Aalto University
School of Engineering

Construction Phase Greenhouse Gas Emissions of a Low Energy Building in Finland

Master's Thesis
Department of Real Estate, Planning and Geoinformatics,
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Abstract of master's thesis

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Abstract

In recent years, climate change has been dominating the focus in environmental sustainability. Buildings are reported to account for around 40 per cent of global greenhouse gas emissions, and the construction phase is often assumed to account for only one tenth of the overall emissions during the life cycle of a building until the development of energy efficient building. Thus, the building sector is expected to contribute significantly to the climate change.

Therefore, in recent years, there has been a growing attention in the building sector to construct and develop buildings with a minimum environmental impact, and thus low energy buildings have become an important research field. Further, since it has also been studied that construction phase seems to dominate the life cycle emissions of energy efficient building, there is a motive to study construction phase emissions of a low energy building more accurately.

This study is a quantitative approach assessing comprehensively the GHG emissions, i.e. carbon dioxide equivalents, of a low energy building in Tampere, Finland during its construction phase. In the study the primary method applied is the process life cycle assessment that is further supplemented with a hybrid life cycle assessment. The research is based on literature and a case study.

The results of the study indicate that the life cycle carbon emissions of the construction phase of the case building are 1.684,0 tons of CO_2 equivalents, which accounts for approximately 808 kg of CO_2 equivalents per gross square meter. The most influenced construction sectors were building frame and roofing with a share of 30.8 per cent and HVAC and electricity systems with a share of 19.3 percent. The results are found to be in line with the existing studies in the field of energy efficient buildings as well as EIO and Hybrid LCAs. Additionally, if the building was not designed to reduce energy consumption during its use phase, the construction phase would have caused 793 kg of CO_2 equivalents per gross floor area. This is in line with the claim that the energy efficient residential development does not gain from the environmentally sustainable choices during the construction phase. However, there are certain limitations and uncertainties associated with the study, which indicate that any generalizations should not be made based on the results of this thesis.

Keywords life cycle assessment, LCA, low energy building, GHG emissions, construction phase

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Tiivistelmä

Viime vuosina ilmastonmuutos on ollut keskiössä tutkittaessa ympäristön kestävää kehitystä. Rakennusten on todettu aiheuttavan noin 40 prosenttia maailman kasvihuonekaasupäästöistä, ja rakentamisvaiheen on oletettu aiheuttavan vain noin kymmenesosan rakennuksen elinkaaren kokonaispäästöistä, kunnes on alettu kehittämään entistä energiatehokkaampia rakennuksia. Näin ollen rakennusten on odotettu vaikuttavan mittavasti ilmastonmuutokseen.

Sen vuoksi viime vuosina rakennusalalla on entistä enemmän kiinnitetty huomiota rakennusten ympäristönvaikutuksiin ja alettu rakentaa ja kehittää rakennuksia entistä ympäristöystävällisemmiksi, jonka johdosta matalaenergiataloista on tullut tärkeä tutkimusala. On myös havaittu, että rakentamisvaihe dominoi energiatehokkaan rakennuksen elinkaaren kasvihuonepäästöjä, jonka vuoksi matalaenergiatalojen kasvihuonepäästöjä on syytä tutkia kattavammin.

Tässä diplomityössä hyödynnetään kvantitatiivista lähestymistapaa arvioimalla kattavasti Tampereella sijaitsevan matalaenergiatalon kasvihuonepäästöt, ts. hiilidioksidi ekvivalentit, sen rakentamisvaiheen aikana. Prosessi-elinkaarianalyysi muodostaa perustan tutkimukselle, jota edelleen täydennetään hybridi elinkaarianalyysillä. Tutkimus perustuu kirjallisuuteen ja tapaustutkimukseen.

Tutkimuksen tulokset osoittavat, että rakennuksen elinkaaren rakentamisvaiheen hiilidioksidipäästöt ovat 1.684,0 tuhatta CO2 ekvivalenttia, joka vastaa noin 808 kg CO2 ekvivalenttia bruttoneliötä kohden. Eniten päästöjä aiheuttivat rakennuksen runko ja vesikatto, jonka osuus on 30.8 prosenttia sekä talotekniikka, jonka osuus on 19.3 prosenttia. Tulokset ovat linjassa aikaisempien tutkimusten kanssa, jotka ovat keskittyneet energiatehokkaisiin rakennuksiin sekä panos-tuotos ja hybridi elinkaarianalyyseihin. Lisäksi, jos rakennusta ei olisi suunniteltu vähentämään energiankulutusta käyttövaiheen aikana, rakentamisvaiheen kasvihuonepäästöt olisivat noin 793 kg CO_2 ekvivalenttia kerrosneliötä kohden. Tämä on yhdenmukainen väitteen kanssa, että energiatehokkaat rakennukset eivät hyödy ympäristöllisesti tehokkaista materiaalivalinnoista rakentamisvaiheessa. Diplomityössä tehty elinkaarianalyysi sisältää heikkouksia ja epävarmuuksia, minkä takia tuloksia ei pidä yleistää.

Avainsanat elinkaarianalyysi, LCA, matalaenergiatalo, kasvihuonekaasupäästöt, rakentamisvaihe

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All in all, the project has been interesting self-learning lesson and journey to get more familiarized with the concept of environmental burden of the building industry.

In the land of Santa, December 22nd 2014

Amalia Pöyry

1 Introduction

According to recent studies the interest in environmental effectiveness has been growing in response to the need of sustainable economy. In addition, development of sustainable housing technologies and construction method had put more interest into the environmental burden of construction industry, as for example Buyle (2013) and Sharma et al. (2011) bring up. As the Intergovernmental Panel of Climate Change (IPCC) (2006) states, the world needs to reduce the CO_2 emissions by 50 per cent from the recent level by 2050 in order to mitigate climate change. Furthermore, the EU has set mitigation goals for the years 2020, 2030 and 2050 (European Union 2010; European Union 2014). The European 2020 targets are set to reduce the emissions by 20% below the 1990 levels by 2020, whereas the European 2050 targets are set to cut the emissions by 80-95%.

However, as for instance Junnila et al. (2003) state there is a risk that energy efficient buildings might shift the reduced impacts from operating and maintenance phase to the end of life and construction phases and increase their impact. The increased construction phase emissions, thus, result from the constructive solutions improving the buildings performance during its use.

Due to the relatively long expected lifetime of building, complexity of the products or process (Dutil et al. 2011) and uncertainty of the caused greenhouse gas emissions (GHG) during a long time span (Säynäjoki et al. 2012) it is difficult to evaluate the potential environmental burdens that may result from each of the life cycle stage. Furthermore, impacts of buildings are often spread across several phases and years and, thus, it is crucial to apply a life cycle approach to assess the impacts and minimize them. Therefore, life cycle assessment (LCA) is a highly recommended tool to assess the environmental performance of buildings, as reported by Buyle et al. (2013). In addition, with the growing attention to design and build more energy-efficient buildings it is highly important to take into account the relevance of other phases of the life cycle, not only the use phase since buildings use energy and cause GHG emissions throughout their whole life time, i.e. from construction phase to demolition, as Dutil et al. (2011) state.

Moreover, if not much attention is paid for the construction phase, the associated materials and processes will not be utilized in the best way in order to improve the environmental

performance of a building. (Guggemos et al. 2006, p.187) Thus, an improvement of the construction phase has a major potential to reduce impacts when the whole life cycle is considered. Furthermore, it is crucial to recognize the expected environmental loads of the entire life cycle, including energy usage and potential emissions, thus improving the environmentally informed decision-making, as Junnila et al. note (2006, p. 16)

Due to the growing importance of construction phase emissions, in this thesis a comprehensive process life cycle assessment (LCA) modelling is made of a low energy building in Finland. The growing importance of LCA as a scientific tool to evaluate environmental burdens is a positive trend; however, there are still many research opportunities and areas to improve current practices, as e.g. Buyle et al. (2013) brings up. In addition, there is a lack of research made as accurately and in detail of the construction phase of similar buildings to the case building where the carbon footprint has been reduced by architectural design and low impact construction materials (e.g. Pasanen et al. 2011; Asdrubali et al. 2013).

The thesis is structured as follows. Section 2 will introduce the framework of the environmental management tool, i.e. LCA, to assess the life cycle of buildings. The section 2 will, in addition, describe the three different methods for life cycle assessment. Section 3 will thereafter define the relevance of the research subject and represent existing researches in the field of construction phase emissions. The case building as well as entire research design is presented in section 4 and the results of the research are presented in section 5. Uncertainties related to the study and sensitivity analyses are discussed in section 6. Finally, section 8 presents the conclusions of the thesis.

1.1 Background and Motivation of the Research

In recent years, the focus in environmental sustainability in urban development has been dominated by climate change, which is due to the fact that nowadays buildings account for over 40 per cent of the worldwide energy use. Furthermore, the built environment produces one third of the global greenhouse gas emissions. (UNEP, 2009 pp. 9) Buildings encompass up to 40 per cent of the Finnish carbon footprint, as KTI Property Information Ltd (2014) reports. In addition, building sector has a significant economic impact since the construction industry accounts for approximately 10 per cent of the gross domestic product (GDB) of the EU. In Europe, almost 90 per cent of their time people spend inside the buildings and, therefore, indoor climate affects the health and comfort of the users. Thus, buildings play a major

role in consumption of energy worldwide and in formulating and executing sustainable development strategies. (Cen TC/350) Bright side for this aspect is that the building sector has been claimed to have the largest potential to reduce carbon dioxide (CO2) emissions from their energy use (UNEP, 2007 pp. 1) and greenhouse gas emissions (UNEP, 2009 pp. 9). Therefore, in order to design and create environmentally effective buildings, the environmental impacts of the entire service life must be known and evaluated correctly, from raw material acquisition to end of life treatment and final disposal.

Apart from the operational energy use, buildings' energy consumption comprises the energy use of mining, processing, manufacturing and transporting of the building materials, the energy consumed in the construction phase and demolishing phase. (Li All et al., 2013, pp.1) Moreover, when considering the relatively short time the construction phase causes a considerable amount of carbon emissions even though the share of its environment loading is minor compared to the use phase, as brought up by Säynäjoki (2014) and Buyle et al. (2013). Therefore, in recent years there has been a growing attention in the building sector to produce buildings with a minimum environmental impact and, thus, low energy buildings have become an important research field, as mentioned by Thormark et al. (2002).

It is possible to optimize these energy efficient features by applying life-cycle assessment (LCA). LCA is the most apposite method to quantify the energy use and environmental emissions during a construction phase of a building. (Guggemos & Horvath, 2005, pp.1) As Branden et al. (2008) report, LCA is an applicable tool to understand emissions that directly associate with the life cycle of a product or process. LCA quantifies the energy material inputs and greenhouse gas emissions, and waste outputs through the complete life cycle of a building, from raw material acquisitions to the end of life and reuse. (Junnila et al., 2006, pp.11) Due to the growing interest in construction phase's environmental impacts in urban development and expectations that the highest economically feasible reduction potential of greenhouse gas emission is suggested to be found in the residential and commercial real estate sector.

1.2 Research Problem and Objectives

The purpose of this study is to analyze the environmental burden produced in a construction phase of a low energy building located in Tampere, Finland. As Huberman (2008, p.837) points out, climatically responsive efforts to moderate the use of non-renewable energy in

buildings have led to major savings mostly during building's ongoing use phase. However, if operational energy use decreases, share of the total life cycle energy embodied into construction materials increases relatively (e.g. Saari 2001; Junnila et al. 2003; Huberman & Pearlmutter 2008). For instance, the construction phase may account for up to 50 per cent of the life cycle emissions according to Heinonen et al. (2011a). Thus, when considering the relatively short time of a construction phase, from approximately 1 to 2 years, the share of its environmental burden is significant. Therefore, the construction phase's environmental burden during a building's life cycle is growing in relative importance. Hence, as new buildings are designed more energy efficiently, there is a need to more comprehensively study the growing relevance of the other phases of building's lifespan in the near future. As Heinonen et al. (2012) points out, a longer point of view of the relevance of construction phase emissions increases the uncertainties of the use phase assessment since during a longer time frame the consumption patterns and production technologies change.

Thus study advances the current state-of-the-art of LCA modelling and carry out a process based LCA model of the reference building as comprehensively as possible. The study evaluates the construction phase emissions of an apartment building in Tampere, Finland designed to mitigate energy consumption during its use phase. In addition, the study compares the results of the reference building as if traditional construction materials were used – whether an energy efficient residential development in the construction phase can gain from the economically and environmentally sustainable choices. Furthermore, the existing studies of the construction phase emissions report a variety of results and regarding process LCAs the results have been relatively low since they often leave some construction parts out of the scope. Hence this study tries to achieve as comprehensive process LCA as possible.

The research aims to answer the following questions:

1. How much life cycle carbon emissions does the referenced low energy building cause during the construction phase?
2. Do the material choices made in the construction phase have the potential to mitigate the caused greenhouse gas emissions of the building?

2 Life Cycle Assessment

This chapter introduces the structure and details of LCA, and its methodology, which is based on International standard series ISO 14040:2006 and series of European standards CEN/TC350. These frameworks have been developed to guide practitioner thus LCA assessments are more standardized. Furthermore, this chapter introduces the structures of the three LCA methods.

2.1 Description of LCA

Life cycle assessment (LCA) is a methodology that evaluates all environmental loads of processes and products (i.e., goods and services) during their life cycle – including raw material extraction, raw material processing, manufacturing, use and maintenance and disposal or recycling, as figure 1 shows. (Klöpffer, 1997; Crawford, 2011, p. 39) ISO 14040 (1997) defines LCA as "technique for assessing the environmental aspects and potential impacts associated with a product, by: compiling an inventory of relevant inputs and outputs of a products system; evaluating the potential environmental impacts associated with those inputs and outputs; interpreting the results of the inventory analysis and impacts assessment phases in relation to the objects of the study." These inputs consist of the raw materials extracted from the Earth's crust; energy and water use, whilst the outputs include emissions to air, land and water, solid wastes; co-products, as well as other releases (Crawford, 2011, p. 39).

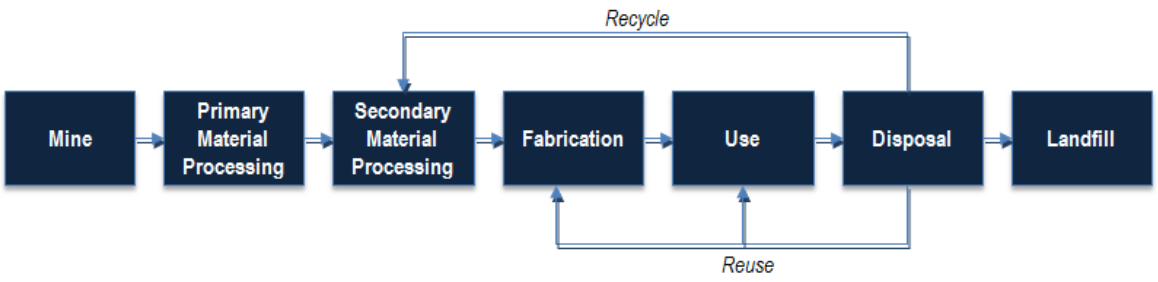

Figure 1 A Generic Supply Chain of Life Cycle Model (Hendrickson et al. 2006)

Furthermore, LCA is a method to assess variety of aspects related with a development of a product or process and its potential impacts during its lifespan from raw material acquisition, processing, manufacturing, use and to its final disposal, including raw material acquisition required to manufacture a product. (ISO 2006) In order for designers and constructors to

focus on their energy efficiency improvement efforts it is vital to know how and when the major environmental emissions occur. Despite the limitations of LCA it is still an efficient and science-based method to assess the environmental impacts. (Guggemos & Horvath 2005, p.93) Furthermore, as Crawford (2011, p. 40) points out, the economic or social standpoints of a product, a process or decision are outside the scope of an LCA. However, the cost effective options can be found applying a life cycle costing (LCC).

2.1.1 Brief History of LCA in the Building Sector

The usage of LCA as an environmental management tool had its beginning in the 1960s and 1970s (Hunt & Franklin 1996, p.4). According to Hunt et al. (1996, p. 4) one of the first unpublished studies using LCA was completed by Midwest Research Institute (MRI) for the Coca Cola Company in 1969, including resource, emission loading and waste flows for different beverage container. In the 1990s Society of Environmental Toxicology and Chemistry (SETAC) started to be a part of the cause of bringing the LCA specialists together and harmonizing the general structure, methodology and terminology of LCA, which resulted in the SETAC 'Code of Practice'. (Klöpffer, 2006; Consoli et al., 1993) From 1994 the International Organization for Standardization (ISO) was involved by taking over what SETAC had initially developed resulting in the ISO 14040 standard series, first published in 1997. This standardization, therefore, created a general methodological framework, which made it easier to compare different LCAs, as Buyle et al. (2013) reports.

Since 1990 the building sector has been using LCA (Fava 2006) and according to Buyle et al. (2013, p. 381) the interest in LCA has been growing fast from the beginning of the 21st century. Thus, it is an important tool for evaluating buildings. Furthermore, Klöpffer (2006) clarifies that LCA has become a widely used methodology due to its qualitative way to integrate important topics, such as framework, impact assessment and data quality.

In addition to the ISO 1040 standards, during the last decade there have been some developments focusing on the construction sector and a suite of new European Standards is being developed for assessing the sustainability of construction products and the built environment. This is being undertaken by the CEN Technical Committee for the sustainability of construction works (CEN TC 350). (Boyle et al., 2013, p. 381) In the context of building and construction LCA, the standards recently developed by CEN TC 350 will be very influential in defining how the environmental impacts of construction products and buildings are assessed

and will ensure that they are undertaken on a robust and consistent basis throughout the EU. As Buyle et al. (2013) brings out, these standards have been developed in response to find a common European approach and to avoid potential barriers to trade, which drove the European Commission to issue a mandate to CEN (CENT TC 350. 2013) to develop horizontal standardized methods for the assessment for the sustainability (i.e., economic, environmental and social) assessment of new and existing construction works (EN 15978), as well as for relevant product information (EN 158004).

2.1.2 LCA to Support Sustainable Solutions

When the impacts caused during the entire life span of a building are evaluated LCA supports the decision-making process optimizing environmentally sustainable decision solutions. Malmqvist et al. (2011, p. 1901) highlight that there are also several other reasons for how LCA can be utilized. The growing interest in environmental issues led to the Kyoto-protocol; an international agreement on reducing the emission of greenhouse gasses and global warming. In the construction sectors, consequently, this resulted in Energy Performance of Building Directive 2002/91/EC (EDBD, 2003) that requires all EU countries to enhance their building regulations and to introduce energy certification schemes for buildings, and thus LCA is the most appropriate evaluation method providing information to reduce environmental impacts. Furthermore, LCA supports Corporate Social Responsibility strategies and enables announcing of environmental performance. (Malmqvist et al. 2011, pp. 1901, Hauschild et al., 2008, pp. 23)

2.2 LCA Framework

As described in the previous section, the leading standards for life-cycle assessment are ISO 14040 series.

- International Standard ISO 14040 (1997) on principles and framework
- International Standard ISO 14041 (1998) on goal and scope definition and inventory analysis
- International Standard ISO 14042 (2000) on life cycle impact assessment
- International Standard ISO 14043 (2000) on life cycle interpretation

In order to analyze the environmental impacts of processes and products during their whole life cycle, four phases have to be gone through, which enables to compare different studies. These phases are goal and scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and an interpretation, as shown in Figure 2 (ISO, 1997).

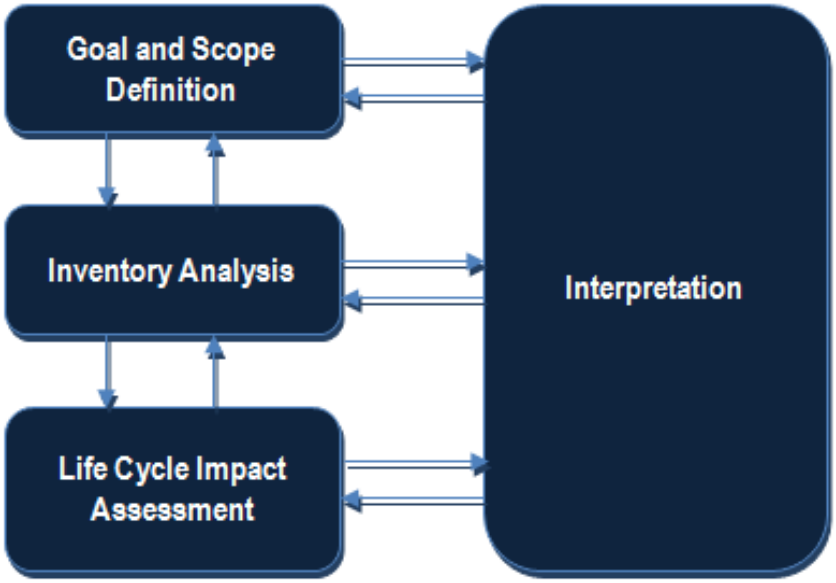

Figure 2 LCA framework based on ISO 14040 (ISO, 1997)

2.2.1 Goal and Scope Definition

The first step of life-cycle assessment, goal and scope, identifies the purpose of the study and determines the questions to be answered. (Crawford, 2011, p. 42) It is an important step determining why an LCA is being conducted and describing the system in terms of the systems boundaries, such as the full life time of a product or one phase of production, and a functional unit. The functional unit is the important basis that enables alternative products, or processes, to be compared and analyzed thus defining the performance characteristics, e.g., floor area. (Rebitzer et al. 2004; ISO 14041) Hence, the definition of the goal and determination of the scope defines the direction of the study and benchmarks with which the study will be evaluated in the interpretation phase. In addition, ISO 14040 (1997) describes LCA as an iterative technique and, therefore, the goal and scope of a study may change while the study is being conducted according to many considerations during the study, e.g., additional information and data unavailability.

2.2.2 Life Cycle Inventory Analysis

The second phase of an LCA is the life cycle inventory analysis, or LCI, which consists of collecting and processing of the data. Rebitzer et al. (2004, pp. 704) define LCI as a methodology for estimating the consumption of resources and the quantities of waste flows as well as emissions to air, water and land caused by or otherwise attributable to a product's entire life cycle. In the inventory phase, the processes within the life cycle and the associated material and energy flows, and other exchanges are modelled to represent the products systems including its total inputs from the environment and outputs to the environment. Thus, its aim is to calculate the quantities of different resources required and emissions, as well as waste caused per the chosen functional unit. According to Kliippei (1997, pp. 7), in most cases LCI has been the phase that requires most intensive work and careful planning. In addition, it is the most scientific component of LCA. (Consoli, 1993; ISO 14041, 1997) Therefore, as Khasreen et al. (2009, pp. 681) note, it is critical to choose the most appropriate data for the modelling as the quality of data sources guarantee the accuracy of the results, as well as drive the study and determine its quality level. Lack of data may result in changing the scope and/or objectives (ibid.).

ISO 14044 (2006) defines the phases to produce an LCI: draw a specific process flow diagrams, develop a data collection techniques, collect the data needed, evaluate and report the results, as Figure 3 shows. The flow diagram should outline all unit processes that are to be modelled as detailed as possible to get a high level of accuracy. The next steps are to set a data collection policy and to evaluate and validate the data. After that, the data have to be related to the defined functional units of the building. The last phase in an LCI is to refine the system boundaries, after which the results and sensitivity analyses are reported.

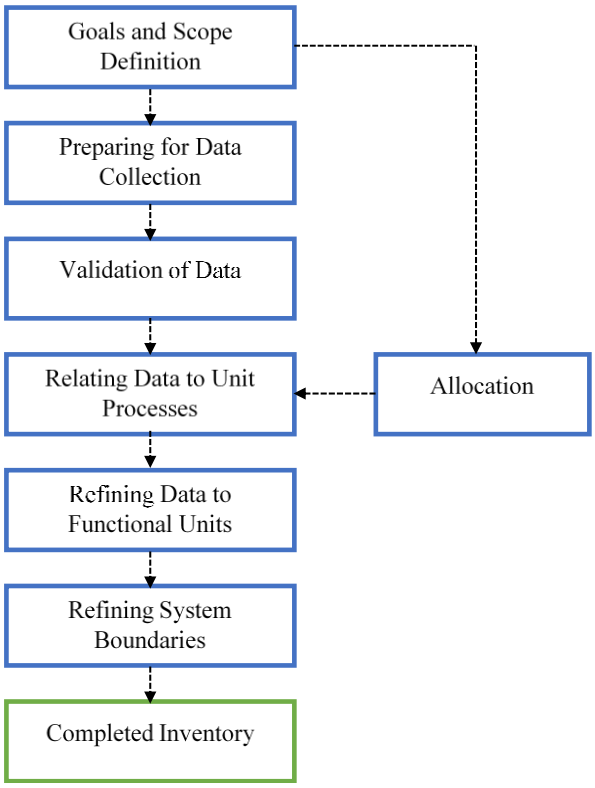

Figure 3 Different phases of Life Cycle Inventory (ISO 14044 2006)

2.2.2.1 Methods to Compile LCI

Hybrid modelling combines both approaches and addresses the limitations in each approach. The three options are discussed in detail later in section 2.3. In order to quantify the inputs and outputs of products or processes an LCA can be applied in a form of a process-based LCA, an input-output LCA (IO-LCA) or a hybrid LCA. Process analysis and input-output (I-O) are the primary LCA approaches for compiling an LCI (Sharma et al. 2011, p.873; Hendrickson, 2006)

Studies that are based on process-based LCA are product-specific thus depending on the inventory data available. (Crawford, 2011, p. 47) An IO-LCA, on the other hand, uses transaction information to estimate the environmental impacts over the entire life cycle, as Treloar et al. (2001) mentions. A hybrid LCA combines elements of process LCA with input-output approaches and addresses the limitations in each approach.

The benefits and limitations of each of these methods are analysed in section 2.3. In this study the primary method applied is the process LCA that is further supplemented with a hybrid LCA.

2.2.3 Life Cycle Impact Assessment

The third phase on an LCA, life cycle impact assessment (LCIA), evaluates the scale and significance of the environmental impacts based on the results of the LCI. ISO 14042 (2006) defines the impact assessment as examining the product system from an environmental point of view using impact categories and category indicators connected with the LCI results. LCIA, additionally, provides information for the life cycle interpretation phase of an LCA. LCIA classifies the life cycle inventory results into different impact categories according to the substance's ability to contribute to different environmental problems. For example, the caused greenhouse gases may be assigned to the global warming category or to ozone layer depletion. (Crawford, 2011, p. 54) Furthermore, classification of the LCI results involves translating the emissions, wastes and resources used to the chosen impact categories, e.g. CO2 and CH4. (ISO 14042, 1999) For instance, greenhouse gas emissions may be conveyed in CO2 equivalents. The collection of the results, therefore, provides information on the environmental burdens contributed by the inputs and outputs of the product system. Crawford (2011, p. 55) notes that during the goals and scope definition phase the choices of impacts that are to be taken into account and their levels of detail are described. As reported by Ortiz et al. (2009) the most commonly studied impacts applied to LCAs of buildings have been global warming, acidification, eutrophication and ozone depletion.

2.2.4 Interpretation

The final phase of an LCA is the interpretation of findings. The purpose of this phase is to combine and analyse the results of the previous phases of the LCA and LCIA, and thus determine the most significant inputs, outputs and potential environmental impacts of a product system. Life cycle interpretation reaches conclusions, explains limitations and provides recommendations based on the findings. (ISO 14043, 1999)

2.3 Methodology for Life Cycle Inventories

This section describes in more detail the three alternatives that exist for life cycle assessment, or more specifically, a life cycle inventory.

2.3.1 Process Analysis

Sharrard et al. (2008, p.327) state that due to the complexity of the construction industry the best understanding of environmental implications would be achieved by applying a process LCA approach. In addition, according to Suh et al. (2004) the most common method used when applying an LCI has been a process based analysis. The objective of a process LCA is to evaluate the environmental impacts of each process of a product's life cycle using a process flow diagram and include all relevant processes into the modelling. (Bilec et al. 2010, p.200) Khasreen et al (2009, p. 682) note that typically a process LCA starts from the final product and ends up to the phase of raw material extraction. As Lenzen & Treloar (2006, p.249) note, a process based LCA approach evaluates in detail the energy consumptions and GHG emissions of the main processes within the material production, as well as some central contributions from suppliers of inputs into the main processes.

In the process based analysis a combination of process, product and location-specific data is used to calculate the environmental impacts of a product system. (Crawford, 2011, p. 47) A process based life cycle assessment aims to capture all environmental loadings of the product system from material extraction to returning of wastes. Thus, a process based LCA approach results in detailed process- specific analyses, detailed product comparisons and high-precise model outcomes (Chang et al. 2011; Lenzen & Treloar 2006. p. 249).

Hence, due to the complexity of the construction industry the process LCA method would result in a better understanding of its environmental impacts. (Sharrard, 2008, p. 328) However, the access to a process data is time consuming and the process is highly data intensive, and, therefore, some parts of the studied system might be neglected or cutoff, which results in relatively lower impact results. Suh et al. (2004, p. 661) disclose that on an average when performing a process based LCA the environmental impacts are reported to be 3 % lower than from an input-output analysis and 18 % lower than from a hybrid LCA due to these limitations.

Moreover, a process analysis tends to suffer from a systematic truncation error, which results from the setting of system boundary and, consequently, exclusion of processes outside of the boundary. On the account of the truncation error it is not possible to achieve 100% system completeness. (Suh et al. 2004, p. 659) Lenzen and Treloar (2006) point out that the extent of this truncation error depends on the product's or activity's type, but can be reduce the

system completeness to 50%. According to Lenzen (2001) even the relatively wide process LCAs do not reach reasonable system completeness thus leading to unreliable or incorrect conclusions, i.e. underestimations. Therefore, several researches have recommended and used a hybrid LCA approach that combines process analysis with an input-output analysis. (Suh et al. 2004, p.660; Treloar et al. 2001, p.52; Crawford, 2011, p. 53) The discussed advantages and disadvantages of the process LCA are outlined in table 1.

Table 1 Advantages and Disadvantages of a Process LCA Approach *(Hendrickson, 2006, p. 25)*

	Advantages	**Disadvantages**
Process LCA	Detailed process-specific analysis.	Systems boundary setting subjective
	Specific product comparisons.	Tent to be time intensive and constly.
	Process improvements, weakpoint analysis.	New process design difficult.
	Future product development assessments.	Use of propriety data.
		Cannot be replicated if conficential data are used.
		Uncertainty in data.
		Tuncation error.

2.3.2 Input-Output Life Cycle Assessment

Input-Output LCA (IO LCA) is the other widely employed method within the building sector that uses economic transaction matrixes (i.e. input-output tables) to assess environmental impacts. IO LCA was developed by Wassily Leontief in the 1930s, who he received a Nobel Prize in the 1970s (Leontief, 1970), and has since been applied extensively to environmental analysis. These input-output transaction tables describe the purchase flows between economic sectors, in other word the foundation for the IO-LCA is the sector-by-sector economic interaction between. (Bilec 2007, p.17) IO-LCA estimates the inputs required in the sectors of economy in order to assess the outputs throughout a whole economy. (Crawford, 2011, pp. 49-50) IO-LCA is particularly valid to national-level researches. By integrating energy and environmental elements into national sector-by-sector economic input–output interaction, IO-LCA undoubtedly provides researchers with a functional assessment tool for macro-level studies (Leontief, 1970).

According to (Crawford, 2011, p. 50) it is possible to add almost any kind of environmental data into an input-output table, such as energy, water, raw material consumption, production of waste and pollutant releases for example, carbon dioxide. Therefore, IO-LCA takes into

account a more comprehensive view of the construction industry. (Sharrard et al. 2008, p.328) As in the process analysis, the environmental data has to be formulated correctly per an economic sector in order to quantify the resources required or emissions released with a specific value's worth of output from any sector of an economy. (Crawford, 2011, p. 50) Comparing to a process LCA, IO-LCA does not suffer from truncation error and is not time consuming since the method transfers costs into emissions according to the section selected. However, the existing IO-LCA models for the construction industry tend to be simplified and underestimate environmental burdens. (Sharrard et al. 2008, p.328)

While a process LCA is generally recognized as being more vulnerable to truncation error and inconsistent system boundary definitions, IO-LCA is criticized as being too aggregated and insufficiently specific for product level assessments. The result is that IO-LCA models assume national average environmental intensities valid for all products manufactured by the certain sector. (Crawford 2011). Furthermore, the IO IO-LCA models assume that product's environmental impacts are positively correlated with its costs within each sectors. This, so-called, allocation error increases the uncertainty of IO assessments (e.g. Treloar 1997; Crawford 2011). Moreover, IO-LCA's suitability to evaluate processes or products is limited since it is assumes homogeneity of prices, outputs and their carbon emissions at sector level as Wiedmann and Minx (2007) report. The input-output model is also linear, thus the effects of a € 1,000 purchase from a sector will be 10 times greater than the effects of a € 100 purchase from the same sector, which limits suitability of the model (Ochoa et al. 2002). A big advantage of input-output based approaches, nevertheless, is a much smaller requirement of time and human resource during the assessment. The advantages and disadvantages of an input-output LCA are described in table 2.

Table 2 Advantages and Disadvantages of an Input-Output LCA Approach *(Hendrickson 2006; Wideman & Minx 2007; Ochoa et al. 2002)*

	Advantages	Disadvantages
Input-Output LCA	Economy-wide, comprehensice assessments.	Some product assessments contain aggregate data.
	System LCA: industriews, products, services, national economy.	Process assessments difficult.
	Sensitivity analysis, scenario planning.	Linear instead of unlinear modelling
	Publicly available data, reproducible results.	Economic and environmental data may reflect past practices.
	Future product development assessments.	Time-lag in reflecting of current practices
	Information on every commodity in the economy.	Difficult to apply to an open economy (with substantial non-comparable imports).
		Uncertainty in data.
		Homogeneity

Regardless, IO LCA requires less resources than the process based analysis, as some IO LCA tools are free of charge and available on the Internet. One of the freely available IO LCA tools is Economic Input-Output LCA (EIO-LCA) developed by Carnegie Mellon University. (Hendrickson, 2006, p. 10)

2.3.3 Hybrid Analysis

The process and input-output LCA analysis have limitations and strengths. A hybrid LCA is a method that combines the best LCA assets of the two approaches. (Suh et al. 2004, p.660; Bilec et al. 2006) Thus, it is regarded as the best LCA method in a case of complex system modelling, as Crawford (2011) brings up. Recent hybrid LCAs for the construction industry have been resulting in accurate assessments of environmental impacts. (Bilec et al. 2006, p.207; Guggemos & Horvath 2005, p.101)

Suh et al. (2004, p.601) state that if the process data or resources are unavailable or the required level of uncertainty is achieved, the process based part of the analysis can be shortened and the remaining gaps covered by input-output analysis. Thus, when applying a hybrid approach the boundary of the analysis can be modified to suit the objectives.

Hybrid approaches can be divided into three different categories: a tiered hybrid analysis, an input-output based hybrid analysis and an integrated hybrid analysis. In *a tiered hybrid analysis* the direct and downstream requirements, e.g., construction, use, maintenance and end-of-life and some important lower order upstream requirements of the product system are evaluated in a detailed process analysis. The remaining higher order requirements, such as material extraction and manufacturing are, on the other hand, covered by an input-output analysis. Nevertheless, the comparability of the boundary between the two methods depends on the data availability, as Crawford (2011, p. 53) states.

In an *input-output based hybrid analysis* the important input-output sectors are further divided as more detailed economic data are available. An *integrate hybrid analysis* combines process LCA with I-O in a mathematical framework. The process data is described in a technology matrix with physical unit per operation time for each process, whereas the units of I-O model are economic. The process-based and I-O data are thus linked through a make and use framework that is connected through the flows at the boundary of each system. (Suh et al. 2004, p.661)

2.4 Limitations related to LCA in the Building Sector

The LCA application is essential to evaluate the environmental impact and energy demand during the entire life cycle of a building. However, even though LCA is a widely used approach to assess environmental impacts of products and processes the method is not without its drawbacks, as Junnila et al. (2003) point out. Consequently, the results of LCA are open to interpretations and should be analyzed carefully (Buyle et al. 2013).

As Buyle (2013) report, buildings are unique, and they have long life cycles and complex product life spans since they are constructed of several materials and material combinations, as well as under local regulations. Therefore, LCA methods may not be straightforward and can comprise difficulties and uncertainties. Moreover, during the LCA subjective choices and assumptions are made, the models used in the inventory and impacts assessment are limited, the local conditions may not be adequately considered, the accuracy of the data may be limited due to lack of data and the lack of spatial and temporal consideration, as ISO

14040 (ISO 1997) has listed. Buyle (2013) also manifests how the current LCA practice within the construction sector isolates the approach of environmental issues.

3 Presentation of the Research Subject

3.1 Relevance of Construction Phase

Buildings use energy and cause GHG emissions throughout their whole life time, i.e., from construction phase to demolition. GHG is any gas that traps heat in the atmosphere, thus keeping the Earth's atmosphere warmer than it otherwise would be. The main GHGs are water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone, as reported by Brander et al. (2012) report. As Crawford (2011, p. 72) notes, buildings are long lasting and their life cycle involve use of resources and, therefore, they cause environmental impacts within several stages, as figure 4 shows. In all stages of the life cycle of energy is required and waste is caused. For instance, the construction phase of buildings consumes significant amounts of raw material, energy and water, which cause pollutants, greenhouse gases, as well as waste. During the building life cycle the only emissions-reducing step is the recycling of materials at the end of the building life cycle, when energy is produced from wooden materials, and metals and other materials are used to replace the secondary raw materials. (Crawford 2011)

Figure 4 Inputs and Outputs throughout the building life cycle (Crawford 2011)

The building sector has become widely recognized as major contributor to global warming since it accounts for approximately 40 per cent of the worldwide energy use and contributes to nearly 50 per cent of global greenhouse gas (GHG) emissions (UNEP, 2009). Furthermore, according to Statistics Finland (2013), the share of residential building sector in Finland is approximately 20 per cent of the whole energy use. Moreover, nearly 54 per cent of the world's population lives in urban areas and cities are estimated to be responsible for up to 80 % of global GHG emissions (United Nations, 2007). Therefore, as McKinsey & Company state, (2009, p.43) buildings play a major role in mitigating climate change in both short and medium terms, which is due to its massive asset base.

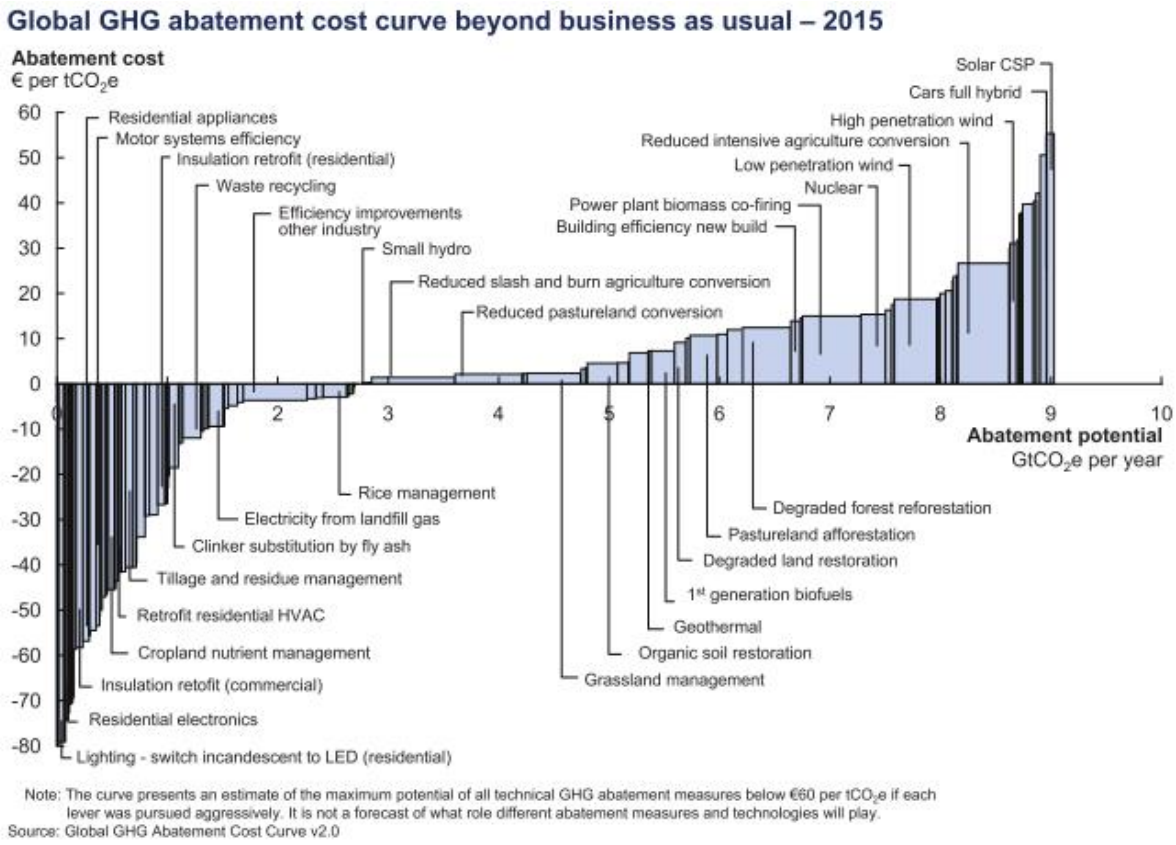

Figure 5 Global GHG abatement curve (McKinsey & Company 2009)

The authors of Pathways to Low-Carbon Economy, McKinsey & Company (2009) exploit the business-as-usual scenario as a starting point to estimate GHG emission reduction potential. As the figure 5 above demonstrates there is a significant economic potential to reduce greenhouse gas emissions within the building sector through various abatement opportunities, many of which come at a negative or low cost. Therefore, as McKinsey & Company (2009) state, the long life time of building, varying from 35 to 70 years, indicates that the

decisions made during the construction phase, such as materials, building's orientation and insulation, affect the future life span emissions.

Due to this significant potential to reduce GHG emissions of buildings National laws (Asdrubali et al. 2008) and EU directives (e.g. European Union, 2003; European Union 2010) have set limitation and restrictions on energy consumption in building, as well as requirements for energy certifications in retrofitted and new buildings, in European countries. The new legislation aims in comprehensive EU-wide energy savings, which has drawn more attention to the embodied energy of buildings, as well as to recycling possibilities of construction materials at the end of building's life. For example, the European 20 targets are set to reduce GHG emissions by at least 20 per cent below the 1990 levels (European Union 2010). However, as Chang (2011, p.6321) points out, compared with the research of the use phase of buildings, study of the embodied energy of construction and its greenhouse gas emissions are relatively rare and superficial.

As Säynäjoki et al. (2012) bring out, even though construction of energy efficient buildings has been considered as one of the primary ways to reduce the energy consumption of buildings, it is has been often ignored that the new construction projects cause a carbon spike in a short time period. In particular, as Buyle et al. (2013, p.384) state, large embodied energy of the construction phase cause this relatively high amount of GHGs thus dominating the life cycle emissions. Also, if the construction phase emissions cannot be reduced to a large extent, new energy efficient residential construction is not a qualified argument to achieve the climate change goals in the near future, i.e. the European 2020 targets, as the scenario analysis written by Säynäjoki et al. (2012) emphasizes. Figure 6 shows how the cumulative construction phase emissions dominate the GHG mitigation goals.

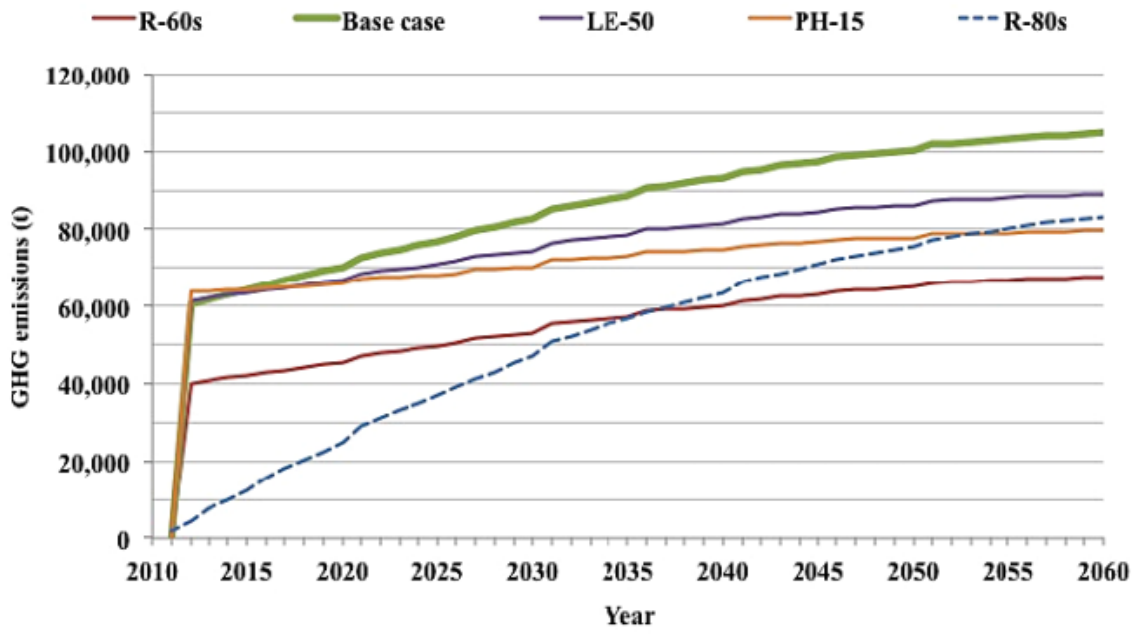

Figure 6 The dominance of construction phase GHG emissions (Säynäjoki et al. 2012)

In their study Säynäjoki et al. (2012) made different scenarios for houses with different energy profiles during a 50 year time horizon compared to a base case building contracted under the 2008 Finnish National Building Code. LE-50 represents a low energy building, PH-50 represents a passive house and R-60s represents a house that is a renovated energy efficient building. R-80 embodied an existing residential area with low energy profile that does not need any major renovations during the assessed life cycle.

There is no single fact for what is the share of construction phase GHG emissions compared to the use phase, since there is variance between different studies. For example, the share of construction phase emissions is estimated to be nearly 10 per cent of the overall building emissions. (Junnila et al. 2006) However, as Heinonen et al. (2011a) broaches, the share might be largely higher depending on the chosen lifetime of the building (Figure 7). Moreover, in a case study reported by Säynäjoki et al. (2012) the construction phase emissions of a residential area in Finland were nearly 60 per cent within a 50 years' time horizon. As a result, the improved energy efficiency of the residential area during its use phase is beneficial merely after several decades.

Even though, some studies suggest that the construction phase causes a small share of the overall building life cycle emissions to a certain extent, the carbon spike, i.e. high GHG emissions in a short time associated with the beginning of the building's life span (Säynäjoki

et al. 2012) is significantly high , regardless of the overall share of construction phase, as the relatively small time frame is considered. Besides, high energy performance of buildings directly lifts up the share of construction phase emissions thus raising the relative importance of the environmental burden of construction phase, as recently studied, (e.g. Huberman & Pearlmutter 2008; Säynäjoki et al. 2012. Hence, the construction phase in building LCA is often overshadowed and the use phase eclipses the opportunities to reduce other building-related emissions, as Guggemos et al. (2006, p.187) state. Moreover, the construction phase emissions are less regulated than the use phase emissions (Dutil et al. 2011; Casals 2006).

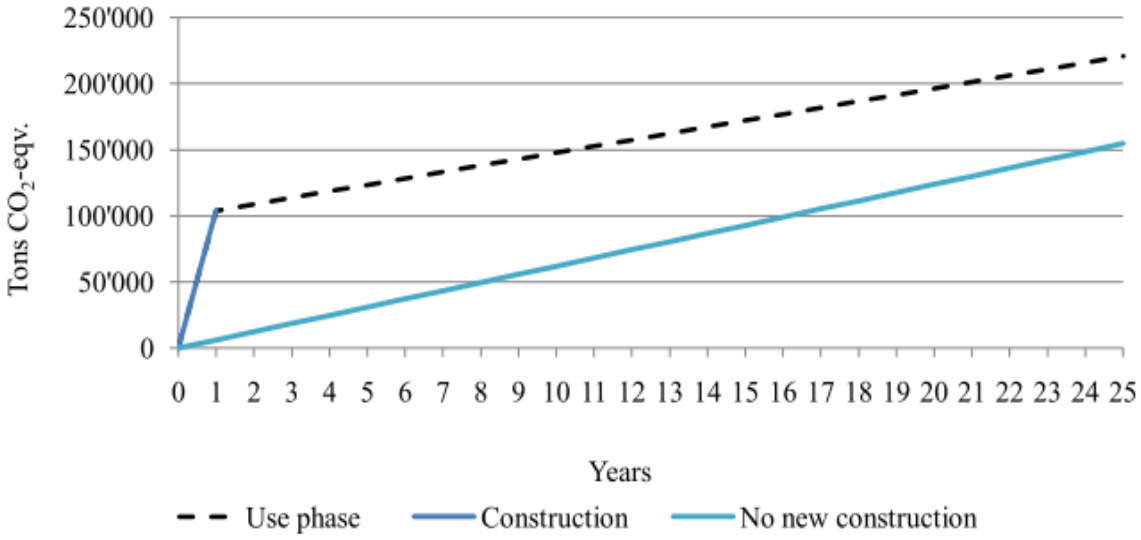

Figure 7 Total emissions of the residential area in Pellaksenmäki, Finland during the 25 years life cycle (Heinonen et al. 2011)

For example, a European case study (Junnila et al. 2006, p.12) resulted that the use phase of the building is the most important phase accounting for 50-90 % of all emissions. In addition, the use phase especially dominates energy use and CO_2 emissions with over 80 %. Ochoa et al. (2002, p.137) also highlight the dominance of the building use phase. In their study the construction phase accounted for approximately 5% of the total energy consumption and over 40% of the economic activity. In addition, the construction phase accounted for over 50% of toxic air releases (TRI) and equal amount of hazardous waste generated as in a use phase. In their study Guggemos and Horvart (2005, p.101) summarize that the environmental impacts of the construction phase encompass 0.4-1 % of the total life-cycle energy use and emissions of a building.

It should also be considered that the chosen life cycles of the buildings affects significantly to the calculated GHG emissions, for the emissions of the building materials and components as well as the construction site only occur on one occasion, as Pasanen et al. (2011) note. Thus, the share of the construction phase emissions depends on whether the life cycle emissions are divided by 25, 50 or 100 years. Nevertheless, the chosen life cycle does not affect the real caused emissions but only calculated emissions and the way of presenting them. A notable aspect is also the fact that the loads of GHG emissions caused by the energy consumption of buildings are entirely unknown and, thus, they may deviate from the recent shares.

Moreover, as reported by Heinonen et al. (2012), in LCAs there generally are no change assumptions made in the emission intensities or the consumption volumes during the building life cycle estimations, excluding assumptions for energy and fuel combustion emissions. For example, technical improvements during the building life cycle may decrease the use of energy thus reducing the GHG emission. Therefore, a chosen life cycle of 100, for instance, increases the error potential of the estimated future emissions, as the becoming changes in energy production are uncertain, as Heinonen et al. 2012 reports. As the technology evolves, the emissions intensities may decrease. However, the scale of the change is unclear, according to Heinonen et al. (2012). Furthermore, as the recent EU wide climate change targets are presented for the years 2020 (European Union 2010), 2030 and 2050 (European Union 2014), estimations of emissions for a 100-year impact time frame might result vague numbers thus either over- or underestimating them if technology or other change coefficients are not taken into account in the analyses.

3.1.1 Significance of the Research

There are two points of views that highlight the importance of construction phase emissions and embodied emissions of the building materials. Firstly, as carbon spike of constructions have been studied the results vary widely due to the truncation error of LCA modelling, thus leading to lower than actual results as Suh et al. (2004) emphasize. Truncation error incompletes the outcomes resulting from the omission of environmental loads on the higher upstream orders of product system, thus leading to a loss of information, as e.g. Lenzen (2001) notes. The upstream flows refer to the extraction of the raw materials and to the manufacturing of semi-products and services used in the production of the analysed final product

systems. In limited LCA models of construction phase emissions the estimated carbon spikes are rather low (e.g. Lenzen & Treloar 2006) whereas there are shortages in more comprehensive models as well, as e.g. Heinonen et al. (2011) conclude.

Moreover, the literature of elaborate LCA models of construction phase emissions is limited. Secondly, most attention has been devoted to the use phase emissions and neglected that the improvements of buildings' energy efficiency directly increase the relative share of the construction phase emissions caused by the additional construction materials, energy production and recovery systems (Dutil et al. 2011, p.406). In their article, as an example, Dutil et al. (2011) showed that there is a need to broaden the acknowledge of the growing importance of the construction phase carbon emissions. Also Gustavsson & Joelsson (2010) state that the minimization of the use phase emissions, does not automatically minimize the life cycle emissions. According to Woolley (2004) this is due to the lack of innovation in the field of construction methods. On the contrary, when the housing stock is designed more energy efficiently, the construction phase accounts for the majority of the life cycle GHG emissions. Hence, as new buildings are designed more energy efficiently the next step is to pay more attention to the growing significance of other life cycle phases.

The thesis represents a case study of a new apartment building in Tampere, Finland, designed to improve energy efficiency during its life cycle, and evaluates the environmental burden on the reference building in detail. In this study a process based LCA structures the basis of the model. Therefore, the paper demonstrates the importance of construction phase emissions as the use phase is designed to be more energy efficient. As Heinonen et al. (2011a, p.1186) suggest the construction phase emissions should be taken into more cautious consideration in order to evaluate whether new residential buildings are expected to reach the climate change mitigation targets.

3.2 Literature Study of LCA within the Construction Phase

LCA is a widely recognized as an innovative method to estimate sustainability in the construction industry throughout all phases of the building life cycle. Several studies have been performed focusing on the environmental evaluation of construction processes, building systems and complete buildings. (e.g. Junnila 2004a; Säynäjoki et al. 2011; Pasanen et al. 2011) However, in this study the main focus lies on LCAs of construction phases. Therefore, this chapter compares the LCA based results and boundaries of the construction phases of 55

different cases. The results of the chosen cases inform more about the characteristics of the LCA methods and less about the chosen materials. Furthermore, there are differences in, for example, building characteristics, sizes, locations and impact methods. Thus, the results are not directly comparable with each other's. Yet, the tendencies can be formed. The indicator used to measure global warming potential (GWP) is CO_2-eq/m^2 thus taking into account the emissions of other GHGs. However, some of the chosen studies use CO_2/m^2 as the indicator.

In order to compare the results, certain alterations were required. At first, if the net floor areas of the case buildings were only published they were modified to gross areas using a constant of 0.7 m^2 of net area per m^2 of gross area, based on Lylykangas et al. (2013) However, the ratio is for residential building, and might not be perfectly accurate, e.g. office buildings. At second, the results of the cases were changed into tons of GHGs per square meter (tCO2-eq/m^2) based on the data provided. The results of few studies estimated from the graphs thus being approximations of the results. Finally, major share of the results chosen for the review reported embodied energy (EE) instead of GHG emissions. Thus, as converting the EE results to GHG emissions EIO-LCA tool of Carnegie Mellon University (2008) was exploited as a reference. According to the EIO-LCA sector "Residential permanent site single- and multi-family structures", the EE-GHG conversion factor is 0,266 kg of GHG emissions per kWh. This figure was also checked to be in line with, e.g. 0,235 kg/kWh of Junnila et al. (2006). However, the alterations among the existing research lifts up the level of uncertainty and comparativeness.

The chosen cases are divided into three different categories according to the methods used or results. The LCAs for the cases in the first and second group are modelled applying a process LCA, whereas the results of the third group are evaluated based on an IO LCA or a hybrid LCA. In addition, the first category contains the buildings that cause nearly 200-500 kilograms of carbon dioxide emissions per a gross square meter (kg CO_2-eq/$m^{2.}$) during their construction phases. The buildings that release CO_2 emissions over 500 kilograms per a gross square meter are part of the second group.

However, it is complex to compare and interpret the reviewed studies in detail due to the lack of definition of what was included within the construction phase analysis, e.g. site work, foundation, level of finishes, building equipment services and furniture. Moreover, as Bilec et al. (2010) report a comparison between the published studies is difficult because the scopes of studied building's' life cycle phase vary. Yet, the most dominant explaining factors

of the results are subjective scope of the research and chosen LCA method, which clarify differences among the results the best.

All in all, the impacts of the reviewed previous studies vary widely. Yet, the results based on each method fluctuate broadly. The highest reported results based on process LCAs are over 980 kg CO_2/m^2 (Passer et al. 2012), whereas the lowest reported emissions among the case studies are 191 kg CO_2-eq/m^2 (Pasanen et al. 2011). On the other hand, the scale among hybrid LCAs and IO LCAs is from 340 kg CO_2-eq/m^2 (Junnila et al. 2006) to 1.900 kg CO_2-eq/m^2 (Säynäjoki et al. 2011).

3.2.1 Process LCA Based Results

Group 1

Pasanen et al. (2011) performed a process LCA on a food framed multi-storey building with passive house energy efficient technology. The data inventory on the study covers all material from foundations to floor surfacing including HVAC services; however, interior furnishing, furniture and household equipment are out of the scope. The scope covers the frame, windows, doors, floor surface materials and building services, such as elevator and ventilation systems. The emissions for the construction phase of the food frame building were approximately 191 kg CO_2-eq/m^2. According to Pasanen et al. (2011), the construction phase of a wood framed multi-storey building with passive house energy efficiency releases 29 per cent less carbon emissions than a similar concrete framed building. The emissions caused by the construction materials are calculated either based on environmental reports or information given by the manufacturer. Comparing the results with a typical concrete framed and three floor apartment building (Saari 2001) the wood framed building releases 13% less carbon emissions.

In his study, Saari (2001) includes to the construction phase all the environmental impacts caused by the material extraction, production of building materials and the construction itself. The input data used to calculate the environmental impacts of the building components was mainly taken from the environmental declarations provided by Building Information Foundation RTS (Building Information Foundation RTS, 2014) Furthermore, Vares (2001), estimates nearly equal results as Saari (2001) for the construction phase emissions of concrete framed apartment building; 203 kg CO_2-eq/m^2

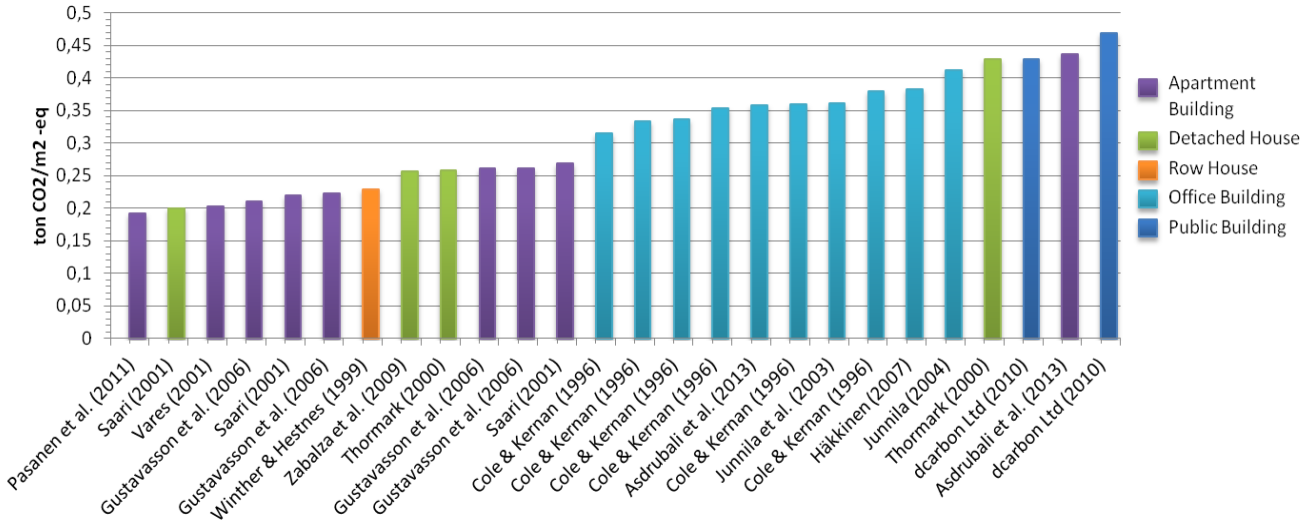

Figure 8 Process LCA based results among existing research

Saari (2001), additionally, modelled the environmental impacts of the construction phase, including global warming and acidification for a typical one floor residential house in Finland. The process based analysis resulted in emissions of 200 kg CO_2-eq/m^2. Zabalza Bribián et al. (2009, p.2510) also performed a process LCA on a single family house in Spain and used BEDEC database for the impact calculations, since it is well adopted to certain features and manufacturing processes of the Spanish building sector. In this study, the construction phase contributes approximately 257 kg CO_2-eq/m^2. The CO_2 emissions linked with the building materials at the construction phase takes into account raw material extraction, transport and manufacturing. In the study of Zabalza Bribián et al. (2009) weights of the most common materials of the building envelope were calculated in order to make LCA calculations. Thus, it does not cover the furniture neither HVAC-systems.

Asdrubali et al. (2013) assessed all life cycle phases for three conventional buildings built in Perugia, Italy during the years 2002 and 2009. The construction phase emissions were calculated for each component, including technical building equipment, and the construction phases include material production phases and building construction phases. The construction phase estimations also contain assumptions on component replacements during the buildings' life span and excavation of the land. The assessed construction phase emissions were 358 kg CO_2-eq/m^2 for a five story office building, 436 kg CO_2-eq/m^2 for a four storey

apartment building and 676 kg CO_2-eq/m^2 for a detached house. All in all, the assessed construction phase emissions represented over 20 per cent of the total life cycle emissions. Thus, the study indicates that the absolute impacts of this phase paper increase alongside the size of the building. Furthermore, Asdbrubali et al. (2013) made different scenarios for the buildings that show how the environmental impacts related to the construction phase grow in importance while the impacts of other phases drop, which is in line with other studies (e.g. Junnila et al. 2006).

As a comparison, Junnila et al. (2003) assessed the GHG emissions of an office building in Finland, which resulted construction emissions of 360 kg CO_2-eq/m^2. The LCI was made in detail, thus, including over 150 building elements and over 50 building materials, only excluding the internal equipment. In their study, the construction materials account for 85% of the construction phase emissions and construction site, including, for instance equipment, electricity, transportation and construction waste, account for 15%. Whereas, according to Junnila (2004b) the emissions of a 9-floor office building were 412 kg CO_2-eq/m^2. In his study almost 130 different building parts and fifty different building material groups were identified in the inventory phase. The energy consumption calculations for the building were performed by an HVAC and electrical design using the WinEtana energy simulation program. The data were taken from the Finnish LCA database for energy, LIPASTO, Eco 1999, Simapro and Boustead.

In addition, Cole & Kernan (1996), examined total life cycle energy of a generic three storey office building with alternative wood, steel and concrete systems either with underground parking or without. The results varied from 315 kg CO_2-eq/$m^2$for a wooden office building without an underground parking to 379 kg CO_2-eq/$m^2$for a steel framed office building with an underground parking space. The assessment is based on energy intensive data of the main components of the building. In addition, the results of Winther & Hestnes' (1999) are calculated based on the energy intensities of the building materials and components.

A company called dcarbon Ltd (2010) published two LCAs of a notional school building with two different beam structures, the results of which were both above 420 kg CO_2-eq/m^2.The assessment included the foundation and structures of the building and excluded, e.g. building equipment services.

Several other process-based LCAs of construction phases were also taken for the review. However, the results were well below the average due to the different assessment scopes. For instance, Börjesson & Gustavsson (2000) and Gustavsson et al. (2006) reported GHG emissions below the average, and their assessments only include emissions caused by the production of construction materials, thus excluding the construction site emissions. Börjesson & Gustavsson (2000) reported emissions of below 80 kg of carbon dioxide emissions per a square meter and Gustavsson et al. (2006) resulted construction phase carbon dioxide emissions of from 220 to 260 kg per square meter.

Group 2

Compared to the case studies in group 1, group 2 consists of case buildings that are energy efficient, which lifts up the construction phase GHG emissions as mentioned earlier in section 2. Furthermore, the scopes of assessments among group 2 are broader compared to the group 1. Passer et al. (2012) analyzed construction phase emissions of five residential building in Austria that represent a range of diverse energy and construction concepts; four of the buildings are low energy buildings and one is a passive house. Thus, all the energy optimizations of use phase improvements have been achieved, as Passer et al. (2012) state. In process LCAs they reported the highest emissions of 982 kg CO_2-eq/m^2. In their study building structures and technical building equipment were analyzed in detail applying EcoInvent database. During their LCI process approximately 2,800 contract items were examined for their LCA relevance and finally the LCI model for the 5 five buildings consisted of 1,700 contract items with nearly 200 different construction products.

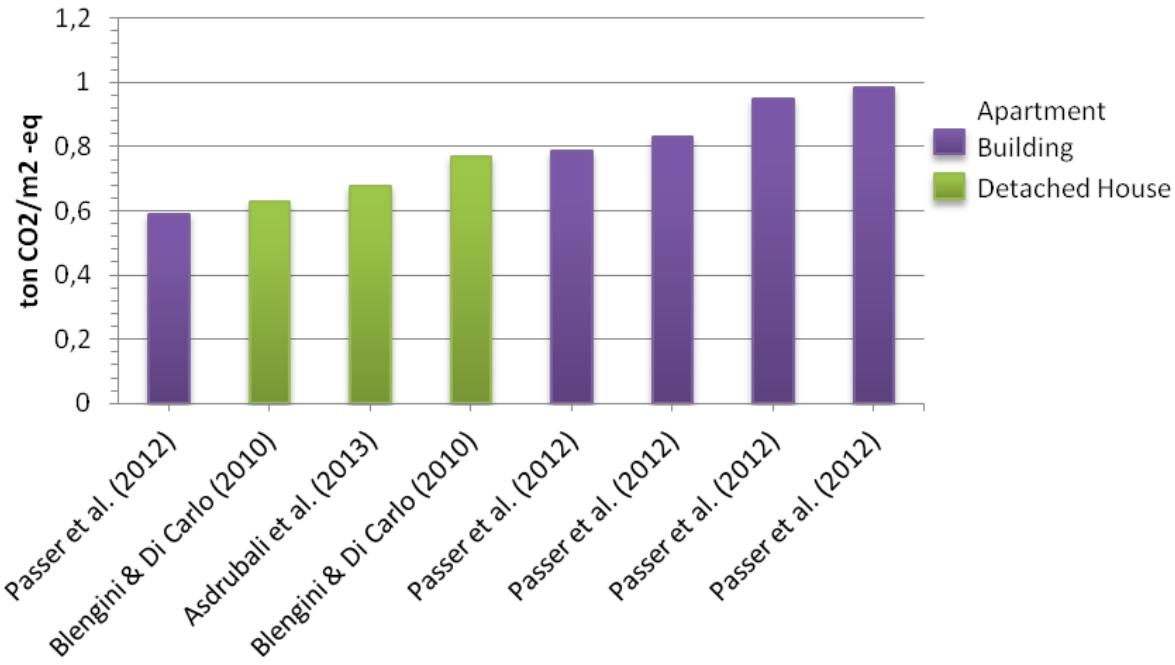

Figure 9 Process LCA based results among existing research

In addition, Blengini & Di Carlo (2010) studied the emissions of a low-energy house and compared to a standard house. In the study, compared to the standard house the energy improvements increased the construction phase GHG emissions by 22%. However, the assessed construction phase emissions include impacts caused by the maintenance thus raising the impact level.

3.2.2 IO-LCA and Hybrid LCA Based Results

Ristimäki et al. (2013) applied both IO and process based LCAs for the modelling of construction phase emissions of residential area in Finland. In the study, costs of the construction phase were utilized in the IO-LCA apart from the electricity and heating. The area in question is the same where the target building of this thesis is located. The GHG emissions of electricity and heating processes were based on their carbon intensities. The area consisted of seven energy efficient apartment buildings, each with a gross area of 3,078 square meters. According to their research (Ristimäki et al. 2013), the construction phase causes GHG emissions of 1,014 kg per a square meter.

Junnila et al. (2006), additionally, performed LCA for two office buildings; one located in Finland and other in the United States. In the study, they applied hybrid- based evaluation for all the construction phase emissions; emissions caused by the materials and material

manufacturing as well electricity production were evaluated applying IO- method, whereas other emissions were process based. The estimated construction phase emissions of the case building in Finland were comparatively 341 kg CO_2-eq/m^2. The office building in the US caused 545 kg of GHG emissions per a square meter. Thus, the Finnish case building causes nearly half less GHG emissions than the US case building, which is due to the difference in the use phase, as Junnila et al. (2006) state. For instance, the energy carries in Finland are less intensive due to combined heat and power production.

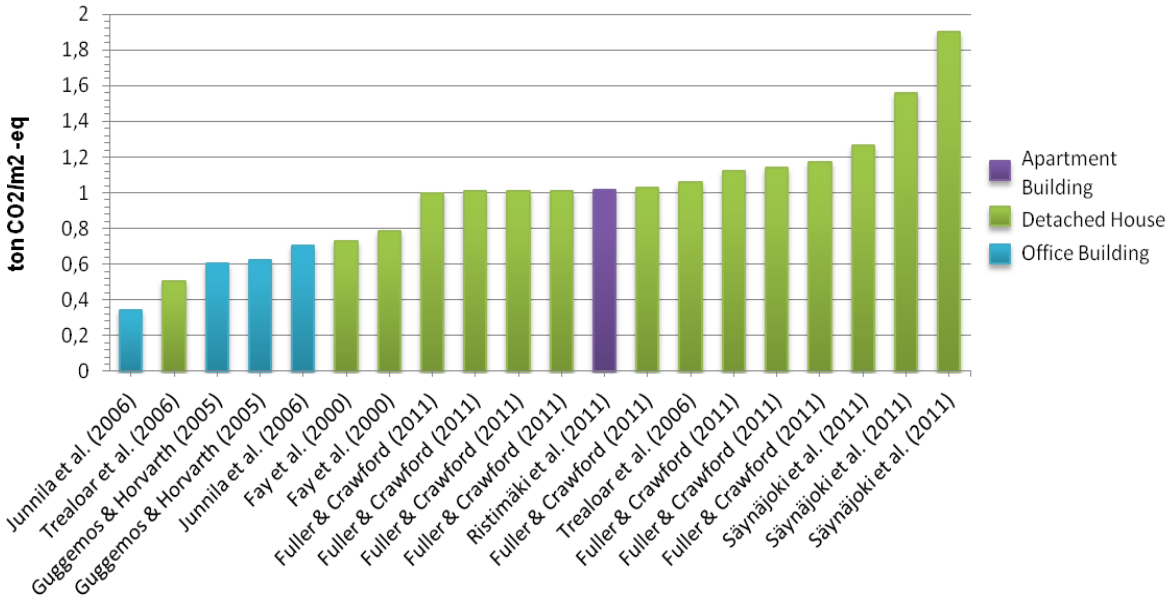

Figure 10 IO LCA based results among existing research

Hybrid LCAs for two standard office buildings have also been reported by Guggemos & Horvarth (2005). Two five-storey buildings with floor area of 4,400 sqm were considered, which were located in the Midwestern US and were expected to be used for 50 years. One of the buildings was steel framed and the other concrete framed. In the study, materials manufacturing phase emissions were assessed through EIO-LCA database, and process-based assessment was applied for manufacturing of temporary materials, transportation of equipment and materials, equipment use, and waste generation on the construction site. The assessed emissions for the steel framed building during the whole construction phase were approximately 502 kg CO_2-eq/m^2 and for the concrete framed building approximately 605 kg CO_2-eq/m^2.

The rest reviewed hybrid or IO- based LCAs are performed for detached houses (Fay et al. 2000; Fuller & Crawford 2011; Säynäjoki et al. 2011). The emissions for the case buildings reported by Fay et al. (2000) and Fuller & Crawford (2011) are based on the embodied energy. The results vary from 729 kg CO_2-eq/m^2 (Fay et al. 2000) to 1,170 kg CO_2-eq/m^2 (Fuller & Crawford 2011). Säynäjoki et al. (2011) applied twice IO based LCAs and one hybrid LCA for a residential area in Finland including 219 houses. In the study the construction projects includes infrastructure and building construction. In the first IO LCA only one construction sector was utilized for the whole project, and the results were the lowest of the three cases, 1,380 CO_2-eq/m^2. In the second IO LCA the construction costs were allocated more precisely between different EIO-LCA sectors. In the hybrid LCA a process data of the most main materials and functions, such as energy, concrete and steel, was utilized alongside EIO-LCA modelling. The reported (Säynäjoki et al. 2011) LCA results were 1,700 kg CO_2/m^2 based on the hybrid LCA, which is 24 % more than from the allocated IO-LCA model due to the difference between local energy provider's carbon profile and the corresponding EIO-sector.

4 Presenting Case Study

This chapter introduces comprehensively characteristics of the building chosen for the study, and also goes through goals and scope of the research. Section 4.3 will thereafter present the LCA methods utilized and section 4.4 introduces the complete process of the study.

4.1 Härmälänranta Case Area

The building chosen for the study is a new low-energy building in Finland with an energy class of A (Skanska 2011). The case building, Pyry, is located in Härmälänranta, which is a former industrial neighbourhood in Tampere, Finland, and is in the process of being redeveloped by Skanska into a new urban district. It is a sustainable residential planning area, approximately 5 km to southwest from Tampere city center. The residential development will be completed in two phases. First phase of Härmälänranta was started in 2007 and the second phase will be completed during the years 2014-2026. (Skanska, 2012)

Figure 1 A picture of the case building located in Härmälänranta, Finland

The first phase of the project includes construction of 18 residential projects, with 450 apartments. The second phase will create approximately 160,000 sqm of mixed-use space, including 1,800 homes. All in all, the purpose of the design process at Härmälänranta was to work towards the sustainable principles and create an enjoyable area to live, work and visit, as well as to encourage developing more sustainable lifestyle choices. Thus, the project focuses on energy, material and water efficiency, and aspires to reduce district carbon emissions. The buildings in Härmälänranta area utilize energy efficient solutions. In addition, the shapes and orientations as well as the building equipment services are designed to improve the low energy usage. Furthermore, the GHG emissions of Härmälänranta residential area have been recently studied by Ristimäki et al. (2013).

Table 3 Characteristics of the Case Building

	Value	Unit
Gross floor area	3 085,50	m^2
Heated net area	2 821,00	m^2
Volume	9 645,00	m^3
Construction year	2012	year
Apartments	28	number

The case building, Pyry, of this research was part of the first phase of Härmälänranta project. It consists of 28 apartments, a gross floor area of 3,085.5 sqm, heated net area of 2,821 sqm and a volume of 9,645 m^3. The construction of Pyry was completed in December 2012. The construction phase lasted nearly 13 months. The characteristics of the case building are presented in table 3 and the second floor layout is represented in the figure 12.

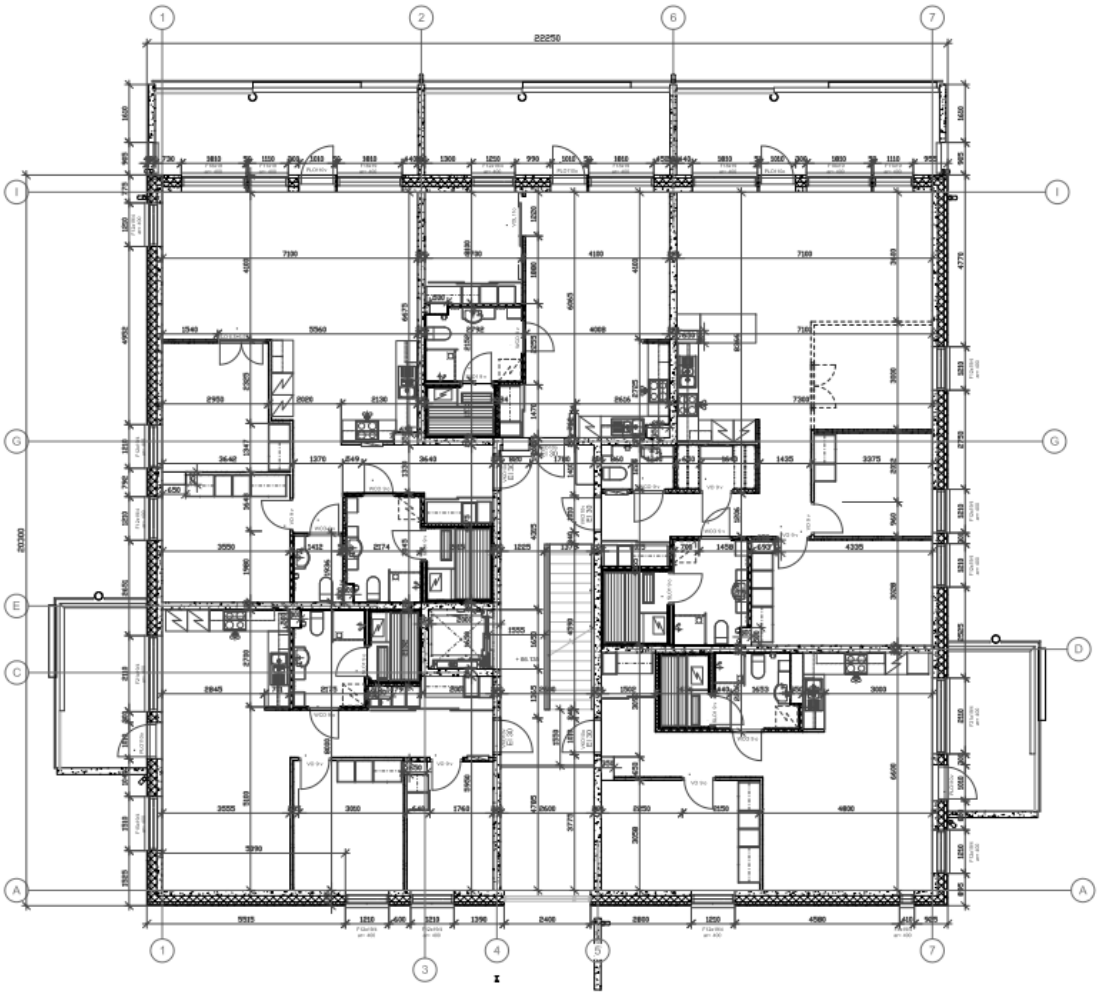

Figure 2 Layout of second floor of the case building

During the construction phase Skanska used materials that are labelled with the emission class of M1. In general, the classification divides building materials into three categories of which M1 is the best, thus standing for the lowest emissions (Building Information Group, 2014). In addition, all the waste produced during the construction phase was recycled and utilized either as material or energy. (Skanska 2011) When developing energy efficient buildings, GHG emissions of buildings, in general, can be reduced through a use of high performance envelope (i.e. insulation, windows and air tightness) together with heat-combined ventilation system, as Harvey et al. (2007) report. In addition, the building utilizes solar energy through photovoltaic panels on the roof. Area of the flat-plate solar thermal collectors is approximately 12 square meters, which has been taken into account during the LCI process. In addition, windows of the building are high performance windows; whole

window U-value < 1 W/m^2/K. Since 2010 the minimum heat transfer coefficient in Finland has been 1 W/m^2/K. (Ikkunawiki, 2014)

4.2 Goal and Scope of the Research

Due to the limitations of similar research, the goal of this study is to accurately and in detail study the construction phase carbon dioxide equivalents, i.e. greenhouse gas emissions of the case building, which carbon footprint has been reduced by architectural design and low impact construction materials (e.g., insulating material).

In the impact assessment the climate change was studied, and it was calculated using SimpaPro software with Environmental Product Declarations (EPD) equivalency factors. The indicator used is GWP, which is measured in kg CO_2-eq/m^2. Thus, the study leaves out the following impact categories: non-renewable resources, renewable resources, acidification, ozone depletion, photochemical oxidant formation and eutrophication.

The developing company Skanska provided budgeted costs and volume data of the materials and estimations of required construction work for the assessment. The received data specified costs and either volume, area, number or running meters of nearly 500 different products. However, all the material and cost information from the data received were not considered in the LCA modelling of the building construction phase. From construction activities the construction site clearing, excavation and construction of outdoor area, including roads, grass area as well as outdoor building equipment (e.g. a sandbox and a flagpole) were not taken into account in the LCA modelling. Also, the use and demolition of different construction molds were left out from the modelling. In addition, five components of the building were left out as a "black box" since the materials and services could not be distinguished from the provided data. However, based on their names and technical drawings, the relative economic costs of the "black box" is minor.

In the first phase the provided data materials was analyzed and modified into requisite units. Thereafter, the global warming potential (i.e. greenhouse gases) of the building was analyzed. Finally, in the last phase of the streamlined LCA modelling (Crawford, 2011) the significant issues were identified and findings were evaluated to reach conclusions and recommendations. Furthermore, the research aims to produce a comprehensive process-based LCA also

taking into account limitations and uncertainties considering process LCA - modelling. The assessment process is described more comprehensively in section 4.4.

4.3 Research Methods

The thesis studies the environmental effects of construction phase of a residential apartment building in Härmälänranta in Tampere by applying a process based LCA method. In the study, process based LCA forms the basis of the analysis and IO-LCA is employed for the budgeted HVAC and electricity systems as well as for products of which there was not adequately specific data available or that were too complex to be modeled applying process based LCA. The database used for the process based modelling was ecoinvent v.2.0 that covers over 4,000 processes (PRé Consultants 2010). The application of IO-LCA method used is the economic IO-LCA (EIO-LCA) provided by the Carnegie-Mellon University (2008). The GHG emissions were modelled using Simparo software. During EIO-LCA modelling it is crucial to choose the most suitable sectors for each material or product.

In order to take into account the currency rate fluctuations and inflation between the present Finnish economy and the US industry 2002 model, the purchasing power parity (PPP) multiplier was used to accurate the output data for the IO-LCA part of the study. The parallel correction has been used by Weber et al. (2008) and subsequently e.g. Säynäjoki et al. (2012) and Heinonen et al. (2012). Since construction phase of the case building was completed in 2012, the PPP multiplier used was 0.93 (OECD, 2014).

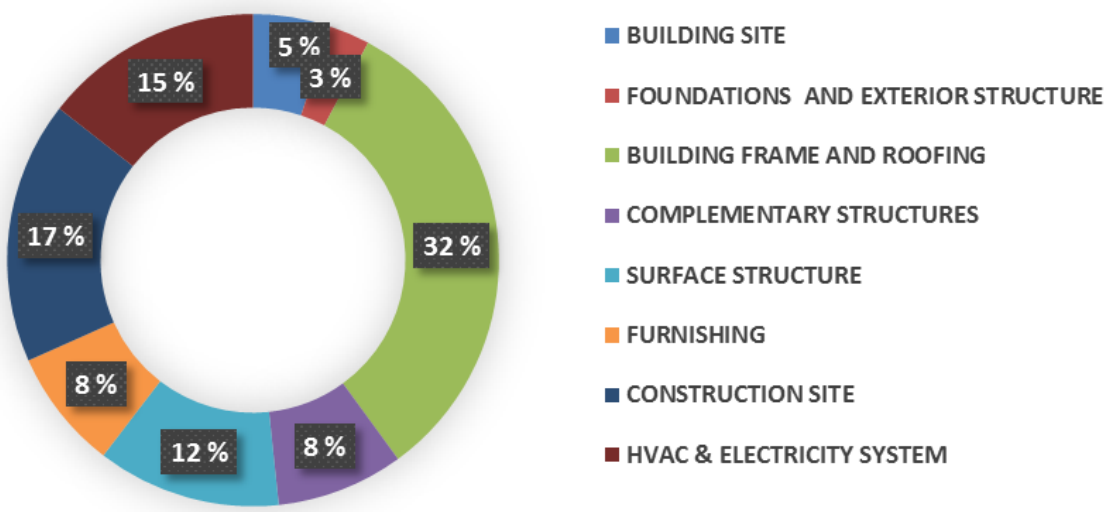

Figure 3 Share of Construction Categories of the Total Budgeted Costs

All in all, the share of products and services in the input-output part of the LCA accounts for approximately 16.7 per cent of the budgeted construction costs, and the share of process data in the construction phase assessment model was 84.2 %. Actual costs of the building service technology and electricity system accounts for 14.4 per cent of the budgeted construction costs, as figure 13 represents, whereas the share of EIO-LCA data considering HVAC and electricity systems in the construction phase assessment is approximately 19.3 per cent of the total GWP. Thus, the EIO-LCA part of the model encompasses less than one fifth of the project's GHG emissions if the HVAC and electricity systems are taken into account.

4.4 Research Process

LCA model of the case building considers the following phase from the figure 4: raw materials extraction, material manufacture and construction. Therefore, the construction phase consists of the whole materials production phase and buildings construction phase. Also, the emissions caused by transportation throughout the phases are considered. In addition, the case LCA model is as detailed as possible, thus taking into account both the comprehensive structure of the building, HVAC and electricity services, as well as the fixed furniture and equipment in the apartments and common areas.

The process inventory data assessment was completed by gathering all available process information. The budgeted material data provided consists of all the materials and work used

in the construction phase of the reference building. The data was divided into eight main construction categories that were divided into more detailed subcategories, as table 4 shows, which were further modeled into product components and materials. These main categories were: building site, foundations and exterior structure, building frame and roofing, complementary structures, surface structure, furnishing, construction site, and HVAC and electricity system. The received data specified costs and either volume, area, number of pieces or running meters of approximately 600 different building components of which ca. 500 were modeled in the construction phase LCA, as explained in section 4.2. For some products, only the costs were specified, which made it more difficult to modify them into accurate ecoinvent units.

Table 4 Construction categories and applied LCA methods

Construction Category		Method Used
1. FOUNDATION		
	Base structure	Process LCA
	Underdrains and pipeages	Process LCA
2. BUILDING STRUCTURE		
	Footings	Process LCA
	Foundation walls and columns	Process LCA
	Bearing ground floor	Process LCA
	Bomb shelter structure	Process LCA
	Special structure	Process LCA
	Exterior structure	Process LCA
3. BUILDING FRAME AND ROOFING		
	Partitioning walls and pillars	Process LCA
	Hollow core slabs and beams	Process LCA
	Stairs	Process LCA
	Exterior walls	Process LCA
	Exterior structure	Process LCA
	Attic floor and roof	Process LCA
4. COMPLEMENTARY STRUCTURES		
	Windows	Process LCA
	Smoke extraction window	Process LCA
	Doors	Process LCA
	Lightweight partition walls	Process LCA
	Special partition walls	Process LCA
	Railings and ladders	Process LCA
	Flues	Process LCA
5. SURFACE STRUCTURE		
	Roofing	Process LCA
	Interior walls	Process LCA

	Ceilings	Process LCA
	Floor coverings	Process LCA
	Saunas	Process LCA
	Paintwork	Process LCA
6. FURNISHING		
	Kitchens	Process LCA
	Hallways	Process LCA
	Walk-in closets	Process LCA
	Bathrooms	Process LCA
	Equipment	Hybrid LCA
	Household appliances	EIO-LCA
	Bomb shelter equipment	EIO-LCA
7. CONSTRUCTION SITE		
	On-site fuel use	Process LCA
	On-site electricity use	Process LCA
	On-site water use	Process LCA
	On-site liquefied petroleum gas use	Process LCA
	District heating	Process LCA
	Transportation	Process LCA
8. HVAC & ELECTRICITY SYSTEM		
	Heating	EIO-LCA
	Plumbing	EIO-LCA
	Automation	EIO-LCA
	Ventilation	EIO-LCA
	Electricity	EIO-LCA

During the inventory of the construction phase the flows of materials related to each building component were defined. These, approximately 500 building components were then divided into nearly 620 subcomponents. Data provided by Skanska considering the case building was, thus, analyzed and modified into the requisite units and ecoinvent classes, as well as grouped in technological units (i.e. construction categories) using SimaPro modelling software. From the worldwide perspective, ecoinvent is the most well-known and acknowledged life cycle inventory database (Frischknecht et al. 2007).

In this study, the lifecycle inventory for the material requirements of the variety of building subcategories (e.g. facade, foundation, exterior walls) within the case building were established mainly using volume estimates of the components (e.g. walls, ceilings, doors) in combination with estimates for the material composition of these components (e.g. of concrete or reinforced concrete) and for the material densities. SimaPro, typically, requires the units

of materials in mass, apart from, e.g. sawn timber and concrete. The material densities used for converting materials into requisite units are provided in table 5.

Table 5 Used material densities

Material	Density (kg/m3)
Brass	7 800
Cement	1 500
Chipboard	630
Chromium steel	7 850
Concrete	2 380
Crushed stone	1 400
EPS	30
Gravel	270
Lightweight concrete	1 400
Mineral wool	40
Paint	1 000
Parquet	620
Plywood	620
Polyvinylchloride	1 410
Propylene	902
Sand	2 000
Sawn timber	450
Stone plate	2 750
Synthetic rubber	1 500
Window glass	2 500

Throughout the inventory phase, architectural and technical drawings as well as components graphs and the provided data of the case building were utilized to instruct with the assumptions and estimations made regarding the volume of components and material compositions.

In order to comprehend the alteration in amounts of materials used during in each construction category, the masses of construction materials per the whole gross floor area of the case building were calculated. These are divided for the construction categories in table 6.

Table 6 Share of masses of the construction materials

Construction Category	Mass /gross floor area (kg/m^2)	Percentage (%)
Building Site	112	1,9 %
Foundations and Exterior Structure	351	5,9 %
Building Frame and Roofing	1 231	20,6 %
Complementary Structures	168	2,8 %
Surface Structure	4 081	68,4 %
Furnishing	20	0,3 %

The share of surface structure (i.e. internal walls, roof, ceilings, floor coverings, sauna structures and overall paintwork) is the highest with a share of 68.4 per cent and building and roofing the second highest with a share of 20.6 per cent. Here, the EIO-LCA based data and mass of the photovoltaic panels were not taken into account. When calculating the masses of materials some assumptions were made about the material densities. For example, the assumed density of concrete was 2.380 kg/m^3, whereas the densities used for sawn timber and plywood were 450 kg/m^3 and 620 kg/m^3. In addition, the masses of window frames and doors were calculated based on the assumption given by ecoinvent.

4.4.1 Research Design of Each Construction Category

Building Site

Building site subcategory encompasses building site structures and reinforcements of the structures as well as underdrains, rainwater wells and pipeages. Underdrains, wells and pipeages are mainly polyvinyl chloride (PVC) and their volumes are calculated based on the provided information of used running meters or quantities and information provided by the product suppliers. Construction site poles are reinforced concrete.

Foundations and Exterior Structure

Concrete and footings comprise the foundation for the case building. The foundation walls are reinforced concrete "sandwich walls". The insulation material used is polystyrene (EPS). Footings of the building are concrete. Normal concrete and reinforcing steel from ecoinvent were used to inventory reinforced concrete throughout the inventory phase. Normal concrete has a density of 2,380 kg/m^3 consisting of 300 kg cement, 1,890 kg aggregate and 190 kg

water. Reinforced concrete with polystyrene insulation is also used for the bearing ground floor construction and bomb shelter structure. The exterior structure modeled comprises a tank for rainwater runoff which is, mainly, made of gravel and filter fabric.

Building Frame and Roofing

Building frame and roofing consists of exterior wall, bearing partitioning walls, hollow core slabs, attic floor, roof and exterior structure, i.e. structure of entrance, terrace and balconies. The exterior walls were both made of reinforced concrete with polyurethane and mineral wool insulation and wooden structure with insulation. In general, polyurethane as the insulation was selected for the case building due to its high thermal resistance, air tightness strength and adhesion, for instance. (PU Eristeet, 2014). All in all, seven different exterior wall elements were modeled with diverse volumes of reinforcing concrete and insulation. Wooden exterior walls contain, for instance, gypsum plaster board, plywood, sawn timber and polystyrene. The bearing partitioning walls are reinforcing concrete and the mineral wool is the insulation material. The form of intermediate floors and attic floor is based on hollow-core slabs. The material volume for stairs and steel beams supports were estimated based on the architectural drawings and provided information by the component producer. The case building consists of six mosaic concrete stairwells. The entrance shelter and terrace comprise the subcategory of exterior structure. In addition, all the 28 apartments have separate glazed balconies with concrete structures that were modeled in detail.

Complementary Structures

Complementary structures encompass windows, doors, partitioning walls, flues and stair handrails. Lightweight partitioning walls are brick, expect for sauna and wet rooms that are steel, as well as for storage space in the basement. The partitioning walls in the storage have wooden frame with wire netting. Wall coverings include wall tiles for e.g. in kitchens and bathrooms. Tiles are inventoried as using the ecoinvent process “ceramic tiles”.

Door and windows are modified into requisite units and right volumes based on provided component graphs with detailed legends. The building has 147 wood-aluminum windows in the external façade with 14 different sizes. The glazed area, window frame area, glass covering, as well as number of windows for each window size were, thus, modeled separately. The glass cover of the windows is estimated to be 3 mm thick and all the windows are triple

glazed thus improving the insulation performance. The wood- aluminum windows are modeled with an ecoinvent process for wood window frames with a U value of 1.5 W/m^2K. In addition, the modelling of the windows covers the window mountings. Also the smoke extraction window on the roof was included in the modelling.

The three outer doors are double glazed doors with aluminum frames. Due to a lack of inventory data on aluminum framed doors, they were considered as aluminum framed windows. One outer door is not glazed and therefore it was considered as wood aluminum door. There are 18 steel doors with 10 different sizes. The steel frames of the doors are extracted from the ecoinvent process "steel, low-alloyed, at plant". In addition, it is assumed based on the technical drawings that all the steel doors have 54 mm thick rock wool insulations. The steel doors have heatproof enamel on both sides, which was modeled by using ecoinvent process "powder coating, steel, at plant". These doors include 28 front doors, 42 bathroom doors, 28 glazed doors for saunas, 71 communicating doors and 4 sliding doors. The 145 wooden doors as well as the doorsteps, mounts and locks were modeled in detail.

Surface Structure

The surface structure include internal walls, roof, ceilings, floor coverings, sauna structures and overall paintwork. The roofing system of the case building consists of, such as bitumen based felt covering, steel wells, polyvinyl chloride under pressure ventilators, steel drainpipes and gutters. Ceiling coverings consists of gypsum base ceiling, metal ceiling, plywood and mineral wool of which volumes were estimated with information in the provided budget data and architectural drawings.

The materials inventoried for floor coverings include for instance, cement mortar, ceramic tiles, moisture insulation and parquet flooring with an area of 1770 square meters. The parquet floor has cement mortar screed and expanded plastic mat underneath. Floor coverings also include the modelling of acoustic insulating plastic carpets on the entrance and corridors. Sauna coverings consists of the walls and ceilings. The wooden walls are insulated with polyurethane and ceilings are insulated both with polyurethane and mineral wool.

Furnishing

Immovable furniture, equipment in balconies, bathrooms, entrance and bomb shelter, and home appliance comprise the furnishing subcategory. Skanska provided detailed technical

drawings of kitchens, bathrooms, hall-ways, walk-in closets, bathrooms and saunas based on which the materials and volumes were inventoried. Thus, the inventory phase of the furniture consist of white lined chipboard shelves and cupboards, including mounts, in all the above-mentioned spaces, sinks in bathrooms and kitchens, water taps, mirrors and toilet seats in bathroom and benches in saunas. There are 7 different layout for kitchens, six different bathroom layouts, two toiler layouts, 9 different layouts for hallways and three layouts for walk-in closets which were all modeled separately based on the technical drawings provided. The building has also 28 saunas with 5 different layout models of the benches that were modeled based on the technical drawings.

Home appliances consist mainly of kitchen devices, i.e. stoves, ovens, freezers, refrigerators, dish washers and devices in saunas; sauna stoves and dry blowers. Due to the material complexity of the devices as well as unavailability of the respective environmental impact data all the home appliances were modeled with EIO-LCA. Additionally, the bomb shelter equipment were modeled applying EIO-LCA. Freezers and refrigerators were converted into carbon emissions with EIO-LCA sector 'Household refrigerator and home freezer manufacturing', whereas sector 'Household cooking appliance manufacturing' was used when converting stoves, 'Industrial process furnace and oven manufacturing' for the ovens and sector 'Other major household appliance manufacturing' was used for the dishwashers and sauna appliances. The equipment in balconies and bathrooms include drying racks, hooks, glazed shower walls and rails. In addition, the name boards in the entrance, polyvinyl chloride carpet in the vestibule and a mirror are modeled into prerequisite encoinvent units.

Construction Site

Six main processes and materials emerged from construction site data: transportation, construction equipment in terms of diesel usage, on-site energy usage, on-site liquefied petroleum gas usage and on-site water consumption. It is important to note that this transport is for the building material from the final supplier to the construction site. To obtain the impact of transportation from the plants to the building site, the provided costs of transportation were used, which accounted for over 20 thousand kilometers. Transportation was modeled with a 28-ton truck. Total ton-kilometers were determined by multiplying the total loaded truck weight by the transported kilometers. For all the products, transport distances in the background data of Simapro remained unchanged.

Modelling of on-site energy usage, including electricity and district heating, water and liquefied petroleum gas usage of the construction phase was based on the provided data by Skanska. Also the estimations for the fuel used at the construction site are calculated based on the reference data.

HVAC and Electricity System

HVAC, electrical, plumbing and lighting system equipment and furniture have been included in the model applying EIO-LCA. During the construction phase of the case building heating, water, atomization, electricity and ventilation systems were put into action by subcontractors. Developing company provided the actual costs that were divided into three subcontracts that were ventilation work, electricity work and a subcontracts that included heating work, plumbing work and atomization work. In order to convert heating, plumbing and automation into precise EIO-LCA sectors the provided subcontract costs were divided by three. Hence, the shares of heating, plumbing and automation were each 11.5 per cent of the input-output part of the LCA. These were, thereafter, converted into carbon emissions with the following sectors: Heating Equipment (except Warm Air Furnaces) Manufacturing, Pump and Pumping Equipment Manufacturing and Automatic Environmental Control Manufacturing for Residential, Commercial, and Appliance Use. Electric Lamp Bulb and Part Manufacturing was the sector chosen for electricity subcontract and Air Purification Equipment Manufacturing sector was chosen to model ventilation subcontract.

5 Results

This chapter presents the results of the GHG assessment of the construction phase of the case building. This chapter, also, presents alternative results if the case building was a standard "business as usual building", during of which construction phase more conventional insulation materials were used. The alternative assessment is performed in order to determine whether an energy efficient residential development in the construction phase can gain from environmentally sustainable choices.

5.1 Greenhouse Gas Emissions of the Apartment Building during the Construction Phase

Life cycle carbon emissions of the construction phase of the case building are 1.684,0 tons of CO_2 equivalents, which accounts for approximately 808 kg of CO_2 equivalents per gross floor area. If HVAC and electricity systems were not taken into account in the LCA the global warming potential of construction phase of the case building would be 652 kg of CO_2 equivalents. Thus, the share of HVAC and electricity systems is 19.3% (325.000 kg CO_2-eq/m^2) Furthermore, if foundation and exterior structure of the building were left out from the assessment, the global warming potential of the construction phase of the case building would be 749 kg of CO_2 equivalents. The most significant source of carbon dioxide equivalents of HVAC and electricity system is the construction of ventilation system. The share of ventilation of the HVAC and electricity systems is around 8 per cent. Figure 14 shows how the caused carbon emissions of the construction phase of the case building are divided between each construction category.

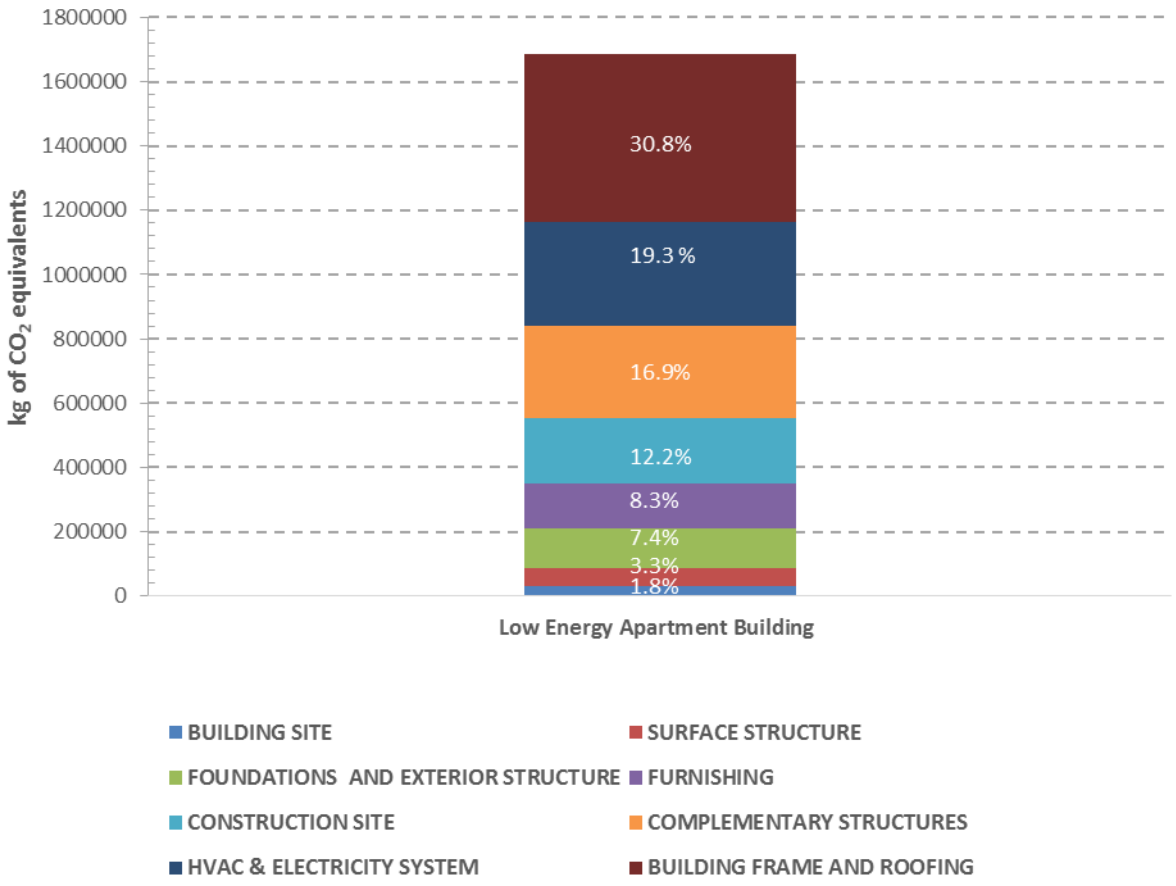

Figure 4 Shares of construction categories of life cycle carbon emissions of the construction phase of the case building

During the construction phase the largest source of carbon emissions is building frame and roofing with a share of 519.000 kg of carbon dioxide equivalents (30.8%). The second most significant source is HVAC and electricity systems that account for 519 000 kg of carbon dioxide equivalents (19.3%). The third major contributor of carbon dioxide equivalents is complementary structures, in other words windows, doors, partitioning walls, flues and stair handrails of the case building with 285.000 kg of CO_2 equivalents (16.9%). The share of construction site is 205.000 kg of CO_2 equivalents (12.2%). Besides, the transportation causes over 60% of the construction site emissions.

Furnishing accounts for shares of 140 kg of CO_2 equivalents (8.3%). Foundations and exterior structure of the case building account for 7.4 per cent of carbon emissions that encompass 124 tons of CO_2 equivalents. Rest of the construction categories comprise 86 000 CO_2

equivalents, i.e. 5.1 per cent of the total construction phase carbon emissions. Surface structure of the building causes 3.3 per cent of the total carbon emissions and building site, i.e. base structure, underdrains and pipe ages, accounts for 30.7 tons of carbon emissions (2.1%).

Transportation emissions against the caused carbon dioxide emissions of materials during the construction phase are 7.5 per cent solely. Subcategories that cause the largest single shares of carbon dioxide equivalents are hollow core slabs and beams with a share of 11.8 per cent, exterior walls with a share of 10.5 per cent and lightweight partition walls with a share of 10.0 per cent. The share of electricity subcontract is 4.8 per cent of the carbon dioxide equivalents. All the other subcategories, expect ventilation subcontract and transportation account for less than 4.0 per cent of the life cycle carbon emissions of the construction phase.

5.2 Greenhouse Gas Potential of a Business as Usual Apartment Building

The additional LCA was modelled in order to find out how specific changes in materials or their volumes would affect the caused GHGs of the case building. The alternative life cycle assessment of the case building applies the same methods and provided material data. However, during the assessment some of the materials or material volumes of the case building were changed in order to modify the reference building thus exemplifying a "business as usual apartment building". All the input modifications are based on discussions with Research Manager Juha-Matti Junnonen from Built Environment Services (BES) -Research Group at Aalto University (Junnonen 2014/12/08).

In standard apartment buildings mineral wool is a common insulation material. Thus, contrary to the case study, during the construction of the business as usual apartment building mineral wool is the dominant insulation application in the exterior walls for which polyurethane as the insulation was selected due to its high thermal resistance, air tightness strength and adhesion.

When replacing polyurethane insulation material into mineral wool, the insulation thickness was assumed to increase by 100 millimeters and the density of mineral wool was assumed to be 40 kg per cubic meter. Furthermore, as the thickness of the insulation material grows

the thickness of exterior walls, respectively, expands. Therefore, due to the increase of insulation material in exterior doors, the area of the metal sheets at the attic floor and below the façade windows are larger than for the parallel but low energy building. Area of the metal sheets are assumed to increase by 50 per cent. Also, since the building a conventional apartment building, there are no photovoltaic panels on the roof to utilize solar power neither does it have an underground tank for rainwater runoff, which were excluded from the provided construction material data.

Yet, as the HVAC and electricity systems were executed as a subcontract, the costs information within the sector was not modified. However, due to the energy efficient targets the costs of the case building's HVAC and electricity construction and e.g. bathroom furniture may be higher than for the business as usual building. For example, the apartments have separate meters and display units to control consumption of hot and cold water in real time, and all the water equipment in kitchens and bathrooms are designed to optimize the water consumption (Skanska 2011). The case building is also equipped with a heat recovery ventilation (HRV) system thus reducing energy requirements for heating by reusing the heat that is normally lost via conventional system. HRV is also more expensive to install compared to a conventional system. (Harvey et al. 2007) Since the costs of equipment and HVAC and electricity services were not modified in the alternative LCA, the level of uncertainty of the scenario analysis is high. Figure 15 shows how the caused carbon emissions of the construction phase of the business as usual apartment building are divided between each construction category.

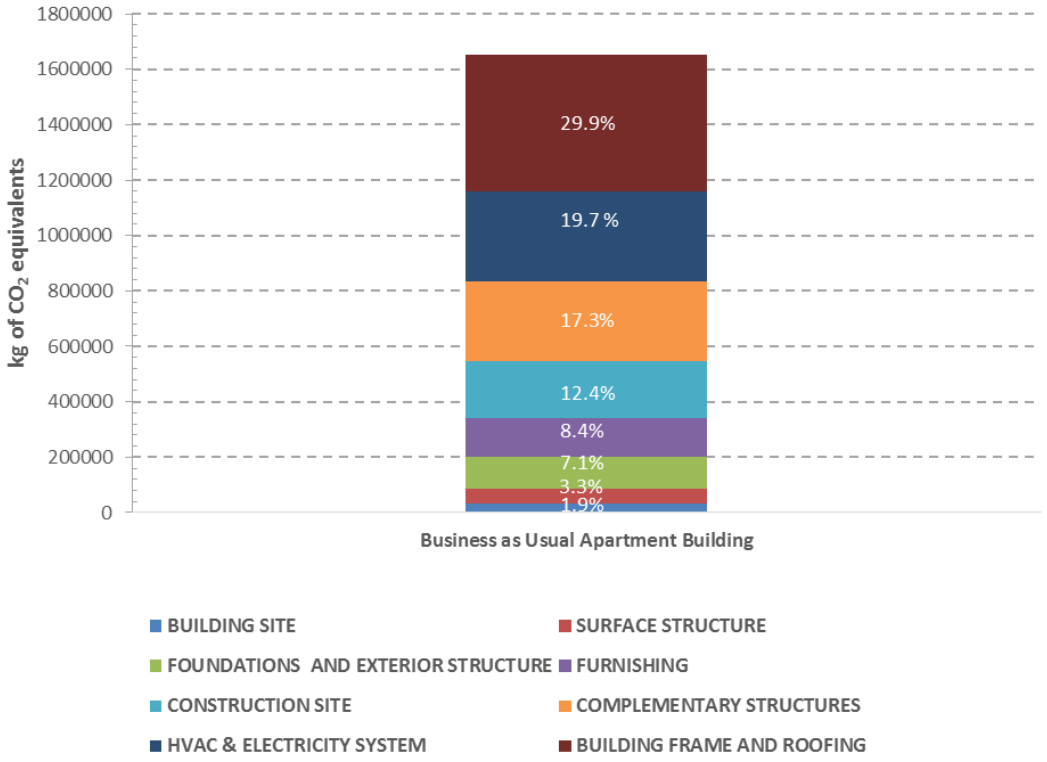

Figure 5 Shares of construction categories of life cycle carbon emissions of the construction phase of the business as usual building

Life cycle carbon emissions of the construction phase of the business as usual apartment building are 1.652,0 tons of CO_2 equivalents, which account for approximately 793 kg of CO_2 equivalents per gross floor area. Thus, construction phase of the business as usual apartment building causes ca. 2 % less carbon emissions, that accounts for approximately 15 kg of CO_2 equivalents per gross floor area, than the low energy apartment building as the above mentioned material replacements and exclusions have been taken into account. The resulted life cycle carbon emissions by each construction category of the construction phase of the business as usual building compared to the low energy case building are additionally represented in table 6.

Table 5 Resulted life cycle carbon emissions by each construction category of both buildings

Construction Category	Business as Usual Apartment Building Global Warming (GWP 100) tons kg CO2	Low Energy Apartment Building Global Warming (GWP 100) tons kg CO2
Building Site	30,7	30,7
Surface Structure	55,3	55,3
Foundations and Exterior Structure	117,0	124,0
Furnishing	140,0	140,0
Construction Site	205,0	205,0
Complementary Structures	285,0	285,0
HVAC & Electricity System	325,0	325,0
Building Frame and Roofing	494,0	519,0
Total	1 652,0	1 684,0

The exclusion of the rainwater tank reduced the carbon emissions of construction of building structure by 7 tons of CO_2 equivalents. In addition, due to the replacement of insulation material into mineral wool and a 50 per cent increase in the metal sheets area at the attic floor (i.e. window ledge), construction of exterior walls caused approximately 15 per cent less carbon dioxide equivalents than construction of exterior walls of the case building. The 50 per cent increase in the metal sheet below the façade windows lift up the caused carbon dioxide equivalents by 200 kilograms. Since the units reported in Simapro are round down to thousands the changes that caused a smaller alteration in the caused emissions have not changed the overall reported carbon dioxide equivalents. The exclusion of photovoltaic panels and volume growth of metal sheets on the attic floor, additionally, reduced the carbon dioxide emissions by around two tons compared to the low energy case building.

6 Interpretation of the Results

This chapter will compare the results of the case building and earlier modelled LCAs based on the results that were examined in the section 3. This chapter will, therefore, find reasons behind the differences in results and analyse how comparative the studies are. In addition, fluctuations in the results, which the data left outside the assessment boundaries may have affected, will be studied in this chapter.

Since the data examined was obtained from diverse sources, the quality of the data used in this study and uncertainties behind the performed LCA will be analysed, thus giving a conception of the reliability of the results. Also, a sensitivity analysis is completed to clarify how sensitive are the assumptions and how changes in the input data might alternate the results. The uncertainties and sensitivity analysis of the results are discussed in the following chapter.

6.1 Comparison to Earlier Performed LCAs

When positioning the study among the existing research within process LCAs of the construction phase, only few studies resulted higher carbon dioxide emissions per a square meter, as shown in figure 16.

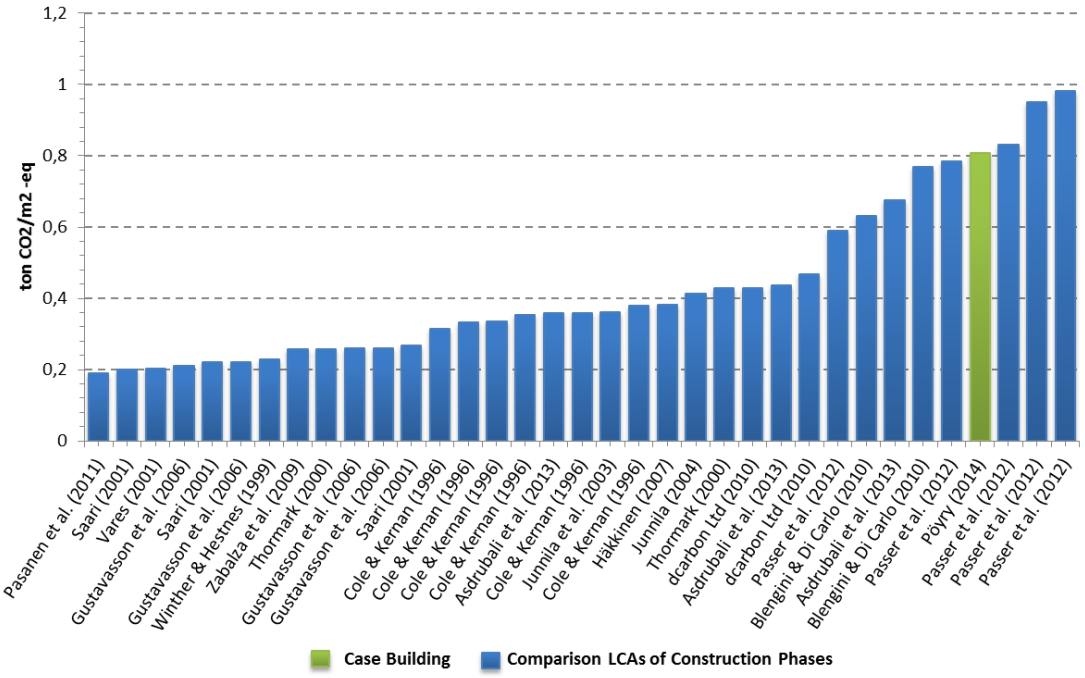

Figure 6 Case building results within the existing research that applied process LCAs

The results are in line with the results earlier reported by Passer et al. (2012). In his study, five LCAs of construction phase emissions were performed; four of them were applied of low energy buildings and one of a passive house. Their study contained about 200 different construction products which were divided into building fabric, technical building equipment and finishing work of which all were analysed in detail. Compared to the case building in

this thesis, Passer et al. (2012) did not include furnishing in the LCI phase, whereas it contained excavations and onsite overhead work that were not taken into account in the LCA of the case building's construction phase.

Blengini et al. (2012), additionally, performed a detailed process LCA of a low-energy building located in Italy which resulted relatively higher results than most of results of existing research. Most of the earlier studies (e.g. Junnila 2003; Fuller & Crawford 2011) did not take technical building equipment, i.e. HVAC and electricity systems, into account which is a major deficiency of LCAs thus leading to lower results. However, the results are challenging to compare due to their specific characteristics, comfort requirements, local construction techniques, local regulations, site-specific climate conditions and used LCA database, as Buyle et al. (2013) and Blengini et al. (2010) point out. Also, there are assumptions and additional refinements made during all the LCA models thus generating uncertainties. Therefore, the results of a LCA among the building sector should not be generalized. Furthermore, there are different ecoinvent database versions used among the literature of building LCAs which increase level of uncertainty when comparing the results. For example, Passer et al. (2012) used ecoinvent version 2.1 and Asdrubal et al.(2013) used ecoinvent version 2.3, whereas in this study ecoinvent version 2.0 was used. As the ecoinvent datebase versions are updated new dataset have been implemented and changes are made in e.g. impact assessment methods, as Weidema & Hischier (2010) note. However, the results are well in line with the most recent and most comprehensive studied among the field. Also, the scope of the assessment is a distinctive factor then comparing the results. As outlined in section 5, if HVAC and electricity systems were not taken into account in the LCA the global warming potential of construction phase of the case building would be approximately 24 per cent lower. In addition, if the foundation and exterior structure of the building were left out from the assessment, the global warming potential of the construction phase of the case building would be around 8 per cent lower.

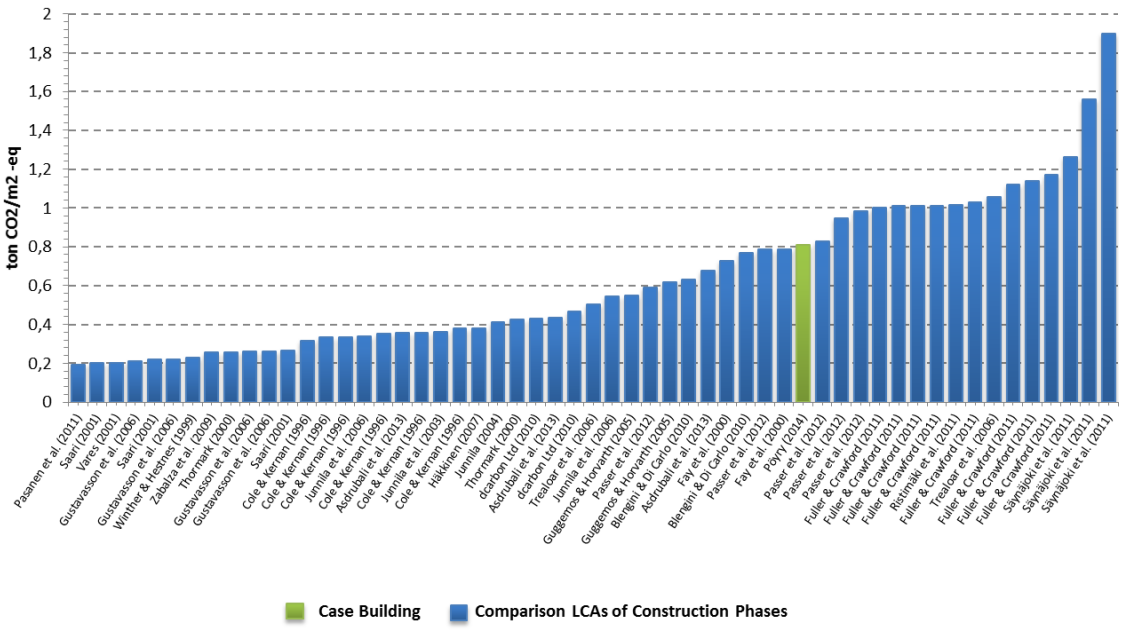

Figure 7 Case building results within the existing research of construction phase emissions

When comparing the obtained results to existing research of LCAs on the field of process LCAs, IO-LCAs and Hybrid LCAs, most of the cases among IO and Hybrid LCAs result in carbon dioxide emissions that are higher than construction phase of the case building, as shown in figure 17. There are two reasons why the case study is more in line with the EIO and Hybrid LCAs. At first, the case building is a low energy building, thus causing a relatively high carbon spike in a short time period and possibly dominating the life cycle emissions of the building, as Buyle et al. (2013) report. In addition, due to the truncation error within process LCA the results of IO and hybrid LCAs tend to be lower than actual results, as Suh et al. (2004) emphasize. However, since over 16,7 per cent of the budget of the entire building was modelled applying EIO-LCA, which accounted for over 19 per cent of caused carbon dioxide equivalents, the method used in the study is rather a hybrid LCA. Thus, the second explanation why the results are more in line with IO and Hybrid LCAs, i.e. higher than if only a process LCA was used, is that since the process method used in the study was supplemented with IO LCA part that does not suffer from truncation error.

6.2 Uncertainties of the Modelled LCA

One problem associated with the study is related to the scope of the research. The defined goal of the research was to examine the GHG emissions of the construction phase of the case building. However, subjective choices had to be made about the products that were included

in the assessment or excluded. For example the furnishing was included but excavation work was excluded. In addition, the provided data by Skanska was modified into requisite units applying area and volume calculations based on the architectural drawings. Therefore, all the used inventory data represent estimations. Also, the material densities applied in the assessment have been taken from a variety of different sources, which adds uncertainty into the model.

There are also uncertainties related to the initial cost data provided by the developing company. The provided costs of the case building construction were budgeted expect for costs of the HVAC and electricity systems that were put into practice by subcontractors. Uncertainties related to initial data are not likely to significantly affect the results, since the costs data may have both under- and overestimated the actual costs.

Another limitations involves the transport distances related to various building products. Even though the actual suppliers of the numerous products and the import locations would be known, it was not possible to take it into account in the LCA modelling. Moreover, it should be pointed out that provided data of the case building is based on the budgeted costs, except for the HVAC and electricity system for which the provided data included actual costs. Therefore, due to the costs estimations the results are subjected to uncertainty.

Moreover, the benefits of green material product manufacturing of the construction materials was not possible to include in the assessment. For example flues of the building were made of green concrete that reduces the GHG emissions of the concrete from 20 to 50 per cent (Rudus, 2014). If the green concrete had been modelled more comprehensively, the resulted GHG emissions might be lower.

Moreover, since IO part of the case LCA struggle with aggregation error arising from aggregation of several potentially different industry sectors into each IO table sector, the results may be either under or overestimated. Further, since the number of different sectors in the IO LCA part is 12 the aggregation error among the IO LCA is a significant factor, as Su et al. (2010) suggest. EIO-LCA hybrid model as the assessments were carried out using the US economy based model and a Finnish cost data with purchasing power parity adjustment.

The share of EIO-LCA, which is 16.7 per cent of the overall construction costs, is based on the US economy. Thus, the use of US economy model in a Finnish context, additionally,

increases the level of uncertainties in the results. However, Heinonen et al. (2011) claim the EIO-LCA method is suitable in Finnish context.

Construction phase emissions depend highly on the construction components and materials being used. Construction components and materials in the case study are quite comparable in northern European countries where the climate-conditions and construction practises are quite similar. However, the conclusions of the thesis should not be generalised when the climate and construction practices differ from the conditions in Finland.

It must, also, be remarked that according to Ortiz et al. (2009) and Haapio and Viitaniemi (2008), due to data limitations and large range of construction techniques and material choices, none of the LCA tools and databases are currently capable of modelling a complete building or computing the environmental impacts from all life cycle phases and processes due to the truncation error.

6.3 Sensitivity of the Results

The database used for the process LCA, ecoinvent, includes consistent LCI data, which is valid for Swiss and other European conditions, as Frischknecht et al. (2005) claim. The processes in ecoinvent represent the average technology in operations, which may not be the actual practice in Finnish conditions. Further, as they note, in some cases, processes cannot be with real, country-specific data, and thus assumption are required, which may distort the actual results.

The results are highly sensitive to the specific ecoinvent sectors selected for the construction components and materials. Moreover, there are several different sector options for a single material, which may affect the results. For example, for sawn timber in the exterior wall element ecoinvent suggests 17 different sectors and the selected sector was "Sawn timber, softwood, planed, air dried, at plant/RER S". If some other sector were selected, the results may have changed.

The study leaves out some of the construction site activities due to the lack of provided data. Therefore, whether the carbon emissions of the construction site activities were modelled more systematically the carbon dioxide equivalent load of the construction phase would have increased, thus improving the modelled LCA. Concerning the construction site activities, the study did not take into account temporary work and ancillary at the construction site. These

include e.g. site offices, temporary infrastructure, lifts, fences, construction shielding and scaffolding.

Moreover, the emissions caused by ground works and landscaping, i.e. treatment of extracted soil and material transported to the site and used in ground works were out of the scope of the construction site as a part of the LCA assessment. Environmental impacts of waste material and waste management were neither covered in the analysis. If groundwork and landscaping, temporary work and ancillary and wasted material were included the construction site modelling, as assessed by Hellsten (2012), the construction site carbon dioxide equivalents would increase by approximately 0.41 tons of CO_2 emissions. In her study, Hellsten (2012) modelled construction site emissions for three different office building projects, of which case 3 was utilized above since it did not include underground parking and it represented an average office building.

Furthermore, if ENVIMAT IO model was used as secondary data for modelling the GHG emissions of construction of HVAC and electricity systems, the GHG emissions would decrease by approximately 52 kg of CO_2 equivalents per square meter, i.e. by 6.4 per cent. The sector selected to model HVAC and electricity system was 'house building'. In this model GHG emissions include fossil carbon dioxide, methane, nitrous oxide and other greenhouse gases that are thus converted into carbon dioxide equivalents. ENVIMAT (Seppälä et al. 2009) is a model that is based on IO matrices in the Finnish economy developed in 2009. Thus the ENVIMAT data is based on more accurate and localized data than ecoinvent when assessing a Finnish product or process.

7 Conclusions

The purpose of the study was to analyze the environmental burden produced in a construction phase of a low energy building located in Tampere, Finland. Recently it has been studied that energy performance of buildings directly lifts up the share of construction phase emissions thus raising the relative importance of the environmental burden of construction phase (e.g. Huberman & Pearlmutter 2008; Säynäjoki et al. 2012). Hence, the topic of the case study of this thesis is significant, thus focusing on the construction phase emissions. The indicator used to study environmental burden is GWP, which is measured in kilograms of carbon dioxide equivalents. The case study was conducted by using the process LCA method

to examine the GHG emissions of the construction phase, which was accompanied by EIO LCA.

In terms of hybrid LCA modelling, the complemented process LCA proved to be effective in modelling the construction phase and allowed for efficiently combine process and EIO based material data. In the case study, majority of the EIO-LCA part encompass technical building equipment. According to Bilec (2007) it is important to include especially construction service sectors in to economic input-output results in construction phase LCA modelling.

In addition, the study compares the results of the case building with similar but "a business as usual building" where more traditional construction materials were used. Therefore, the study, additionally, aims to answer the question: "Do the material choices made in the construction phase have the potential to mitigate the caused greenhouse gas emissions of the building?"

The results of the study indicate that the environmental burden of the construction phase of the case building is 808 kg of CO_2 equivalents per gross floor area. The most dominant construction phase contributors to the climate change are building frame and roofing with a share of 30.8 per cent and HVAC and electricity system with a share of 19.3 per cent. Additionally, if the building was not designed to reduce energy consumption during its use phase, the construction phase would have caused 793 kg of CO_2 equivalents per gross floor area. Therefore, the energy efficient residential development does not benefit from the environmentally sustainable choices during the construction phase. This emphasizes further the significance of a comprehensive life cycle assessment of the emissions regardless of the life cycle phase. However, there are uncertainties concerning the alternative LCA results, due to which the results may be too high for the business as usual building.

Sensitivity analyses were performed to test reliability and robustness of the study's results and assumptions behind the selected ecoinvent sectors and material volumes. The first sensitivity analysis increased the construction site carbon dioxide equivalents by approximately 0.41 tons of CO_2 emissions. The second sensitivity analysis increased the construction site carbon dioxide equivalents by around 6.4 per cent.

A study like this always includes subjective assumptions, additional refinements and other probable sources of insufficiency that may lift up the level of uncertainty of the results. One of the identified sources of uncertainty is related to the subjective choices made about the

products that were included in the scope of the research and subjective estimations of the material volumes or densities. Another limitation concerns the overall transportation of the products. Moreover, during the assessment, it was not possible to modify the used materials so that they were energy efficiently produced, which increase the uncertainty level of the results.

Furthermore, regardless of the limitations and uncertainties of the study, the results are in line with earlier studies within the field. Thus, this study supplements the existing study of the construction phase emissions, especially when the linchpin is energy efficient building. However, since this study represents a single case of construction phase LCAs it is unjustified to make any generalizations based on the results. Nevertheless, the study is a powerful source to further investigate the life cycle GHG emissions of low energy buildings.

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