research and to find element based optimal solutions.

An important part of the thesis was the evaluation of the early stage BEBE. Limited information in emission data created a challenge for the study. Varying data was compared to get more reasonable and reliable initial values. During the process some errors with a significant impact on the results were found from the early stage BEBE. For example, the thickness of the in-situ casted intermediate floor and the amount of loadbearing partition walls. The calculation error in the loadbearing intermediate walls did not affect the results, because it could be avoided with manual input, which was used. The changes in the tool, created a few challenges, but improved the final results.

Reference data for specific weight of bitumen was not found during the initial inspection process of the values. Later, it more correct value was discovered. Because at that point all results were ready, change was made only in roofing of optional structures, where bitumen was used, to get realistic results. Correct value would lower the overall emissions, but results stay comparable by not changing the values of bitumen in other structures in all cases.

It was surprising to notice how few EPDs is there in Finland and how a few free open sources of emission data was available. It is understandable that cost data is wanted to keep as a company secret making the values used in the research also be company specific and hidden. It can be assumed that the lack of knowledge does not encourage on emissions studies within companies. Commercial tools are available, but often the input is materials and their amount by which the calculations are made with. The tools often do not openly present their base values, such as specific weight or GHG emissions, which challenges the comparison with other tools. When these tools are used, it can be, that the reliability ant sources of the used values cannot be evaluated.

The estimated values from early stage BEBE were compared with more detailed material quantities found from the cost estimate. The detailed amount were challenging to find, because of the large coverage of all materials in the cost estimate compared to the early stage BEBE. The comparison helped on finding that the tool does not consider a ridge roof in a right way. It does not take into account the trusses creating the slope to the roof but expects the roof to be built from concrete blocks. Still, the amount of roofing is correct. This means, that when comparing structures, solely the roofing is compared, not what differences are caused by a ridge or a flat roof. Overall, the detailed study of the early stage BEBE improved the tool also for future use.

Finding data to evaluate GHG emissions for materials was challenging. The selection of the reference data to compare with was done focused on openly available Finnish materials. The information was gathered from publishers that were considered well known and reliable. Sources do not provide knowledge how the emissions divided between different stages. For example, when the source considers emitted GHG from cradle to grave, it is not known how large part of that comes from each stage. Because of the low number of references found and some of them having great variation, the estimation on the most accurate one was demanding some.

The used Excel had several hidden tabs to make it as simple to use as possible. Analysing a big Excel which is made by someone else and edited multiple times during its use and analysis, showed how important clarity is when creating files for common use. The Excel was made in a way that the everyday user has simple pages to work with, but a great amount is hidden from the user. This created problems when analysing the input data. A lesson on how to use early stage BEBE helped on understanding the basics of the tool, but the real learning started when following the formulas to find their origin.

To get the thesis results, data from a few files was merged. Without clear notes, what data can be found from more than one file, changes to the initial values when the first set of results are done was challenging to make. Linking between files should occur, but this may cause difficulties when creating new versions of the documents.

During the thesis process, the progress of the thesis could be seen from week-based folders used. At the beginning of the week, all files were copied from previous week and only the latest versions of files were left, others deleted. Some files were not edited at all, such as reference articles, and they were kept in the same place during the whole process. The method was chosen so that the changes could be later revised. This arrangement felt good, especially when comparing the changes of initial data during the process but the working and saving technique would not work in larger studies taking longer time. The number of unnecessary duplicates of files and folders would be higher than the benefits from the method.

The importance to have the ability ask rising questions relatively quickly was clearly visible during the vacation season. The possibility to talk about the subject and progress and to ask quickly some small questions is valuable during the research process. Keeping this on mind, the common vacation seasons are not the best time to work on case type of thesis, especially if the case study is planned to do in the beginning when the vacation time starts.

The literature review performs as a good base for the study. It helped on re-evaluating the scope of the thesis. Because the case part took a lot more time to study, in the end the combining of two parts and finding their relation was important. During the analysis, the literature review was revisited to find the same sources to refer to.

The time line studied appeared to be used also in other studied published by reliable sources. Even though in the end, the maintenance and renewals were felt unnecessary to study in the future, including the taught how large the variation can be. The use stage is always considered as producing a lot of emissions and the customers are very eager to know about the costs during it. It was noticed that the construction cannot affect to a lot of it, except by providing energy efficient appliances and structures, that were not studied.

7 Conclusion

The thesis had three goals: to find a cost-efficient way to reduce total GHG emissions of a building, to test that early stage BEBE provides reliable emission data and to provide information on how to determine LCC and GWP of a building. The research succeeded on finding answers to the first two and started the third one well when the building materials are considered.

The case project, As. Oy Helsingin Venny, forms from two buildings: a single stair building and a slab block. The GHG emissions and costs were determined by using the early stage BEBE. A separate calculation on the maintenance and renewals for the 25-year study period. In addition, the used solutions were compared with optional ones. All options are the standard structures used in Skanska projects.

Most of the costs and emissions come from class three, Structural frame and roof construction, 36.1% and 62.3% respectively, which makes it to have the most opportunities on finding savings. The top ten building elements producing the most emissions compose 70.3% of the total emissions. The costs were studied for more elements and their top ten conclude 39.1% of the total costs. Six building elements were found from both top ten lists:

- Hollow core slab, intermediate floor (1. in emissions/6. in costs)
- Loadbearing partition wall (2./7.)
- Plaster element, thin coat render, slab block (6./1.)
- Concrete element, exterior painting, slab block (7./4.)
- Plaster element, two-coat reinforced render, single stair building (9./2)
- Wooden windows and doors (10./5.).

These elements have high possibility to have an impact on both studied aspects if improvements on them can be made. Another option is to replace the structure with another solution.

Different options in building parts created mostly small changes to costs and emissions. It could be noticed that brick façade had the most meaningful change, if it was used for the whole façade. If the structure allows, the optimal solution would be the following:

- roofing: concrete tiles
- intermediate floor: thinner hollow core slab
- base floor: ground supported floor slab
- façade: all concrete elements.

Concrete element can be found from both, top ten lists and the optimal solutions. This is explained by the fact that the buildings have a large façade that needs to be covered. From the studied option concrete element was the best façade.

The optimal solution and the comparison of different building element options can be seen as an answer to how cost-efficiently lower the GHG emissions of a building. The studied element types, roofing, intermediate floor, base floor and façade, can have a great effect on final results.

The narrowed selection of classes included in the emissions study was considered to help on providing comparable information. Results got from early stage BEBE are used to see on what level the projects are when compared to other projects. The most emissions from material come from large concrete structures, which are included in the study and to the calculation of early stage BEBE.

The maintenance and renewals only conducted 1% of the total emissions and 6% of the costs. When the product life cycle emissions are considered, the use stage should not be included. Compared with their uncertainty in estimating needed actions, it does not provide meaningful information. It would be more beneficial to study the energy efficiency created by the selected materials, to see the environmental impact of a building.

Early stage BEBE is a great tool on helping the planning phase on making environmentally and cost conscious decisions. It focuses only on the product stage, A1-A3, for the emissions and provided reliable information that can be compared with other researches. When using the early stage BEBE, for future projects following GHG emissions targets are proposed:

- all projects: under 350 $kgCO_2eq/m^2$
- projects with a want to be better than average: under 300 $kgCO_2eq/m^2$.

The single stair building and slab block were compared with each other. The classes 1 and 8-9 were excluded because of the shared plot and workforce. The division of the gross area of these two was 37% single stair building and 63% slab block. When their GHG emissions and costs were compared per gross area the division was identical to both 38% single stair building and 62% the slab block. The results propose that the single stair building is less efficient at both costs and emissions than the slab block. The trend in the distribution of the researched aspects between classes is similar to both building types.

GWP provides a rather simple and informative solution when emissions are considered. CO_2 emissions and the common referring to GHG emissions as a carbon footprint ensures that the results are understandable to many customers. Producing building material creates about the fourth of the total emissions during buildings life cycle and it can be seen as a good way for a construction company to be emissions conscious.

Environmental and cost assessments have different goals and units making it hard to merge them. The combination would help on making cost effective solutions when aiming for more environmentally friendly solution. Some relation between them could be detected, but it cannot be said that a product with large emissions is always expensive. It can be seen that mostly large amounts lead to large costs and emissions.

References

Bierer, A., Götze, U., Meynerts, L. & Sygulla, R., 2015. Integrating life cycle costing and life cycle assessment using extended material flow cost accounting. *Journal of Cleaner Production,* Volume 108, pp. 1289-1301.
Bionova Oy, 2017. *Tiekartta rakennuksen elinkaaren hiilijalanjäljen huomioimiseksi rakentamisen ohjauksessa.*
Borg, M., 2001. *Environmental Assessment of Materials, Components and Buildings.* Stockholm.
BRE Global Ltd, 2018. *Certified BREEAM Assessments.* [Online]
Available at: http://www.greenbooklive.com/search/scheme.jsp?id=202
[Accessed 2 August 2018].
Cole, R. J. & Sterner, E., 2000. Reconciling theory and practice of life-cycle costing. *Building Research & Information,* pp. 368-375.
Council of EU, 2018. *International agreements on climate action.* [Online]
Available at: http://www.consilium.europa.eu/en/policies/climate-change/international-agreements-climate-action/ [Accessed 23 July 2018].
Davis, M. et al., 2005. *Guidelines for life cycle cost analysis.*Stanford University.
Dodd, N. et al., 2016. *Summary findings and indicator proposals for the life cycle environmental performance, quality and value of EU office and residential buildings.*
EPD International AB, 2018. *What is an EPD?.* [Online]
Available at: https://www.environdec.com/What-is-an-EPD/ [Accessed 26 July 2018].
European Environment Agency (EEA), 2001. *EEA Glossary,* s.l.: EEA, based on: IPCC Third Assessment Report, 2001.
GBC Finland, 2013. *Rakennusten elinkaarimittarit (2013).*
Green Building Council Finland. [Online]
Available at: http://figbc.fi/elinkaarimittarit/laskentaohjeet/elinkaarikustannusten-laskenta/
[Accessed 8 3 2018].
GreenBookLive, 2018. *Certified BREEAM Assessments.* [Online]
Available at: http://www.greenbooklive.com/ [Accessed 14 June 2018].
Hoogmartens, R., Van Passel, S., Van Acker, K. & Dubois, M., 2014. Bridging the gap between LCA, LCC and CBA as sustainability assessment tools. *Environmental Impact Assessment Review,* Volume 48, pp. 27-33.
Häkkinen, T. & Vares, S., 2018. *Rakennusten khk-päästöjen ohjauksen vaikutusten arviointi: Impact assessment of different measures for controlling GHG emissions of buildings.* VTT.
ISO 14040 + 44 series, Environmental Management, Life cycle assessment, Principles and framework. 2006.
ISO 14064-1:2006 Greenhouse gases, Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals. 2006.
ISO 15686-5 Building and Construction Assets, Service-life Planning, Part 5: Life-cycle costing. 2008.
Julkaisufoorumi, 2018. *Julkaisufoorumi.* [Online] Available at:
http://www.julkaisufoorumi.fi/en [Accessed 9 August 2018].
Kauppa- ja teollisuusministeriön päätös sähköllä toimivien hissien käyttöönotosta ja käytöstä. Act 663/1996. Helsinki 4.9.1996.
Khasreen, M. M., Banfill, P. F. & Menzies, G. F., 2009. Life-Cycle Assessment and the Environmental Impact of Buildings: A Review. *Sustainability,* 1(3), pp. 674-701.

Kiinteistömaailma, 2010. *Yli 40 prosenttia asunnonostajista haluaa ekologisen asunnon.* [Online] Available at: https://app.danskebank.fi/fi-fi/tietoa-danske-bankista/media/Tiedotteet/Pages/20100511_KIMA_ekologinenasuminen.aspx [Accessed 14 August 2018].
Kuittinen, M. & le Roux, S., 2017. *Vähähiilisen rakentamisen hankintakriteerit.* Ympäristöministeriö, Rakennetun ympäristön osasto.
Laki elinkeinotulon verottamisesta. Act 1968/360. Helsinki 24.6.1968.
Lindberg, R., Kivimäki, C. & Hotinen, H., 2018. *Korjausrakentamisen kustannuksia 2018.* Rakennustieto Oy.
Mateus, R. & Bragança, L., 2011. Life-Cycle Assessment of Residential Buildings. *International Conference sustainability of Construction Sustainability of Constructions Towards a Better Built Environment,* pp. 255-262.
Ministry of the Environment, 2015. *Ilmastolainsäädäntö.* [Online] Available at: http://www.ym.fi/fi-FI/Ymparisto/Lainsaadanto_ja_ohjeet/Ilmastolainsaadanto [Accessed 14 June 2018].
Ministry of the Environment, 2018. *Suomi eturintamassa testaamassa eurooppalaisia rakentamisen resurssitehokkuusmittareita.* [Online] Available at: http://www.ym.fi/fi-FI/Ajankohtaista/Uutiset/Suomi_eturintamassa_testaamassa_eurooppa(47070) [Accessed 13 June 2018].
Motuziene, V., Rogoža, A., Lapinskiene, V. & Vilutiene, T., 2016. Construction solutions for energy efficient single-family house based on its life cycle multi-criteria analysis: a case study. *Journal of Cleaner Production,* 112(1), pp. 532-541.
Myyryläinen, L., 2008. *Elinkaariajattelu kiinteistönpidossa.* 2nd ed. Kiinteistöalan Kustannus Oy.
Myyryläinen, L., 2008. *Kiinteistön teknisen huollon käsikirja.*
Myyryläinen, L., 2012. *Taloyhtiön kuntokirja.* Kiinteistöalan Kustannus Oy.
Nissinen, A. S. & Rintala, T. P., 2010. *Materiaalitehokkuus ja hiilijalanjälki, lähtötiedot ja hiilijalanjälkilaskennan tuloslomakkeet Synergiatalo.*
Norris, G. A., 2001. Integrating Life Cycle Cost Analysis and LCA. *The International Jornal of Life Cycle Assessment,* 6(2), pp. 118-120.
Nykänen, E. et al., 2017. *Puurakentaminen Euroopassa LeanWOOD.* VTT.
Ochsendorf, J. et al., 2011. *Methods, Impacts, and Opportunities in the Concrete Building Life Cycle.*
Pasanen, P., Bruce, T. & Sipari, A., 2012. *Ympäristöystävällisen kivitalon suunnittelu ja toteutus.* Bianova Consulting.
Perera, O., Morton, B. & Perfrement, T., 2009. *Life Cycle Costing: A Question of Value: A White Paper from IISD.* International institute for sustanable development.
Peuranen, E. & Hakaste, H., 2014. *Rakentamisen materiaalitehokkuuden edistämisohjelma.* Ministry of the Environment.
Popescu, D., Bienert, S., Schützenhofer, C. & Boazu, R., 2012. Impact of energy efficiency measures on the economic value of buildings. *Applied Energy,* Volume 89, pp. 424-463.
Pöyry, A., 2014. *Construction Phase Greenhouse Gas Emissions of a Low Energy Building in Finland.*
Rakennustietosäätiö RTS, 2018. *Ympäristöseloste EPD.* [Online] Available at: epd.rts.fi [Accessed 3 August 2018].
Realia Isännöinti, 2017. *Mitkä asiat taloyhtiössä kuuluvat isännöitsijälle ja mitkä huoltoyhtiölle?.* [Online]

Available at: https://www.realiaisannointi.fi/ajankohtaista/mitka-asiat-taloyhtiossa-kuuluvat-isannoitsijalle-ja-mitka-huoltoyhtiolle [Accessed 30 August 2018].
Rebitzer, G. et al., 2004. Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment international,* 30(5), pp. 701-720.
Ristimäki, M. & Junnila, S., 2015. Sustainable Urban Development Calls for Responsibility through Life Cycle Management. *Sustainability,* 7(9), pp. 12539-12563.
Ristimäki, M., Säynäjoki, A., Heinonen, J. & Junnila, S., 2013. Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design. *Energy,* Volume 63, pp. 168-179.
RT 18-10922. 2008. *Kiinteistön tekniset käyttöiät ja kunnossapitojaksot.*
Rudus, 2018. *Vihreä betoni.* [Online]
Available at: http://www.rudus.fi/tuotteet/betoni/vihrea-betoni/5798/vihrea-betoni [Accessed 25 July 2018].
Ruuska, A., 2013. Carbon footprint for building products, ECO2 data for materials and products with the focus on wooden building products. *VTT Technology,* Volume 115.
Ruuska, A. & Häkkinen, T., 2013. *Rakennusmateriaalien ympäristövaikutukset - Taustaraportti.* VTT.
Ruuska, A. & Häkkinen, T., 2015. The significance of various factors for GHG emissions of buildings. *International Journal of Sustainable Engineering,* 8(4-5), pp. 317-330.
Saari, A., 2001. Elinkaarikustannusten ja ympäristökuormituksen ohjaus rakennushankkeissa. *Rakentajan kalenteri,* Volume 85, pp. 753-762.
Schade, J., 2007. Life cycle cost calculation models for buildings.
Shine, K. P., Fuglestvedt, J. S., Hailemariam, K. & Stuber, N., 2005. Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. *Climatic Change,* 68(3), pp. 281-302.
Sisäasiainministeriön asetus väestönsuojien teknisistä vaatimuksista ja väestönsuojien laitteiden kunnossapidosta. Act 506/2011. Helsinki 1.7.2011.
Skanska Kodit, 2016. *As. Oy Helsingin Venny Rakennustapaselostus.*
Skanska Kodit, 2018. *Helsingin Venny.* [Online]
Available at: https://kodit.skanska.fi/asuntohaku/helsingin-venny/kuvat [Accessed 18 June 2018].
Skanska Kodit, 2018. *Helsingin Venny.* [Online] Available at: kodit.skanska.fi/Venny [Accessed 14 August 2018].
Skanska Kodit, 2018. *Helsingin Venny.* [Online] Available at: https://kodit.skanska.fi/asuntohaku/helsingin-venny [Accessed 19 June 2018].
Skanska Oy, 2018. *Asuinkerrostalon suunnittelualusta, Suunnittelualustan käsikirja.*
Stake, R. E., 1995. *The art of case study research.* Sage.
Swarr, T. E. et al., 2011. Environmental life-cycle costing: a code of practice. *The International Journal on Life cycle Assessment,* June, 16(5), pp. 389-391.
Säynäjoki, A., Heinonen, J. & Junnila, S., 2012. A scenario analysis of the life cycle greenhouse gas emissions of a new residential area. *Environmental Research Letters,* 7(3).
The Finnish Real Estate Federation, The Finnish Real Estate Management Federation, Kiinteistöalan hallitusammattilaiset AKHA ry & Ministry of Justice, 2017. *Taloyhtiön hyvä hallintotapa -suositus 2016.* 2 ed. Kiinteistöalan Kustannus Oy.
United Nations, 2018.. *Sustainable development goals.* [Online]
Available at: https://www.un.org/sustainabledevelopment/sustainable-development-goals/ [Accessed 6 August 2018].

USGBC, 2018. *Projects.* [Online] Available at: https://www.usgbc.org/
[Accessed 14 June 2018].
Vainio, T. et al., 2012. *Kestävän yhdyskunnan rakentaminen - näkökulmia ja liiketoimintamahdollisuuksia.* VTT.
WCED, Bruntland Commission, 1987.. Or common future. *Report of the world commission on environment and development.*
Wiedmann, T. & Minx, J., 2008. A Definition of 'Carbon Foorprint'. In: *Ecological Economics Research Trends.* Hauppauge NY, USA: Nova Science Publishers, pp. 1-11.

Appendixes

Appendix 1: Used material properties: specific weight and emissions

Appendix 1. Used material properties: specific weights and emissions

Material	Emissions
Concrete roofing tile	0.042 t/m2, 0.140 t CO2eq/m3
Metal windows	0.143 t CO2/m2 of metal windows
Fire door 1.0x2.1	0.182 t CO2/pc
Wooden window	0.094 t CO2/m2 of wooden windows
Wooden door	0.089 t CO2/m2 of wooden doors

Material	Specific weight [t/m^3]	Emissions [t CO_2eqm^3]
Acoustic sheet, rock wool	0.100	0.099
Acoustic spring structure	7.580	13.038
Aluminium parts	2.700	8.883
Balcony plate element	2.500	0.338
Bar Railing	7.850	13.502
Base wall plate	0.500	1.205
Bitumen	1.200	1.452
Brick masonry	1.300	0.300
Brick plate	1.500	0.347
Clinker	1.900	1.330
Column element, concrete	2.500	0.338
Compo mortar	2.000	0.380
Compressed crushed stone	1.500	0.005
Concrete	2.500	0.338
Concrete flue	1.700	0.206
Concrete reinforcement	7.850	11.383
Concrete screed	2.500	0.303
Crushed stone	1.500	0.004
Expanded polystyrene	0.040	0.136
Exterior wall moisture barrier, civil shelter	0.910	2.166
Extruded poly styrene	0.038	0.129
Ferro concrete	2.500	0.338
Fibre concrete plate	2.500	0.338
Fixative mortar	1.300	1.430
Granite	2.700	0.006
Heat insulation SPU-AL	0.038	0.160
Hollow core slab P27	1.434	0.244
Hollow core slab P37	1.378	0.170
Laminate	0.696	0.439
Light gravel	0.320	0.128
Mineral wool	0.035	0.036
Mineral wool rendering sheet	0.100	0.103
Paint, water-soluble	1.200	2.100
Paroc Fatio Plus render insulation	0.130	0.129
Parquet	0.500	0.300
Plasterboard	0.700	0.248

Plastic carpeting	1.300	1.820
Plywood	0.450	0.270
Rendering	2.000	0.380
Screed	1.700	0.289
Steel parts	7.850	13.502
Steel reinforced rendering	2.500	0.303
Steel tendon	7.850	15.700
Stone breeze block	0.848	0.348
Strainer cloth	0.910	2.066
Surface concrete	2.500	0.303
Tempered glass	2.500	1.650
Thin coat render	2.000	0.242
Tilting and levelling concrete	2.500	0.303
Timber	0.500	0.040
Tin roofing	7.850	13.502
Underdrain membrane	0.038	0.046
Vapour barrier	0.940	2.265
Water proofing	1.200	1.452