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Life Cycle Assessment (LCA) for an apartment project in Nardovegen

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Abstract:

Life Cycle Assessment (LCA) is a holistic method that is, nowadays, the most used framework to calculate the potential environmental impact of any type of product, with no limit regarding geographic location, function or time. Many different available software aim to facilitate the assessment of this type of study and, for the specific case of this master thesis, SimaPro has been finally used given that it includes EcoInvent, one of the most complete and updated databases.

The present study assesses the LCA for a set of three buildings included in a new apartment project in Nardovegen, Trondheim. Specifically, it puts special attention on the construction phase of the building, including the production of all materials, their transportation to the construction site and all construction activities. On the other hand, it also contributes in the increase of the available bibliography regarding building LCA, which is not really extensive due to the complexity of the product considered.

First, a literature review has been performed in order to establish the main guidelines when carrying out a building LCA and also a detailed description of the methodology that has been followed is presented, always referencing the corresponding ISO standards. When assessing the analysis for the case of study, all these points have been considered in order to ensure the reliability of the results obtained.

Finally, the overall results show that the total environmental impact regarding the climate change impact category of the system considered is 1.618,9 kg CO_2-eq per FU and it is found that the major contributors are the concrete production processes and the energy consumption during the operation phase. Therefore, specific sensitivity and uncertainty analysis are carried out in this sense to finally be able to establish recommendations and possible improvements for future assessments.

Keywords:

1. Life Cycle Assessment
2. Building
3. Climate change
4. Environmental impact

Summary

Construction industry has been considered as one of the most resource-consuming for long time and hence also one of the least sustainable industries in the world. Nevertheless, we cannot renounce to it as our society continues to depend on many different types of buildings such as homes, offices, shops or hospitals. Building and infrastructure constructions damage the environment in two main ways: by consuming resources and by producing waste and pollution. Specifically, construction industry contributes with the 40% of the total energy use, 30% of the energy-related GHG emissions, approximately 12% of the water use and 40% of waste production (UNEP, 2015).

This point of view has produced a considerable increase of the awareness of the need of an industrial development towards sustainability and a lack of appropriate and reliable tools for evaluating the environmental impact has been found. In this way, Life Cycle Assessment (LCA) has been recognized as a robust and powerful methodology to analyse the potential environmental impact through the complete life cycle of a product.

As a master exchange student in the Department of Civil and Transport Engineering (BAT) of the Norwegian University of Science and Technology (NTNU) in Trondheim, the main goal of my Master Thesis is to assess the environmental impact of a new project of apartments in Nardovegen applying LCA methodology. This thesis contributes in increasing the literature regarding LCA of Norwegian buildings and paying special attention on the impact produced during the construction phase, including also all material production processes.

I would like to thank you my supervisor in NTNU, Amund Bruland, for his continuous advice and support and Rolf André Bohne for the support with SimaPro software.

Norwegian University of Science and Technology

Trondheim, June 2015

Sílvia San Elias Portet

Resum

En els darrers anys s'ha produït un important increment en la consciència social sobre la necessitat d'un desenvolupament sostenible de les noves tecnologies i s'ha descobert una important falta d'eines apropiades i fiables per a l'avaluació de l'impacte ambiental. D'aquesta manera, l'Anàlisi del Cicle de Vida (ACV) s'ha reconegut com una metodologia robusta que permet l'anàlisi de l'impacte ambiental al llarg del cicle de vida complet d'un producte.

Com a estudiant d'intercanvi a la Norwegian University of Science and Technology (NTNU), a Trondheim, l'objectiu principal d'aquest Treball Final de Màster és avaluar l'impacte ambiental d'un nou projecte d'apartaments a Nardovegen (Trondheim) aplicant la metodologia de l'ACV. Així, aquesta tesina contribueix a incrementar la bibliografia disponible referent a l'ACV d'habitatges a Noruega, posant especial èmfasi en la fase de construcció.

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List of abbreviations

A	Acidification
AoP	Area of protection
BMCC	Building and material components combination
BOQ	Bill of quantities
CH_4	Methane
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
E	Eutrophication
EAF	Electric arc furnace
EC	Eco-toxicity
EN	Energy consumption
EOL	End of life
EPD	Environmental Product Declaration
EU	European Union
FU	Functional unit
DA	Depletion of biotic resource
GHG	Greenhouse gases
GWP	Global warming potential

HT	Human toxicity
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MJ	Megajoule
NO_X	Nitrogen oxides
NS	Norwegian Standard
OD	Photochemical ozone creation
R&D	Research & Development
SETAC	Society of Environmental Toxicology and Chemistry
SLCA	Social Life Cycle Assessment
TFS	Transoceanic freight ship
tkm	Tonne-kilometre
UCTE	Union for the Coordination of the Transmission of Electricity
UNEP	United Nations Environmental Programme
W	Waste creation
WC	Water consumption
WDC	Waste during construction
WPC	Whole process construction

1

Introduction

Buildings are one of the most complex industrial products, as they involve a wide range of materials for the construction and have a considerably long active lifetime. Nowadays, a sizable increase of research towards a major management and control of the quality in building construction is observed. Anyway, holistic approaches, which consider complete systems rather than individual parts, are still playing a minor role. This lack of general studies is specially observed during the construction-planning phase, which is also the most appropriate phase to make the necessary changes on the design without producing an unnecessary increase in the final cost. (I. Zabalza, 2012)

Related to this idea, the awareness of the current society on the necessity of a change towards sustainability produces that the environmental impact of buildings is also an issue that is necessary to be treated. In this specific case, a holistic approach is much more appropriate, as it would include all life cycle phases from the extraction of raw materials, throughout the construction, use and maintenance of the building and finishing at the end-of-life phase.

Thereby, a good basis could be established in order to take environmentally friendly decisions for the building design.

Life Cycle Assessment (LCA) is a powerful tool that takes into account all these phases and, nowadays, it is also the most used framework to calculate the potential environmental impact of any type of product, with no limit regarding geographic location, function or time (G. Finnveden, 2009). It exists many different software that aim to facilitate the assessment of this type of study and, for the specific case of this master thesis, SimaPro has been finally used given that it includes EcoInvent, one of the most complete and updated databases.

The present study aims to assess the LCA for a set of three buildings included in a new apartment project in Nardovegen, Trondheim. Specifically, it puts special attention on the construction phase of the building, including the production of all materials, their transportation to the construction site and all construction activities. The main reason is that it includes a big number of different processes that are interesting to study in order to find out the most sustainable solution. On the other hand, this study also contributes in the increase of the available bibliography regarding building LCA, which is not really extensive due to the complexity of the product considered.

It is also important to take into account the limitations that are also involved when carrying out an LCA, which in this case is basically the uncertainty related with the data collection for the assessment. At different stages, it has been necessary to make generally assumptions and, in order to minimize the error produced, measurements have been made the most accurately possible through all drawings and information available from the project and, in specific cases, also contacting the main responsible in the construction site. This process has been one of the most time-consuming when assessing this master thesis given that the complexity of the building and all calculations are attached in the Excel file *"LCI"*.

Considering all this points, firstly it has been necessary to define the concept of Life Cycle Assessment, specifying the concrete aspects that should be taken into account when studying buildings, and also carry out a literature review in order to obtain a clear idea of the methodology that has to be followed.

Next step will be to assess the LCA for the specific case of study presented, including its four main phases: goal and scope definition, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA) and interpretation of the results. For the interpretation phase, a sensitivity and uncertainty analyses have been carried out in order to ensure their reliability. Finally, results obtained will be discussed, paying special attention on the results obtained for the climate change impact category. In this section, it will be important to process all results obtained from SimaPro, breaking them up into the different phases studied, the main materials and the main categories in which the three buildings have been divided in order to facilitate the measurements and the comprehension of the results. In the last chapter, the main conclusions regarding this specific study but also general conclusions and recommendations for future assessments will be presented and justified.

2

Description of the concept of Life Cycle Assessment (LCA)

2.1 Introduction

Buildings produce impact to the environment along all the different stages of the active life, from the extraction of raw materials and transportation, the energy consumption necessary during the fabrication procedures and transportation to the building site, soil movements and possible wastes produced during the construction, energy and water consumption during the operation of the building, maintenance and even the demolition and disposition of all the elements used during the active life. Moreover, all this stages of the buildings are strongly interrelated and so previous stages can condition environmental impacts of future stages. (I. Zabalza, 2012)

Regardless of the high environmental impact produced by buildings during the use phase, it is indispensable to analyse also all the other phases of the active life of the building so as to find all different possibilities of improvement, not only during the active phase but also during future phases. With this aim, it is necessary to take into consideration the actual normative framework that will probably limit impact during the use stage and so it will produce higher impacts during the rest of phases of the life cycle of the building, specially the one related with the production of construction materials.

Bearing all the above points in mind, the reduction of the environmental impact in buildings requires the application of complex methods of evaluation of impacts. In the particular case of this master thesis, the major phase of study will be the construction stage including all possible impacts derived direct and indirectly from it.

Life Cycle Assessment is a method which main goal is to evaluate the environmental impact of a product, a building in this case, during its whole active life. The following figure describes the general stages of the life cycle of any product:

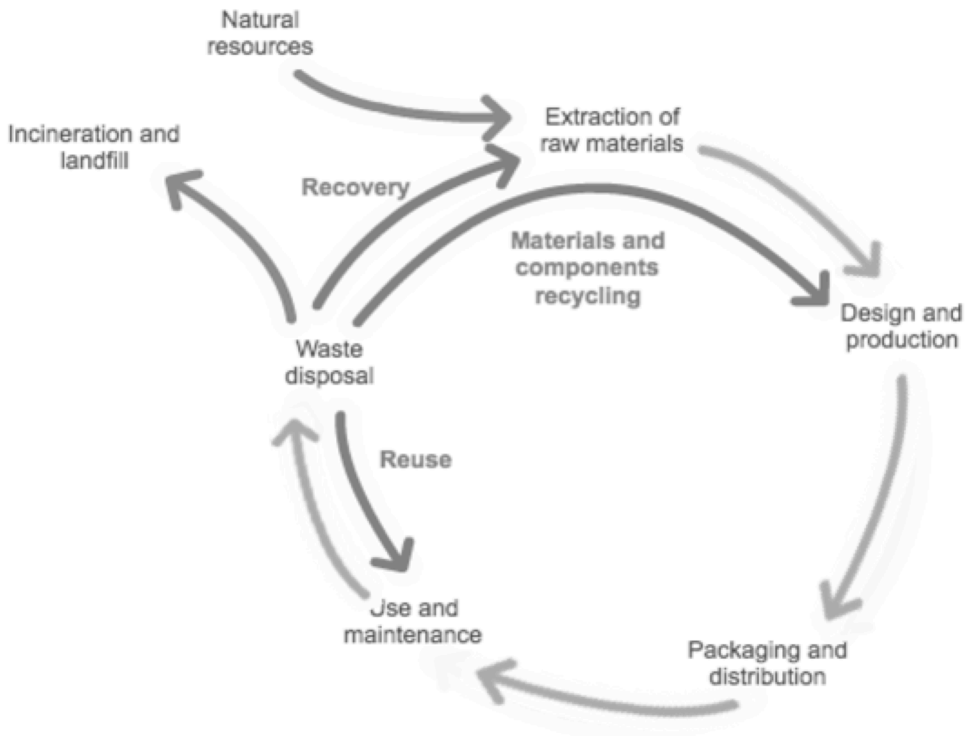


Figure 2.1. Product life cycle **(I. Zabalza, 2012)**

Nowadays, Life Cycle Assessment (LCA) is the most used framework to analyse the potential environmental impacts of any activity, product or service without geographic, functional or temporal limits (as it takes into account all the processes since the extraction of raw materials, transformation and use to the return to the environment as a waste). So, as it has been said, a clear advantage of LCA in front of other analysis frameworks is that it allows to detect the situations in which a specific product seems to produce less environmental impact than another one because it transfers the impact to other procedures or geographic places without producing a real improvement from the global point of view. (SETAC, 1994)

It is important to say that despite LCA has been used for long time to study the impact produced by industrial products, the application of this type of analysis to building constructions is quite recent and so it requires a higher effort to adapt the methodology.

Commonly, the application of Lice Cycle Assessment in building construction leads to more complexity than other types of systems that are simpler due to they take place in more controlled environments such us the fabrication of product and components in the industry. So, buildings represent a special product given that they have a considerably longer use life, usually more than 50 years, and they can suffer frequent and important changes of use. This produces that the Life Cycle Assessment has to be much more complex, including many different types of materials and components that are usually specific for the building that is being studied as it is rarely seen two buildings which are exactly equal even they are constructed with the same materials.

Moreover, these components has to be integrated into a specific urbanization with its road infrastructures, which gets more complicated the establishment of the boundaries of the system that is going to be analysed and the distribution of the impacts produced by roads infrastructures between all the buildings that take profit of them. (Sanz, 2012)

In this context, the Life Cycle Assessment is a versatile and useful methodology that helps into reducing the energy consumption and emission of greenhouse gases (GHG) of the construction industry and it also establish the different strategies to follow in terms of environmental pollution from a global point of view.

For this reason, LCA allows to give a specific optimal solution for each building and specify relevant aspects such as which is the best combination of construction materials to use at the facade, which type of structure is more respectful with the environment, which is the optimal thickness of the insulation system and many others (M. Asif, 2005). Finally, it allows establishing the environmental goals that are adequate for each building and in which measure they has been accomplished.

2.2 Origin and development of LCA

First Life Cycle Assessments were made during 1960's and the beginning of the 1970's. Because of the petrol crisis, a strong need of reducing the energy consumption appeared in the industry and, with this aim, there was a great change in this type of studies in order to make them more accurate. With respect to the building construction, in 1982 it was published a study that, using a input/output flux diagram (Bekker, 1982), established a first approximation of the life cycle of buildings emphasizing the exhaustion of natural resources used in building construction:

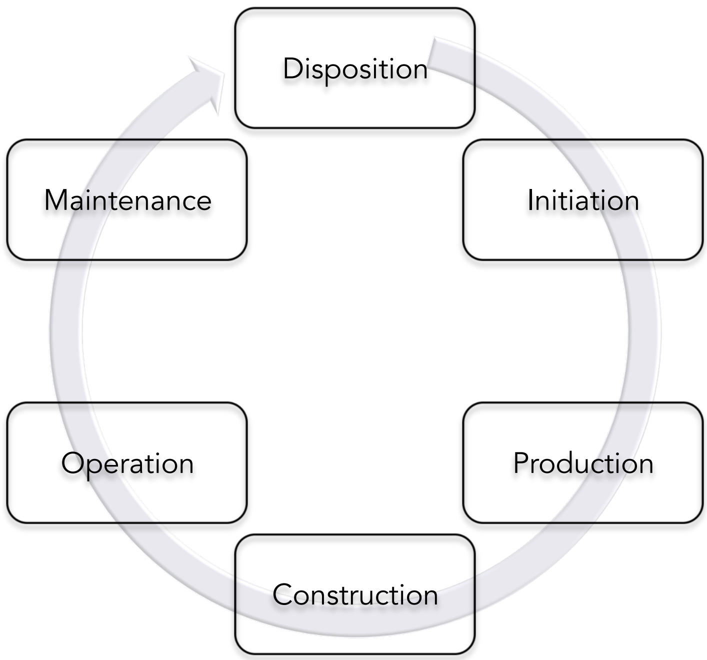


Figure 2.2. Building life cycle

However, until 1990's the LCA methodology was not enough developed and, for this reason, its application was clearly limited. It was in 1994 when it appeared the first official definition for Life Cycle Assessment by SETAC (Society of Environmental Toxicology and Chemestry). According to SETAC (SETAC, 1994), the prime objectives of carrying out a LCA are:

- To provide an idea as complete as possible of the possible interactions of an activity or process with the environment.
- To contribute to the understanding of the environmental consequences of human activities.
- To help during decision−making processes with information which defines the environmental effects of each of the options and identifies opportunities for environmental improvements.

In contrast to other methodologies that focus the attention in improving the environmental impacts of the processes, LCA studies the environmental aspects and potential impacts during all the active life of both products and services. In 1996, SETAC made the report "Towards a Methodology for Life Cycle Impact Assessment", which was used as the base for the first normative framework for LCA (ISO 14040-14044). It was published between 1997 and 1998 by the International Organization for Standardization ISO 14040 and it provides the general methodology and gives the principle guidelines for Life Cycle Assessment (LCA) and Life Cycle Inventory (LCI). ISO 14041 describes the Life Cycle Inventory Analysis (LCIA) stage, ISO 14042 the Impact Assessment stage and finally ISO 14043 provides guidelines to correctly make the interpretation of the entire LCA.

Later there was a second edition of the ISO 14040 (ISO 14040:2006 standard, environmental management, 2006) and it was published the ISO 14044 (ISO 14044:2006 standard, environmental management). This normative framework replaced the previous one and is currently in effect.

In recent years, different authors have suggested to widen the approach of the LCA attending the triple "P" of the sustainability: people – planet – profit, proposing a life cycle analysis for the sustainability, which integrates the conventional LCA with the Life Cycle Cost Analysis

(LCCA) and the Social Life Cycle Assessment (SLCA) (I. Zabalza, 2012). However, this is not going to be taken into consideration for the particular case of this master thesis.

2.3 Advantages of implementing a LCA

The implementation of a Life Cycle Assessment has some main advantages that have to be remarked. LCA is a really powerful sustainability assessment tool focused to address the environmental aspects of sustainability at the product level (G. Finnveden, 2009). It is considered an effective tool because of the following characteristics:

- It can examine the system as a complete unit (cradle-to-grave).
- It can analyse multiple media (air, water, residual…).
- It analyses multiple attributes.
- It helps in comparing and identifying the advantages and weaknesses between different alternatives.
- It supports decision-making processes.
- It is a highly recommended tool to covers sustainability aspects.

So, performing an LCA involves important benefits as it represents a systematic evaluation of environmental consequences associated with a given product or process, which also allows comparing between alternatives and so, it helps at the moment of the choice and during decision-making processes.

Furthermore, it analyses the environmental trade-offs associated with one or more products in order to find the opportunities of processes or products improvement. Finally, it can also represent a useful tool for communication with stakeholders, as LCA is becoming a credible and verifiable communication tool for expressing the sustainable value of products to consumers. This is an important point given that the concern about environmental issues between the general populations has been considerably increased during recent years.

2.4 Components of a LCA

The standards stated in the previous point (1.1 Origin and development of LCA) define a calculation method that allows evaluating the environmental behaviour of any construction and also establish how to communicate the results of this evaluation.

The general methodology of an LCA consists on four phases (in some cases, when is possible to apply a simplified analysis, the number of phases can be reduced), which are the following (I. Zabalza, 2012):

- **Goal and scope definition:** In this first phase is necessary to establish the main goal of the study and the limits or scope of this. Moreover, the necessary data and other possible hypothesis have to be defined.
- **Life Cycle Inventory (LCI):** At this moment is when are defined all the incomes and outcomes of energy and materials during all the life cycle of the system that has been defined in the previous phase.
- **Life Cycle Impact Assessment (LCIA):** This point consists on the evaluation of the environmental impacts derived from the flows of energy and materials defined in the inventory analysis and their classification in terms of the different types of environmental impacts that each one of them can produce.
- **Interpretation:** Finally all the results obtained in the previous phases have to be analysed as a whole unit taking into account the objectives defined. Then it is possible to establish the conclusions of the study and the final recommendations.

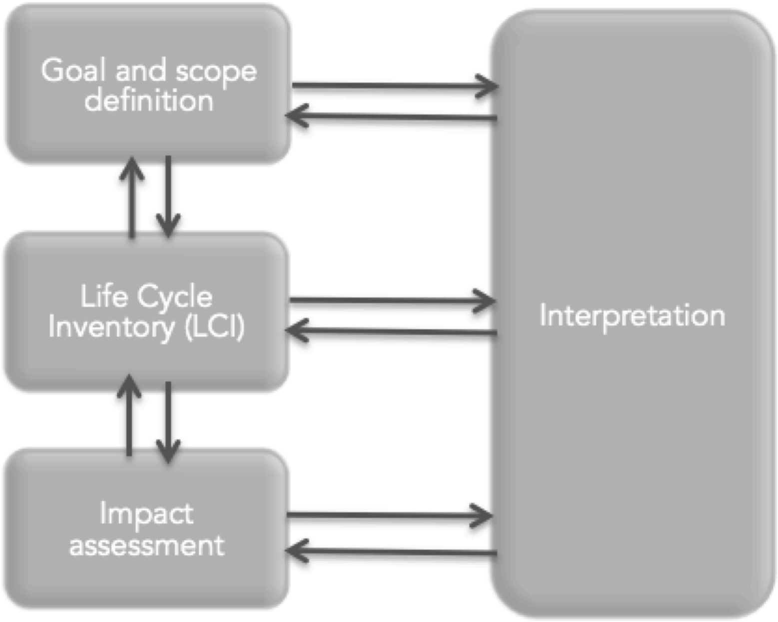


Figure 2.3 General LCA methodology

In the following points these different phases will be defined in detail. The methodology of the LCA has a dynamic or iterative behaviour, which means that all four phases are interrelated. For this reason, when we obtain the first results, hypothesis done during the first phase can be changed and data used in the rest of phases can be refined.

2.4.1 Goal and scope definition

In accordance to the standard ISO 14044, the goal and scope of a Life Cycle Assessment have to be clearly defined and be consistent with the application established (ISO 14044:2006 standard, environmental management).

Thus, in reference to the goal, it has to be defined the application and the reasons for the development of the study, also the target of it and whether if the results obtained from the analysis are going to be used for a comparison or not. Is obvious that in case of LCA related with buildings, goals and scope can be really different depending on the type and purpose of the building, its geographic location and the moment of the active life of the building when the analysis is carried out (preliminary stage of design, construction, use, rehabilitation or demolition). However, if the goal of the study is to compare the results with other analysis, then it is necessary that all of them are carried out at the same stage of the active life of the building and taking into consideration the same functional unit and other considerations such as the main function, limits of the system, quality of data, evaluation of data…

On the other hand, in reference to the scope of the analysis, some aspects have to be clearly defined (I. Zabalza, 2012):

- **Function of the system:** it is important to define the main characteristics of the system and it has to be taken into account that a system can have more than one function. This point is very important in case the goal of the analysis is to compare two different systems given that we cannot compare a residential building with an office building because the function of each one of them is totally different. In the same way, if we want to compare two different construction processes, they must follow the same regulatory framework and accomplish the same requirements.
- **Functional unit:** it establishes the reference unit for all incomes and outcomes of the system that will be obtained in the inventory analysis. It varies in terms of the type of study that one wants to carry out. For instance, an example of functional unit related with building could be the following: a building designed for a concrete number of residents or employees supposing an occupation of 100%, in a determined location, accomplishing the applicable law in reference to thermal comfort, salubrity, limitation of energy demand, etc., during an active life of 50 years. It is important to say that 50 years is a common value given to the active life of buildings, as it is very difficult to anticipate the real duration of a building.
- **The system:** it is defined as everything that is being analysed including the whole set of unit processes or subsystems needed. All of them, interrelated in terms of materials and energy consumption, allow the product studied to be sold and ready to use.
- **Limits of the system:** they limit the unit processes that have to be included during the analysis. It has to be taken into account that it is not necessary to use the resources to calculate the flows of energy at the boundaries that will not vary significantly the conclusions obtained from the study. With this aim, it is necessary to establish the limits in accordance to the goal of the LCA and, moreover, these limits must have the

possibility to be adapted in function of the first results obtained during the analysis. In any case, if it is decided to skip one of the stages of the active life or any unit process that produces income or outcome of energy it has to be clearly justified and all the criteria used to define the limits of the system must guarantee the precision and representativeness of the result obtained at the end of the analysis.

In case of buildings, the system considered should include the following different stages or subsystems when carrying out a Life Cycle Assessment: production, construction, use and final disposition:

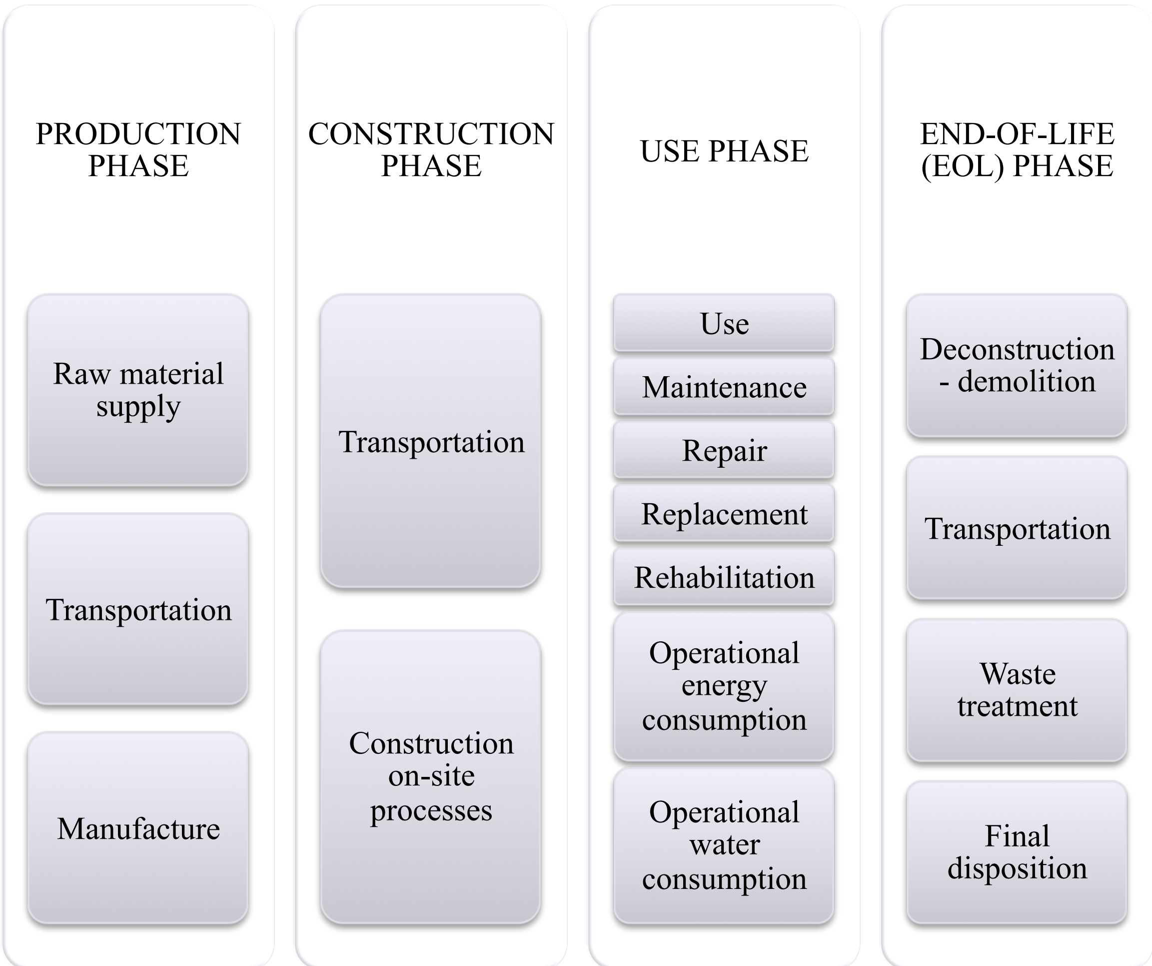


Figure 2.4. Life cycle phases of a building (I. Zabalza, 2012)

- **Categories and methodologies of impact evaluation that are going to be used during the analysis**: each one of the methods of evaluation is different depending on the impact category that is being studied and the importance given during the weighting. The following table includes the category of impacts that are strongly recommended to include when performing a LCA on a building:

IMPACT CATEGORIES
Global warming
Ozone depletion
Land and water acidification
Eutrophication
Water and terrestrial ecotoxicity

Table 2.1 Impact categories for building LCA

- **Quality requirements of data:** data used to carry out the assessment has to accomplish specific requirements in terms of temporal coverage (antiquity of used data), geographic characteristics (local, regional, continental, global…), technology (best available technology, weighted average of technologies…) as well as precision, width and representativeness of data.

All in all, the scope of a LCA is determined by the main aim of the study and its definition has to provide the context in which the study is going to be carried out, including the boundaries of the system considered and also all the assumption that will be made.

2.4.2 Life Cycle Inventory (LCI)

The next stage when performing a LCA is Life Cycle Inventory (LCI), which includes the obtaining of data and calculation procedures so as to quantify the relevant incomes and outcomes during each one of the unit processes that are included in the analysed system. So, the main idea is to perform a flow balance taking into account the incomes and outcomes of the system along all the active life for the functional unit chosen. The elemental flows are the energy and natural material flows (such as oil, coal, water and natural sand) without any previous transformation and the emissions going directly to the environment (such as CO_2 and water spill nitrates). (G. Finnveden, 2009)

For each one of all the unit processes, the quantified entrances include the energy and raw material consumption while the quantified outcomes include air, water and soil emissions, by-products and other spills. In the following figure it is shown a scheme of this idea:

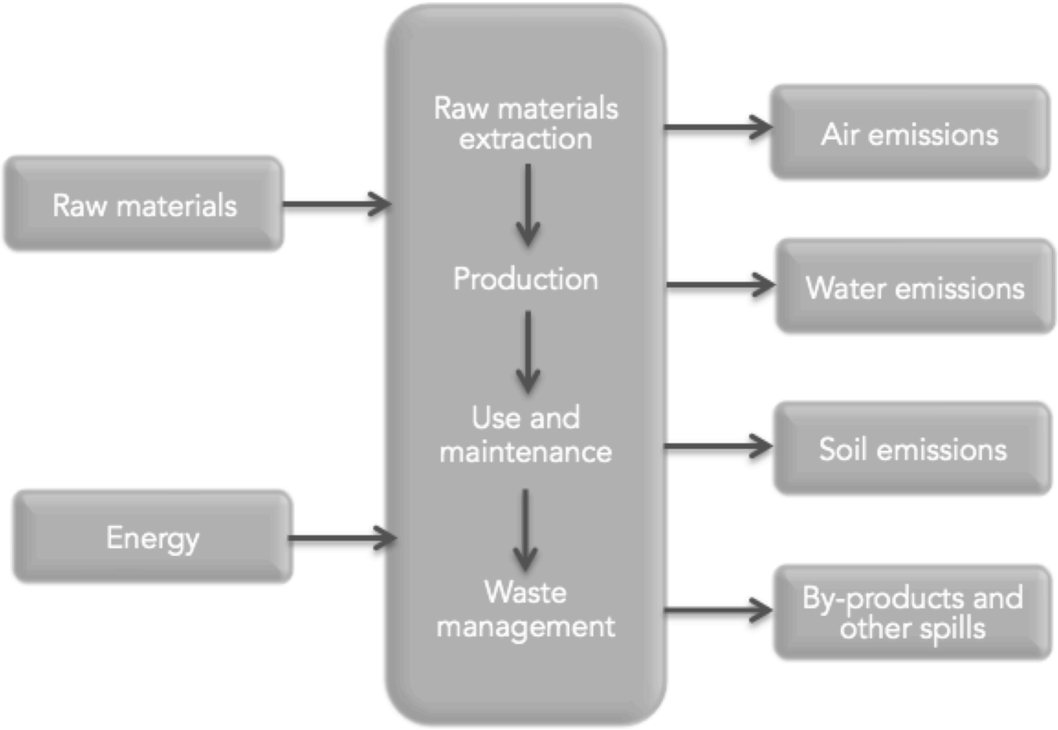


Figure 2.5 Inputs and outputs of a Life Cycle Inventory (LCI) (I. Zabalza, 2012)

In case of existing different processes that lead to more than one product or that the residuals of one product are recycled or reused to create a new product, it is important to apply the adequate criteria, which allows to a fair distribution of the impacts between all the different products.

2.4.3 Life Cycle Impact Assessment (LCIA)

This third phase consists on grouping and evaluating the results of the Life Cycle Inventory realised at the previous stage in accordance to the impact categories such as global warming potential (GWP) or soil and water acidification, which has been determines in the first phase of the LCA. Each one of the categories has to be quantified through numerical indicators so impact evaluation methods can be applied.

The evaluation of impacts must include the following stages (I. Zabalza, 2012):

- **Classification:** This first step consists on assigning all data from the inventory to the impact categories previously selected and following the evaluation method chosen. Specifically, all the incomes and outcomes of the inventory are classified in the different impact categories in terms of the possible changes that can produce to the environment. The final result is a grouped and simplified inventory where only energy and material flows that affect a particular category will appear.
- **Characterisation:** This means the relevance evaluation of the different energy and material flows so as to be able to calculate the numerical indicators of each one of the impact categories, for example the kg of equivalent CO_2 for the global warming. It is based on the conversion, for each of the impact categories, of the LCI results into common units using characterisation factors. These represent the quantity of each one of the possible compounds that, in case of being spilled, will produce an environmental impact quantitatively comparable with the base unit of the impact category. For instance, 1 kg of CH_4 produces approximately the same impact in the global warming as 21 kg of CO_2. The result of the characterisation is the environmental profile of the system including all the numerical indicators for all the impact categories considered.

Optionally, the numerical results of the characterisation can be normalised, grouped and weighted in the following steps (PRé Consultants, 2013):

- **Normalisation:** This consists on evaluating the relative magnitude of the impact indicators of the analysed system in front of the real or predicted magnitudes in a national, continental or global scale. Knowing the contribution of each one of the impact categories considered in a global context helps in understanding the relative magnitude of the numerical indicators obtained during the characterisation. In the standardisation, the results of the characterisation are divided in terms of normalised factors that express the results for a geographic area and time determined. For example, the environmental impact produced by a European average citizen during one year.
- **Weighting:** This is the most subjective part of this stage of the LCA and consists on weighting the results obtained for the different impact categories with the aim of make a more direct comparison or even aggregate them into a single global indicator. In this step, the results of the normalised indicators of the different impact categories are converted into common units using weighting numerical factors that are determined trough subjective evaluations or value judgments. These numerical evaluation factors can be obtained from socioeconomic data but, anyway, these cannot be considered as scientific relevant factors. (ISO 14044:2006 standard, environmental management)

It is important to remark that different impact evaluation methodologies can be used in the same study with the aim of contrasting the results for different impact categories. The evaluation methodologies usually include some of the environmental indicators presented previously.

2.4.4 Interpretation

In the interpretation phase, all results obtained on the previous phases of the LCA are compiled and evaluated in order to obtain the conclusions and useful recommendations for the system studied (ISO 14040:2006 standard, environmental management, 2006). Not only the environmental damages can be important in the decision process, but also social, cultural or economical criteria. In this last phase, the significant aspects of the life cycle of the product considered can be identified and some activities can be adjusted if required. It is all part of an iterative process that leads to achieve the main goal and make improvements in the Life Cycle Assessment study that has been carried out.

The interpretation of the results must be consistent with the goal and scope defined in the first phase and it includes three fundamental elements: Identification of the significant variables, verification of the results and, finally, conclusions and recommendations. During the first of them, the processes that carry a greater impact are identified an also the ones that can be obviated for the study. The aim of the verification of the results is establish and reinforce the reliability of the results trough an integrity, sensitivity and consistency analysis.

The integrity analysis is done in order to prove that all the relevant information and data needed for the interpretation are available and are correct. The sensitivity analysis evaluate the reliability of the final results and conclusions determining if they are affected by uncertainties in data or in evaluation methods that have been chosen. Finally, the consistency analysis evaluates if the hypothesis, methods and data are coherent with the goal and scope of the study (I. Zabalza, 2012). Anyway, all these analysis are not mandatory but helpful for the final conclusions and recommendations.

At this point, it has been defined a theoretical presentation of the LCA framework also with the aim of familiarizing the reader with common vocabulary that is going to be used along this thesis.

2.5 Application of LCA in building construction

The application of LCA methodology in buildings provides countless opportunities for the construction industry as it makes much easy the decision-making for the construction companies and other organisations of the same sector in many different aspects of the strategy planning of eco-efficiency in edification, such as (UNEP, 2015):

- Identification of the opportunities in order to recognize the environmental impacts produced by the construction industry taking into consideration the whole active life of buildings.

- Establishment of the priorities for the ecologic design or eco-rehabilitation of buildings.
- Correct selection of suppliers for the construction materials and energy equipment.
- Comparison between different options for the design and for the selection of specific products or materials.
- Establishment of strategies and fiscal policies so as to manage the construction residuals and the transport of the materials.
- Definition of new programs of Research and Development (R&D) and eco-efficiency regulations.
- Implementation of aid policies in construction and rehabilitation.

On the other hand, the potential users of LCA in the building sector is a group of many different actors as the construction products manufacturers, consultants, architects, engineers, energy managers of the local administration, urban planners, developers and others.

USER	CONSTRUCTION PROCESS PHASE	LCA MAIN GOAL
Urban planers and municipal advisers	Preliminary phase	Establishment of goals in a municipal or estate scale. Inform about construction and rehabilitation policies. Establishment of goal for developing areas.
Developers and clients	Preliminary phase	Choose the building location. Calculate building design. Establish specific environmental goals.

Construction products manufacturers	First and detailed designs	Evaluation of the impact during the production of the materials. Eco-labelling and Environmental Product Declarations (EPDs).
Architects, engineers and consultants	First and detailed designs of new buildings in collaboration with engineers Rehabilitation projects	Comparing between different design options. Comparing with past researches.

Table 2.2 Users of building LCA (I. Zabalza, 2012)

An LCA assessment allows evaluating the influence of the principal decisions made during the design stage of the building not only about the maintenance and the expenses associated with its operation, but also about the real environmental impacts of the building. Thus, it is possible to evaluate the potential energetic saving and the reduction of the emissions related with the implementation of different constructive and architectural solutions. It is important to remark that LCA assessment allows making decisions from a global point of view, taking into consideration all the possible environmental impacts of all the active life avoiding partial points of only one stage of the active life or one type of environmental impact.

On the other hand, and even though this is not the goal of this thesis, an important application of the LCA is the combination of this with Life Cycle Cost Analysis (LCCA). This type of analysis studies the economic profitability of the investments related with the edification and rehabilitation sector, contributing to a better energy management of buildings. For instance, this combination can be used to choose the construction alternative, identifying the solution that fulfils the environmental goal determined with the minimum cost. (M. Khasreen, 2009)

In terms of material and construction materials, LCA assessment allows realising a quantitative evaluation of the impacts, stimulating its improvements and the eco-labelling to communicate the obtained benefits. Eco-labelling is a mechanism that allows distinguishing the products that have been manufactured with a minor environmental impact but it is not compulsory. Anyway, eco-labels give the consumer (professional or private) information about the environmental repercussion of the products, helping to compare between products to choose the best option. Nowadays, it exists different types of eco-labelling, being the type III (called Environmental Product Declaration, EPD) the most related with the methodology of LCA. This eco-labelling consists on a declaration of the environmental impacts that a specific product produces along all its active life or until the end of its production. The information that is declared in this case is based on LCA methodology, applied following certain rues depending on the type of product that is being studied. (García, 2010)

The following table presents the principal EPD programmes (normalized trough ISO 14025:2006 and ISO 21930:2007) related with products of the construction industry that are used nowadays worldwide:

	SYSTEM	MANAGER	COUNTRY
sia	Déclaration sur les caractéristiques écologiques de produits utilisés dans la construction	SIA (Schweizererischer Ingenieur – und Architektenverein)	Switzerland
bre	BRE	BRE Environmental Profiles Certification	United Kingdom
MRPI®	MRPI® (Milieu Relevante Product Informatie)	NVTB (Nederlands Verbond Toelevering Bouw)	Netherlands
	Unwelt – Deklarationen (EPD)	IBU (Institut Bauen und Umwelt)	Germany
inies	Programme de Déclaration Environnementale et Sanitaire pour les produïts de construction	AFNOR Groupe	France

RT ENVIRONMENTAL DECLARATION	RT Environmental Declaration	The building Information Foundation RTS	Finland
NHO	EPD – Norge	Næringslivets Stiftelse for Miljødeklarasjoner	Norway
EPD®	EPD® system	International EPD Consurtium	International
THE GREEN STANDARD	The Green Standard EPD System	The Green Standard	USA
dapc	DAPc – Declaración Ambiental de Productos en el sector de la Construcción	CAATEEB (Col·legi d'Aparelladors, Arquitectes Tècnics I Enginyers d'Edificació de Barcelona)	Spain

Table 2.3 Principal EPD programmes of the building industry

Specific products EPDs can be used during the elaboration of LCA studies of more complex systems or even when a building is being analysed. In this sense, EPDs allow the availability of higher quality and more accurate information of construction materials than the information that can be obtained from current databases, public or commercial, which are usually generated from average values. However, given that EPDs are not compulsory nowadays, are only available for a reduced number of products. Fortunately, this amount of products is increasing every year.

2.5.1 Main tools for applying LCA in the building industry

With the aim of making easier to apply LCA methodology, many software programmes have been developed during the last decades. These help the analyst in the process of implementation of the LCI, calculation of the impact evaluation results and interpretation of these results.

Some of these tools are more general, which means that can be applied in a wide range of LCA analysis. For example, GaBi (released by PE International, Germany) and SimaPro (Pré Consultants, Netherlands) are found in this group. On the other hand, there are some software that have been specifically developed for the building industry as they include predetermined modulus to describe the principal characteristics of the buildings. This helps non-expert users to apply LCA methodology and in this group we can find many different tools such as BEES (released by NIST, USA), SBS (Fraunhofer, Germany) and Elodie (CSTB, France) between others. (I. Zabalza, 2012)

In case of LCA informatics applications of general use, the analyst has more freedom when choosing the initial hypothesis. However, a higher knowledge about the building and LCA methodology is required in these cases as well as more time for the elaboration of the LCA is needed. Anyway, these tools are more precise as they need the analyst to specify the exact amount for all the construction materials that are going to be used, the energy consumption… On the other hand, when working with adapted tools for the building sector the interface is simpler, which simplifies the process and makes easier the introduction of data and the interpretation of the results. In this master thesis, accuracy and reliability of the results obtained are given more importance than speeding up the different processes and so a general use tool will be used, as it is SimaPro. (PRé Consultants, 2013)

An important aspect when using this type of tools is that they must contain an enough accurate database, which will help when carrying out the Life Cycle Inventory. Data used can proceed from different database depending on the requirements for the LCA that is being realised. In the following table, a list of the main databases that are being used nowadays can be found:

DATABASE	CONTENT	NUMBER OF PROCESSES (2010)
ELCD core database v.II (2009)	Materials, energy, transportation and waste management	316

US Life-Cycle Inventory database v.1.6.0 (2008)	Energy and material flows for the most common unitary processes	355
Ecoinvent v3 (2014)	Huge variety of processes including energy, transportation, construction materials, chemical products, waste management…	>10.000
IVAM LCA Data v.4.06 (2004)	Dutch data about materials, transportation, energy and waste management	1.350
Boustead Model v.5.0.12 (2006)	Materials and fuel and energy production database	-
Athena database v.4 (2009)	Energy consumption and emissions of construction products along their active life	1.200
Idemat (2001)	Dutch database, compiled with data from different sources	508
Gabi database	Includes agricultural, construction, chemical and electronic processes, energy, alimentation…	4.500
ETH-ESU (1996)	Swiss database focused on energy, transportation and waste	1.200
GEMIS 4.5 (2009)	Free database that includes energy and transportation processes, materials, recycling and waste management	-

Table 2.4 Principal LCA databases (I. Zabalza, 2012)

For the specific case of this thesis, the database contained in SimaPro software is Ecoinvent.

This is considered as the world's leading database given that it contains the highest number of data for the performance of LCI and it is being continuously actualized. It contains several thousands of LCI datasets divided in the following area: agriculture, energy supply, transport, biofuels and biomaterials, bulk and speciality chemicals, construction and packaging materials, basic and precious metals, metals processing, ICT and electronics and waste treatment. Ecoinvent is one of the most comprehensive international LCI databases. (PRé Consultants, 2013)

2.6 Uncertainties in LCA

Often uncertainties are not considered in LCA assessments although they can be considerably high. For this reason, is always recommended to carry out a specific analysis of these possible uncertainties involved when performing an LCA study so as to, for instance, make easier the interpretation of LCA study results. In order to know the main that may be necessary to deal with when writing this thesis, some review papers has been consulted. (G. Finnveden, 2009) (M. Khasreen, 2009)

Uncertainty is a complex concept that has many different definitions, but when studying LCA assessments this is found as one of the most widely accepted: ''the discrepancy between a measured or calculated quantity and the true value of that quantity'' (G. Finnveden, 2009). It is also interesting to differentiate between sources and types of uncertainties. Firstly, sources are defined as the different input data that may be unknown or contain a certain error, while types are the different characteristics that can be wrong with these sources. In LCA, the following sources of uncertainty are considered:

- **Data:** many types of data can be included such as electricity use of a heating boiler or CO_2 emissions from a coal fired power plant.

- **Choices:** many hypotheses have to be made during the process when carrying out an LCA and they may contain a high level of uncertainty. For instance, system boundaries, allocation processes, time horizon…
- **Relations:** general assumptions are made such as linear dependence between distance and fuel use in transportation and linear dependence of acidification on SO_2.

As it has been said, the different types of uncertainties are related partially with these sources. Some examples are shown in the following list (G. Finnveden, 2009):

- **Data may present variability:** for instance, electricity consumption of boilers may be different depending on the conditions or even it may differ through time.
- **Data may be miss-specified:** it can happen if we approximate input data for a specific product with data related with a similar model.
- **Data may contain error:** different problems can be observed in this way such as confusion with the units or a typo when introducing when introducing data.
- **Data may be incomplete:** it may happen that not all data needed for the assessment is available.
- **Data may be subject to round-off:** for instance, if 0.247 is entered as 0.2, the error induced is higher than 10%.
- **Choices may not be consistent:** all choices made during the process have to be consistent with the goal and scope of the study.
- **Relations may not be correct:** linear dependence between variables may induce big errors.
- **Relations may not be complete:** sometimes background sources of environmental imapct are neglected.
- **Relations may not have been introduced accurately in software:** relations also depend on the algorithm implemented.

In addition to all these types of uncertainties, many others exist and some of them will appear when carrying out a LCA assessment.

The ISO 14040 framework (ISO 14040:2006 standard, environmental management, 2006) specifies that main uncertainties are related with LCI and LCIA phases but it is important to take into account that, as with all the other tools for decision-making processes, the uncertainty for the interpretation phase can be also really important. However, the ISO does not specify concrete guidelines to perform an uncertainty analysis and, in this way, other posterior studies have been made in order to cover this issue.

In order with the way to deal with all types of uncertainties, three main ways can be considered: scientific, social and statistical way.

Uncertainty can be dealt with in several ways, it is useful to distinguish between the scientific way, the social way, and the statistical way (G. Finnveden, 2009). The first of them is characterised basically by doing more research in order to find out better data and make better models. This is a very accurate way as always considerably reduces the level of uncertainty but usually not enough time is available and, for this reason, main assumptions are usually made.

Secondly, the social way consists basically on dealing with the uncertainty in collaboration with the main stakeholders in order to define the assumptions that will be made regarding data and choices. In this case, also the legal way can be considered when an authoritative body is in charge of establishing the main choices and models that has to be used. A common example is the specification of the general recommendations for LCA assessments, which are established by the European Commission in collaboration with other governments, industries, the United Nations Environmental Programme (UNEP) and various scientific advisory bodies. It is important to take into account that sometimes these general agreements, which are considered as recommendations or policies, are not consistent with new investigations and researches. Thus, it is important to be cautious although all recommendations and policies can also represent the basis for further investigation.

Finally, the main difference between the statistical way and the two previous ones is that, instead of reducing the uncertainty, this last one tries to incorporate it. There are many different methods to apply statistical theory:

- Sensitivity analysis, which consists on applying changes to some parameters and evaluating the response.

- Classical statistical theory taking into account different probability distributions, tests of hypothesis…
- Monte Carlo simulations or bootstrapping.
- Applying analytical methods based on first-order error propagation.
- It also exists other methods but less used such as non-parametric statistics, Bayesian analysis and fuzzy set theory.
- Using qualitative uncertainty methods, which are less reliable but easier to use. For instance, data quality indicators can be used.

Thanks to recent studies, uncertainty analysis is increasingly included in LCA analysis nowadays. However, usually it only incorporates the analysis regarding parameter uncertainty. In the specific case of the database used for this thesis, EcoInvent, it includes probability distributions for almost all data included and also uncertainties have been avoided for the materials that had available an EPD.

As it has been pointed out at the beginning of this point, a type of uncertainty is widely accepted to be the difference between data included in the LCI and real values. This brings us to think about the concept of validation, which aims to compare measured and real values. As it was published by A. Ciroth, "validation in LCA models offers tremendous possibilities for model improvements as well as improvements of the quality of decisions supported by LCA models" (A. Ciroth, 2006). On the other hand, many authors have also argued that validation of LCA assessments is impossible.

In conclusion, it can be said that the area of validation as well as the larger area of uncertainty in LCA needs further research and development. (M. Khasreen, 2009)

3

Methodology

3.1 Introduction

The methodology followed in this thesis must apply the recommendations from the standards to a case study but the scope, assumptions and limitations should remain wide enough to allow comparisons of the results with future building assessments. It will be established the general limits that can be applied to a wider range of apartment buildings.

This methodology must be sufficiently accurate and focused on the impact assessment of apartment building projects, but it should be able to include the maximum of different possibilities regarding the building designs, geometries… However, it is easy to think that the choices of materials or the location of the new building can lead to very different conclusions in terms of the environmental impacts of a whole building active life. In order to deal with this issue, limitations will be stated regarding the scope but also for the interpretation phase.

So, a first part of the methodology of this thesis is then the realization of a literature review on buildings LCA cases of study. Once the basis for the performance of building LCA assessment is established, SimaPro software will be applied for the specific case of study, the new apartment project in Nardovegen.

3.2 SimaPro

SimaPro is the world's leading LCA software among industry, research institutes and consultants in more than 80 countries (PRé Consultants, 2013). This tool is used in order to analyse complex product life cycles in a systematic and transparent way. It is important to say that in the assessment, SimaPro follows the ISO 14040 series recommendations, already presented in the previous point of this thesis. When results are obtained, it is easy to refine data included and it is also possible to zoom into the hotspots or the areas of attention.

The Ecoinvent Ceter is considered to be the world's first supplier of data of the performance of Life Cycle Inventories as its database, EcoInvent v3, contains robust and reliable data for more than 10.000 processes. Regarding LCIA, the methodology applied by SimaPro software that has been chosen for this assessment is ReCiPe, which assesses 18 midpoint impact categories and 3 endpoint impact categories.

As shown in the figure next page, each one of the products is defined in an assembly, which contains the list of materials, production processes and transportation processes. However, assemblies do not contain environmental data but they are linked to the production processes that contain such data. Thus, these production processes contain the list of all raw materials needed and sub-processes. SimaPro release the results as a large table of emissions and, although it is accurately detailed, it is not easy for the user to analyse and interpret correctly all data. So, user is able to specify the midpoint or endpoint impact indicators that are going to be studied, as it is established in ISO 14044. (ISO 14044:2006 standard, environmental management)

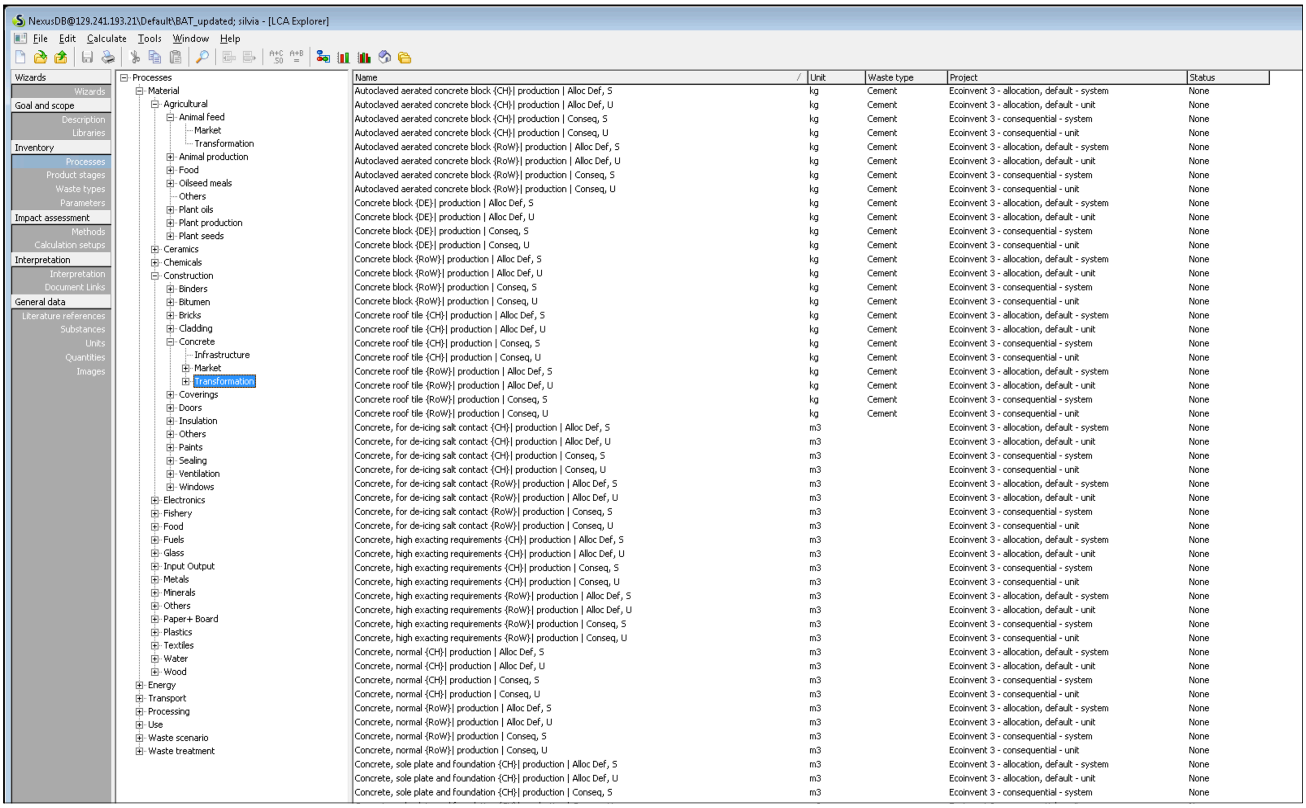


Figure 3.1 Concrete production processes within SimaPro

3.2.1 ReCiPe method

The primary objective of the ReCiPe method is to transform the large table of emissions resultant from the LCI, into a limited number of indicator scores chosen by the user. These indicator scores show the relative contribution on an environmental impact category. As it has been said, in ReCiPe we determine indicators at two levels (PRé Consultants, 2013):

- Eighteen midpoint indicators
- Three endpoint indicators

As described by Dahlstrøm (2011), “midpoint categories are problem oriented and based on a scientific background but can sometimes be difficult to interpret, while endpoint categories are damage oriented an easier to interpret, but have higher uncertainty”. (Dahlstrøm, 2011)

As it will be seen in the literature review, energy consumption and climate change impacts are usually the focus of LCA studies, but studying a wider range of impact categories gives a wider basis for decision-making. This has been considered a potential for improvement in the literature on building-related. For the impact assessment of the present study, some midpoint categories have been selected from the hierarchic version of the ReCiPe method. Anyway, and although the study of a wide range of environmental indicators is desirable, it is still useful to limit the study somehow. For this reason some ReCiPe impact categories have been finally excluded but these decisions will be further justified.

These categories are ozone depletion, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, and fossil fuel depletion. They are considered to be less relevant for various reasons, which are now related.

The first two are indicators of environmental problems that have less relevance for a study of buildings in the Norwegian context. Land use indicators are not included because of uncertainty for the Norwegian conditions and fossil fuel depletion is considered to be less important than CO_2 emissions associated, which are included in the climate change impact category considered. Finally, as water consumption is not a major issue in Norway, the indicator about water depletion has been excluded.

3.3 Building construction in Norway

The main issue of the Norwegian energy policy in buildings is to ensure that consumption does not increase, but remain stable around 80 TWh until 2020 through regulation and retrofitting. The goal for 2040 is to reduce the annual energy supply to the operation of buildings by 40 TWh compared to the current level.

Norway is affiliated to the European Union regarding some issues through the EEA Agreement. For instance, this produces that EU directives that establish guidelines for the construction are also applied in Norway. Hence, all these regulations have to be included to Norwegian regulations by the corresponding authorities. The main aim for Norway to accept this framework is to avoid a technical block between this country and other nations.

Thus, Norway is regulating energy consumption taking into account EU Renewable Energy Directive, which sets three main goals called the 202020 targets for 2020: a 20% reduction in greenhouse gas emissions, 20% renewable energy and 20% energy efficiency by 2020 (UNEP, 2015).

The Ministry of Local Government and Regional Development (KRD) is the main building authority and the responsible of overviewing all planning is the Ministry of the Environment. The SINTEF Building and Infrastructure journal “Byggforsk kunnskapssystemer” is published by SINTEF Byggforsk (BKS). These journal series are the most complete source of technical solutions, which completely fulfil the Norwegian building code. Thus, the Norwegian Building Authority (DiBK) recommends the use of Byggforskserien when designing a building project.

Regarding the specific framework, NS 3700 establishes the regulations that must be fulfilled in residential buildings considered as passive houses or low energy buildings. The building studied is not designed following the passive house standard but it will be interesting to compare the environmental impact produced in this case with other LCA results assessed for passive houses.

The Planning and Building Act (TEK) is the main framework used for regulation of building construction in Norway and, thus, its regulations are periodically revised in order to keep them updated with the research. It is up to the customer and contractor to prove that the designed solutions meet the requirements of this regulation. On the other hand, in TEK regulation it is also specified that it has to be the manufacturer the one in charge to ensure the documentation of the properties of all the materials and products before they are sold or used in a construction. The current revision is TEK 2010, or TEK10, which was published in July of that year.

4

Previous researches

4.1 Introduction

In order to make easier further comparison of the results of the present case study, a literature review of previous building LCA analyses has been performed. Finally, 13 references are presented in this section, dating from 1995 to 2014.

It is important to say firstly that, although LCA has been used in the building sector since 1990, it does not yet exist an internationally recognized methodology for assessing and organizing LCA inventory data for buildings (I. Zabalza, 2012). As pointed out in some of the studies consulted, this makes more difficult the direct comparison of results from different LCA case studies given that they usually do not follow exactly the same methodology. So, it also represents an obstacle to the application of LCA within the building industry.

LCA of buildings is particularly complex because buildings are more complex than most other products. This complexity is basically due to the big amount of different building materials needed and the possible combinations between them, which makes of every building a unique product.

Buildings active life is long, which makes it difficult to predict the whole life cycle. Also, many changes may be applied to buildings throughout their active life, potentially leading to significant structural differences between the building that is demolished at end-of-life phase (EOL) and the building that was initially constructed. Furthermore, while most other types of products that have been studied through LCA assessments do not have any significant impacts throughout their use phase, the operation stage of buildings is often found to be the major contributor to total life cycle impacts.

Finally, the number of stakeholders is higher in the building industry, including designers, builders and users, among others. This means that a house may not be built or used according to the idea of the designers. For this reason, the methodology to follow when applying LCA to buildings is presented and discussed by several papers.

The first part of this point consists on a description of the different studies chosen. In a second part, the main findings are summarised with the aim of drawing a preliminary list of elements that are important to focus on when performing an LCA analysis. A comparison between the different studies regarding the main impact categories assessed is also performed.

4.2 Literature review

So, at this point, different LCA assessments used as reference for this thesis will be presented. Thus, carrying out the comparison between them to conclude with the basis for the LCA that is going to be performed will be easier. As it has been said, a total of 13 references has been consulted, which are the following:

Antonio García Martínez in 2010

Methodical proposal for the development of Environmental Declarations of Dwellings in Andalusia

The objective of this study is to develop a methodology for conducting Type III environmental declarations (presented in this thesis as EPD), which provides quantified environmental data using default parameters and additional environmental information, of new dwellings in the Autonomous Community of Andalusia, in Spain. Then, an environmental assessment of three case studies is made using LCA methodology: a conventional town house, a detached wood house and a dwelling from a multi-storey building. These LCA assessments take into account the following impact categories: climate change, acidification potential, eutrophication potential, ecotoxicity in water and terrestrial ecotoxicity. Furthermore, they consider all phases of the active life of buildings except for the end-of-life phase.

The main conclusions of these assessments are that the energy configuration of the building, the selection of building materials and systems and the site of the building in relation with the urban infrastructure are significant aspects when calculating the environmental impact. (García, 2010)

Jaime Sanz San Pablo in 2012

Life Cycle Assessment of an average dwelling in Murcia

I this case, the main purpose of the thesis is to carry out a detailed calculation of the energy consumed along all the active life of an average dwelling in the city of Murcia, in Spain. With this aim, the author takes into consideration all the phases of the life cycle of the building and calculates the total energy consumed, establishing the exact percentage used during each one of the phases. As a last step, in this thesis also the results are compared with other similar studies made before in order to know if the consumption of energy in Murcia is similar to the consumption in other parts of the world.

One of the main conclusions of this study is that, although the construction phase requires the most energy consumption due to the required energy during the production of concrete and steel, little increments of consumption during the construction phase would derivate in high reductions of the consumption during the operation phase. This fact could even reduce the total energy consumed along all the life cycle. (Sanz, 2012)

Duygu Aral in 2012

Life Cycle Environmental Impact Assessment of a multi-storey residential building in Izmir

The main purpose of this study is to make a quantitative assessment on the environmental impacts of multi-storey-mass housing, which is the most common type of building in Turkey. In this case, and at the contrary of the majority of previous researches consulted, the purpose is not to make a comparison between some similar buildings or products, but to know the exact impact produced along all the life cycle of the building. In this case, impact categories studied are the following: ozone layer depletion, human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, global warming, acidification, abiotic depletion and eutrophication.

The main outcome of this study indicated that the use phase has the highest environmental burden in the life cycle of that type of residential building. Accordingly, the major improvement opportunity is related with the reduction of the environmental impacts of use phase, mainly depending on energy consumption. Operation phase is responsible for 66-97% of the total impacts, while the pre-use phase is 3-34%. The end-of-life phase is accounted for less than 1%, which is the minimal contribution for all environmental impacts. (Aral, 2012)

M. Asif *et al.* in 2005

Life cycle assessment: A case study of a dwelling home in Scotland (LCA for eight different materials for a dwelling in Scotland)

This article provides a life cycle assessment (LCA) of a 3-bed room semi detached house in

Scotland. Detailed LCA of five main construction materials, which are wood, aluminium, glass, concrete and ceramic tiles, have been provided to determine their respective energy consumption and, hence, their associated environmental impacts. The impact categories studied in this case include energy consumption, global warming potential and acidification. On the other hand, it is determined that the whole life cycle of the building is taken into account when performing the LCA study.

Then, it is found that concrete, timber and ceramic tiles are the three major energy expensive materials involved. It has been calculated that concrete alone consumes 65% of the total embodied energy of the home and its share of environmental impacts is even higher. However, it is also concluded that concrete as a material has smaller values of energy consumption and environmental impacts as compared to other construction materials involved such as glass, aluminium and ceramic tiles. It is because concrete is used in a very large quantity proportion in any construction, that it becomes responsible for a large share of the gross embodied energy and environmental impacts. (M. Asif, 2005)

Cole and Kernan in 1995

LCA of a three-storey, office building for alternative structure materials in Canada

In this case, the total life-cycle energy use is examined in a three-storey, generic office building for three alternative structural systems (wood, steel and concrete) and with or without underground parking. Detailed calculations are made of the initial energy consumption, the energy associated with maintenance and repair, and finally also operating energy. So, in this case only one impact category has been studied, which is the energy consumption during the whole life cycle of the office building.

Conclusions of this study show that structure can represent a significant proportion of the initial energy consumption of a commercial office building. The differences between the energy used in wood, steel and concrete framed buildings are also found to be significant. However, structural systems are rarely composed of a single material type and the choice of a particular structural material or system means also the use of many other non-structural materials. Moreover, it is shown, as in some of the already presented researches, that operating energy represents the largest component of life-cycle energy use. (R. Cole, 1995)

Junnila in 2004

The environmental impact of an office building throughout its life cycle

This dissertation quantifies and compares the potential environmental impact caused by an office building during its whole life cycle, from the extraction of raw materials to disposal of waste. Using both a multiple-case study method and life cycle assessment (LCA) the study determines which are the life-cycle phases and elements contributing most to a building's life-cycle impact. The impact categories taken into account in this dissertation are energy consumption, global warming potential, photochemical ozone creation, water consumption and waste creation.

In the study, it was found that the contribution of the different phases were similar for both buildings studied, being building operations (electricity, heating and other services) the main contributor to the climate change, acidification and eutrophication impact categories, while for building material manufacturing (in construction and maintenance), main contributors were summer smog and heavy metals. (Junnila, 2004)

Petersen and Solberg in 2005

LCA by comparing wood and alternative materials in Norway and Sweden

This article gives a state of the art overview on quantitative analyses from Norway and Sweden of Life cycle analyses (LCA), which compare the environmental impact produced when using wood or other alternative materials, with emphasis on the impact category regarding greenhouse gas (GHG) emissions, acidification and waste creation. However, it also pays attention to economics and methodological issues.

In conclusion, this study shows that wood is usually a better alternative than other materials regarding GHG emissions. Furthermore, wood is causing less environmental impact regarding acidification and also generates less waste compared to the alternative materials considered. Wood as a building material is competitive on price in the economical studies. This study establishes that the fact that most of LCA studies do not include economical issues is an important weak point and, thus, it would be interesting to carry out a more specific research in order to combine traditional LCA with economic analysis. (A. Petersen, 2005)

Junnila *et al.* in 2006

Life-Cycle Assessment of Office Buildings in Europe and the United States

This study deals with the life cycle assessment of office buildings. Offices are chosen instead of other types of building given that they are thought to be significant sources of energy use and emissions in industrialized countries, but quantitative assessments of all of the phases of the life cycle of office buildings are still quite rare. With this aim, it calculates energy consumption and global warming potential along all the phases of the building life cycle.

The significant environmental aspects that were studied with this assessment indicate the dominance of the use phase in the quantified environmental categories. However, an important aspect shown was that the results draw attention to the importance of expected maintenance investments throughout the assumed 50-year service life, especially for particulate matter emissions. (S. Junnila, 2006)

Helena Monteiro and Fausto Freire in 2011

Life-cycle assessment of a house with alternative exterior walls: Comparison of three impact assessment methods

In this case, a life-cycle model has been implemented for a Portuguese single-family house. The first goal of this study was to characterize the main life cycle processes (material production and transport, heating, cooling, maintenance) studying seven alternative exterior walls for the same house to identify environmentally preferable solutions. On the other hand, the second goal is to compare the results of three life-cycle impact assessment (LCIA) methods in order to compare them and see how the method implemented can affect the final results of an LCA. So, in this case many impact categories are taken into account so as to be able to make comparisons.

The results for the first goal showed that wood-walls are the preferable solution while for the second one it was found that it exists a correlation between the different methods regarding climate change/global warming potential (GWP), acidification and eutrophication. However, no correlation was found with the remaining impact categories. (H. Monteiro, 2011)

Van der Lugt *et al.* in 2006

LCA for using bamboo as building material in Western Europe

This paper discussed the potential of bamboo as a building material for Western countries. In the study, a comparison between bamboo culms and other more common materials in Western Europe buildings was carried out regarding environmental impact and economical issues. It is also important to say that only temporary buildings were studied for this assessment. Moreover, in this case impact categories taken into account are different than all the other researches consulted but it deals, between others, with the energy consumption during all the phases of the building life cycle.

Finally, this paper showed that, within certain boundary conditions and with consideration of the recommendations established in the case of study, bamboo is a very sustainable building material for Western countries and it even can be competitive to materials more commonly used. However, bamboo is a natural product and will therefore always have some irregularities in its properties. So, it is suggested that in Western European countries it should be used only in functions were the measurement requirements are not precise or fixed, as in some types of temporary buildings or small civil constructions such as bridges. (V. der Lugt, 2006)

Rachel Spiegel in 2014

Life Cycle Assessment of a new School Building designed according to the Passive House Standard

This thesis contributes on growing the body of literature for LCA of public buildings in Norway. It deals with the life cycle assessment of two buildings for the comparison of the construction and use of a school built after the Norwegian building code, TEK10, and a school designed following the passive standard. In this case, impact categories that were taken into account are: climate change, photochemical oxidant formation, ozone depletion, terrestrial acidification, freshwater eutrophication and human toxicity.

The overall conclusion of this thesis was finally that it is environmentally beneficial to build and operate a passive school compared to a school following the TEK10 building standard. Moreover, it was found that the energy use from the operation phase of the building had the highest impacts for most of the indicators that were studied. (Spiegel, 2014)

Martin Melvær in 2012

Life-cycle assessment of a multi-family residence built to passive house standard

The present study evaluates life cycle performance of two passive buildings and two low energy buildings that are all part of the housing cooperative Løvåshagen in Bergen. The main goal was to prove what a high number of previous studies had found before: that low energy buildings generally have better life cycle performance than passive buildings. In this specific case, many impact categories were studied such as climate change, toxicity, photochemical oxidation formation, terrestrial acidification and freshwater and marine eutrophication between others.

The LCA results in this thesis showed practically no difference between the climate change performances of the two house models studied, which is surprising as usually it is expected that the passive house produced a significantly higher impact than the low energy building. Moreover, an interesting conclusion was that in simulation-based LCA literature appeared to be a trend of over-estimating the operational performance of passive and low energy buildings and, for this reason, the measured electricity consumption is high, both compared to estimations and to the results of other simulation-based studies. (Melvær, 2012)

Oddbjørn Dahlstrøm in 2011

Life Cycle Assessment of a Single-Family Residence built to Passive House Standard

The objective of this thesis was to assess the environmental costs and benefits of moving to a passive house from the building standard operating at that moment. One TEK07 and one passive house model of the same wooden framework house design were analysed. So, the environmental costs and benefits for both houses were analysed in a cradle-to-grave life cycle assessment. With this aim the impact categories taken into consideration for this study were climate change, human toxicity, photochemical oxidant formation, terrestrial acidification, freshwater and marine eutrophication and some others.

The overall conclusion was that it is environmentally beneficial to build, operate and waste treat a passive house compared to a house following the TEK07 building standard. Firstly, it was showed that passive houses produce higher impacts when studying the construction phase and the end-of-life treatment than the TEK07 house in all impact categories studied. However, an overall impact reduction between 15% and 20% is achieved for the passive house, also in all categories, when the house operation phase is included. (Dahlstrøm, 2011)

4.3 Main points in common

Once all cases considered in this point are presented, it is possible to summarise all the information in order to make it easier further comparisons and, finally, obtain principal conclusions. In the following table (M. Khasreen, 2009), it can be observed the main characteristics of all the cases:

AUTHOR	BMCC	WPC	CONTENT, COUNTRY AND YEAR	IMPACT CATEGORIES INCLUDED										
				GWP	A	E	OD	HT	EN	WC	DA	W	EC	O
A. García Martinez		x	LCA of three different buildings in Spain (2010)	x	x	x							x	
J. Sanz San Pablo		x	LCA of an average dwelling in the city of Murcia, Spain (2012)						x					

D. Aral		x	LCA of a multi-storey-mass housing in Turkey (2012)	x		x	x	x			x		x	x
Asif *et al.*	x		LCA for eight different materials for a dwelling in Scotland (2005)	x	x				x					
Cole and Kernan	x		LCA for different structural materials for a office building in Canada (1995)						x					
Junnila		x	LCA for the construction of an office building in Finland (2004)	x			x		x	x		x		
Petersen and Solberg	x		LCA for comparing wood and other materials in Norway/Sweden (2005)	x	x							x		x
Junnila *et al.*		x	LCA for comparing office buildings in Europe and the United States (2006)	x					x					
Monteiro and Freire	x		LCA of a house with alternative exterior walls in Portugal (2011)	x	x	x	x	x			x		x	
Van der Lugt *et al.*	x		LCA for using bamboo as building material in Western Europe (2006)						x					x

Spiegel	x	LCA of a new school passive building in Norway (2014)	x	x	x	x	x						
Melvær	x	LCA of a multi-family passive house in Norway (2012)	x	x	x	x						x	x
Dahlstrøm	x	LCA of a single-family house in Norway (2011)	x	x	x		x		x			x	x

Table 4.1 Characterisation of previous researches

Abbreviations:

BMCC Building and material components combination

WPC	Whole process construction	EN	Energy consumption
GWP	Global warming potential	WC	Water consumption
A	Acidification	DA	Depletion of biotic resource
E	Eutrophication	W	Waste creation
OD	Photochemical ozone creation	EC	Eco-toxicity
HT	Human toxicity	O	Others

In the following point some of this aspects will be analysed and compared between all the studies considered and so the main basis will be established for the new LCA that is going to be performed in this thesis.

4.3.1 Preliminary results

First, as it can be seen from the descriptions of the previous studies chosen, the majority of assessments are from Europe and USA, so, so mostly northern countries. The published LCA case studies also demonstrate a noticeable increase of performances of this type of assessment starting in approximately 2005 given that is much more easy to find LCA assessed since this year.

On the other hand, it is also interesting to see that approximately 60% of the cases have been applied to the WPC approach, while the rest had the BMCC one. The WPC cases cover different functions of buildings such as residential, office and educational. Specifically, the review results point out that the most examined functional group is the residential buildings with a 54% rate, followed by office buildings with 23%. So, this is a favourable point due to a residential building LCA is going to be carried out in this thesis.

The LCA for WPC studies usually have more than one aim. The most common and principal goal is whole life cycle impact analysis of the building. On the other hand, there are many other goals, which aim is to draw the attention to specific issues depending on the situation, the final use and the complexity of the building studied. From the reviewed literature it is also found that comparative LCA are really common so as to find out the most adequate materials or solutions in building constructions. Examples of common comparisons in LCA assessments are the following (G. Finnveden, 2009):

- Different locations in order to compare buildings situated in different countries or climate regions.
- Different material in order to compare two similar buildings that have been projected with different solutions.
- A building versus its different material, component, structure or system options in order to find out the best option for an specific building.
- Energy performance improvements (in order to calculate the results when, for instance, constructing following passive house standard).

Finally, it is important to take into account that hotspot determination is also a common application for whole process construction LCA. Thus, it is possible to identify the most harmful materials or life cycle stages in order to come up with more effective improvements.

In front of comparative LCA, building total footprint is a different approach, which aims to provide detailed environmental impact analysis information. In this case, the main goal is not to compare specific options to help in a decision-making process, but to find out the environmental information from a further aspect. For this reason, it doesn't judge whether the building is favourable or not for the environment.

On the other hand, BMCC studies focus their attention into a specific part of material of the building. Last years, industrialized countries have made a big step in order to improve construction processes and buildings towards sustainability. What is interesting in this point is that these improvements are strongly dependent on many aspects of the location such as the climate area or the availability of raw materials. For this reason, LCA studies calculating the environmental impacts of BMCC can be really helpful.

Regarding the functional unit (FU) used for building constructions is usually a square meter of usable floor area for a specific time but, in some cases, the whole building is considered to be the FU. In case of analysing the whole active life, the most common life span used is 50 years. Furthermore, in some cases and depending on the main goal of the study, the functional unit can be modified adding other parameters such as occupancy, performance or site of the building. On the other hand, when performing an LCA to study a building material or component, it is more common to use as the FU a kg or m^2 of the product.

4.4 Conclusions

In this point it has been presented a wide range of studies regarding building LCA. Firstly, it is important to say that, as expected, the most studied impact categories were energy consumption and global warming potential. On the other hand, many of the studies presented take profit of the facility that represents this type of analysis for performing comparisons between different construction materials or different versions of the same type of building.

Concretely, when looking at the conclusions of all researches, we can see that the use phase is generally pointed out as the most polluting. However, the wide range of assessments considered, which makes them too different, produces that no more conclusions in common can be made.

5

Case of study: Life Cycle Assessment for an apartment project in Nardovegen

5.1 Introduction

In this chapter an LCA study is performed on a specific building project. First, a general description of this project will be realized in order to make it easier the comprehension of the following steps. In the case of not having access to all data needed to perform the analysis due to lack of detailing drawings, assumptions will have to be made. Given that the aim of this thesis is to perform a reference for future LCA studies carried out in similar buildings, these assumptions will have to be made taking into account typical solutions used in this kind of buildings.

First, the scope of the LCA will be defined and general assumptions will be made and justified so as to avoid performing a too complex assessment, which is unnecessary to obtain reliable results. Then, for each one of the building life cycle phases that are going to be considered, a detailed inventory of all energy and material resources will be performed. At this point it is important to bear in mind the system boundaries and assumptions made during the goal and scope definition phase.

Finally, the results from the LCA software SimaPro, which uses EcoInvent database, will be presented and analysed, performing also uncertainty and sensitivity analysis at the end.

5.2 Description of the building

The building that is going to be studied is situated in the city of Trondheim (Norway), capital of the county of Sør-Trøndelag. Specifically, the area of study is limited Nardovegen and Kringsjøveien. A scheme of the building on an overview of the area is represented in the following figure:

Figure 5.1. General overview of the location of the buildings

The project consists on the construction of 3 buildings situated on the North part of the location and 5 smaller buildings on the South. The available information of this project describes the works necessary to build the three white buildings located on the northern part. These buildings have mainly a residential purpose and have been chosen because they can be used as a reference when performing future LCA assessments in similar projects. Moreover, this LCA can be used also with the aim of comparing the environmental impact produced during the life cycle of future buildings. In the corresponding point, a more detailed description of each one of the parts in which buildings have been divided will be presented.

5.3 Goal and scope definition

This is the first stage of the LCA methodology presented on the first chapter of this thesis. This is a basic part, as it is when the purpose of the study, its aim, boundaries, assumptions and hypothesis will be established. It is important to take into account the importance of these decisions, as the results obtained will only be valid for the specific conditions detailed in this first phase.

5.3.1 Goal of the study

As it is established I the standard ISO 14040 (ISO 14040:2006 standard, environmental management, 2006), this point should define the aim of the study as well as the reasons for which this study has to be carried out. On the other hand, also the target of the study has to be defined, which means defining to who is addressed the study.

Aim of the study

The main goal of the study is to estimate the life cycle environmental impacts produced mainly during the construction phase of the project for the new apartments in Nardovegen, Trondheim. It is important to take into account the relevance of carrying out an LCA for a building project given that construction industry represents a high percentage of the CO_2 emissions in the world.

On the other hand, the most interesting aim of this thesis is the possibility to compare the environmental impact of this construction compared to other future constructions of residential buildings with similar characteristics.

Reason for carrying out the study

It is widely proved the necessity of being conscious about the effects on the environment due to building and construction industry.

In order to understand this impact of urbanization on natural environment, it is important to have a close look at the construction sector, which is responsible from a significant resource consumption and waste production during the whole life cycle of buildings. Common Carbon Metrics (UNEP, 2015) states that the environmental footprint of construction sector includes 40% of energy use, 30% of use of raw materials, 25% of solid waste, 25% of water use, and 12% of land use.

Life cycle assessment is, as it has been said, one of the methodologies intending to assess those impacts and the main advantage is that it allows taking into account all the life cycle phases of the building, which was not possible through previous methodologies. Hence, this approach allows obtaining more detailed and reliable results regarding environmental impact of any type of product or process.

Target of the study

Given that this is an academic master thesis, the target of this study is the Norwegian University of Science and Technology (NTNU) University. It has to be considered that, as the intended audience may not be familiar with the general LCA methodology, a complete description of it has been carried out. This way, it makes easier to understand Life Cycle Assessment methodology.

Once defined the main characteristics of the goal of the study it is possible to define the limits that will be taken into account as it is established in the following point.

5.3.2 Scope of the study

In this case, according again to the standard ISO 14040 (ISO 14040:2006 standard, environmental management, 2006), this point should include a definition of the product or system that is going to be studied, its functions, the functional unit, the system boundaries, allocation procedures, impact categories to be analysed, initial data quality requirements and assumptions and limitations.

System description

As it has been defined, the system that is going to be studied is the one projected for the new apartments at Nardovegen, in Trondheim. It is a set of 3 buildings, which involves a total of 46 apartments.

Figure 5.2 Main design of the buildings considered in the study

Drawing above shows the three buildings studied. In order to carry out the study and be able to easily analyse data obtained, all measurements have been made separately for the three buildings and dividing them in the different categories listed below:

Foundations	General flooring
External walls	Terrace and balcony flooring
Internal walls	Roofing
Partitions	Doors and windows

Function

The purpose of this set of buildings that have been projected is mainly residential. It also includes a parking area at level 0 of building A and two bicycle parking areas in this same level and at the first level of building C.

It is important to know the surfaces used for each building in order to be able to perform the LCA. Specifically, most of the apartments consist on two rooms with a total surface of 44 m^2 and there are also some apartments of one room and two bigger apartments distributed in the following way:

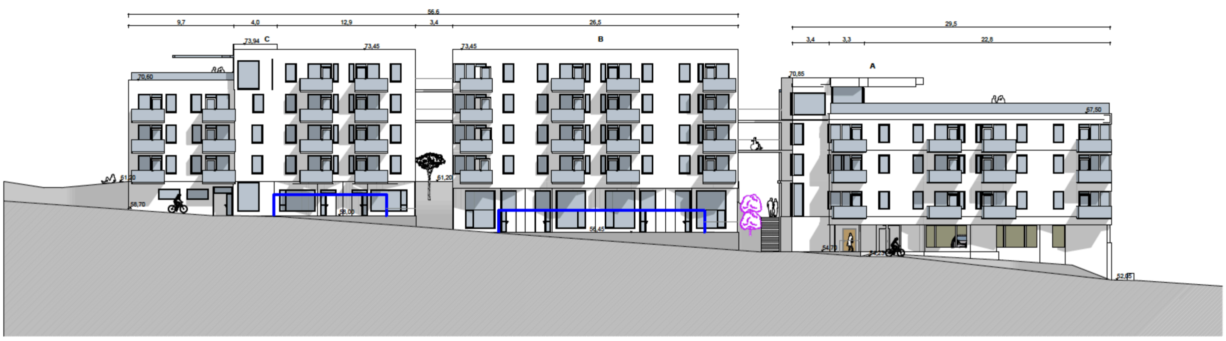


Figure 5.3 Facade east

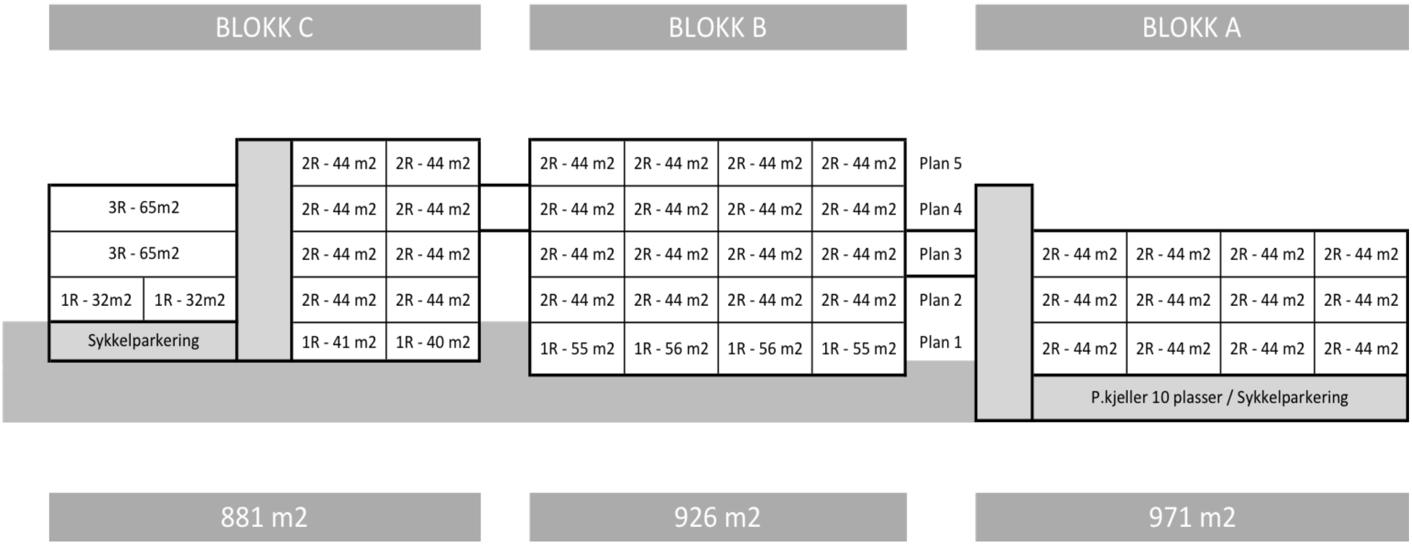


Figure 5.4 Distribution of the apartments

Functional unit

According to the standard ISO 14040 (ISO 14040:2006 standard, environmental management, 2006), the functional unit is defined as *the quantified performance of a product system for use as a reference unit*. Defining an adequate functional unit is essential when one of the main goals of the study is to allow future comparisons. Moreover, if one stage or part of the building is not considered, it must be explained and justified.

The following functional unit is used for the present Life Cycle Assessment: 50 years of 1 m^2 utility floor space of a residential apartment in a block of flats, including the following building life cycle phases: production of the materials, construction, maintenance and operational energy and water use.

The functional unit is equal for all buildings that are taken into account in order to give an overall understanding of the life cycle impacts produced by the new apartments in Nardovegen as a whole. Furthermore, we can observe that this functional unit combines physical and temporal criteria and that the presentation of results on a square meter utility floor space basis enables an easy comparison to other studies in the future.

System boundaries

Figure attached below shows the system boundaries that have been used for the present study. Finally, only three of the four main phases presented in the first point of this thesis are taken into account: production, construction and operation phase (including maintenance activities).

As the most analysed phase in this study is the construction phase, data taken from generic databases includes background processes, whereby more accurate results for the environmental impacts taken into account are obtained at the end. On the other hand, processes that are represented in red have been excluded from the present analysis. It is important to say that EOL phase has been finally excluded given that it has less relevance when comparing with the construction phase. On the other hand, operation or use phase has been taken into account for this study in order to study its proportion of environmental impact in comparison with the production and construction phase.

A description of the works included in each phase is also presented bellow:

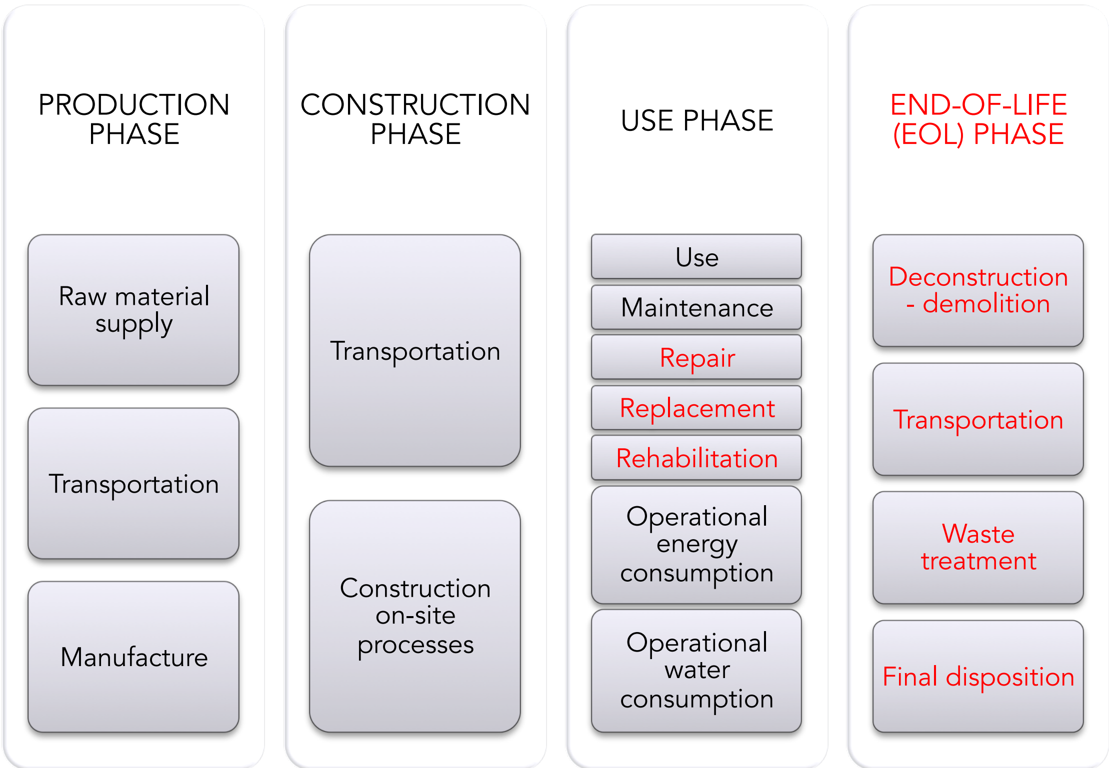


Figure 5.5 Life cycle phases and works considered in this study

- **Production phase:** the production phase includes mainly concrete, reinforcing steel and formworks. The production of the rented equipment is not considered in this analysis as this equipment is usually reused in other constructions and so the environmental impact related to a specific project is difficult to assess. However, some products or equipment processes from the generic database, EcoInvent, include infrastructure use.
- **Construction phase:** construction phase includes the environmental impacts produced from transportation of material, equipment and personnel to the construction site in Nardovegen, energy consumption on the site from machinery equipment use as well as waste management on the site.
- **Use phase:** this third phase studied includes, firstly, maintenance of building elements and operational water and electricity consumption. On the other hand, it has to be taken into account that the maintenance processes generate building material waste as well, which is not taken into account for this study. Finally, it is important to say that household waste generation, replacement and rehabilitation are also not included in the system considered.
- **End-of-life (EOL) phase:** Last phase of the building life cycle, which is not considered for this assessment, includes demolition of the buildings, which generates and important amount of building waste. This would be transported to a sorting plant or an incineration plant. Then, residues from the incineration are transported to an inert material sanitary landfill.

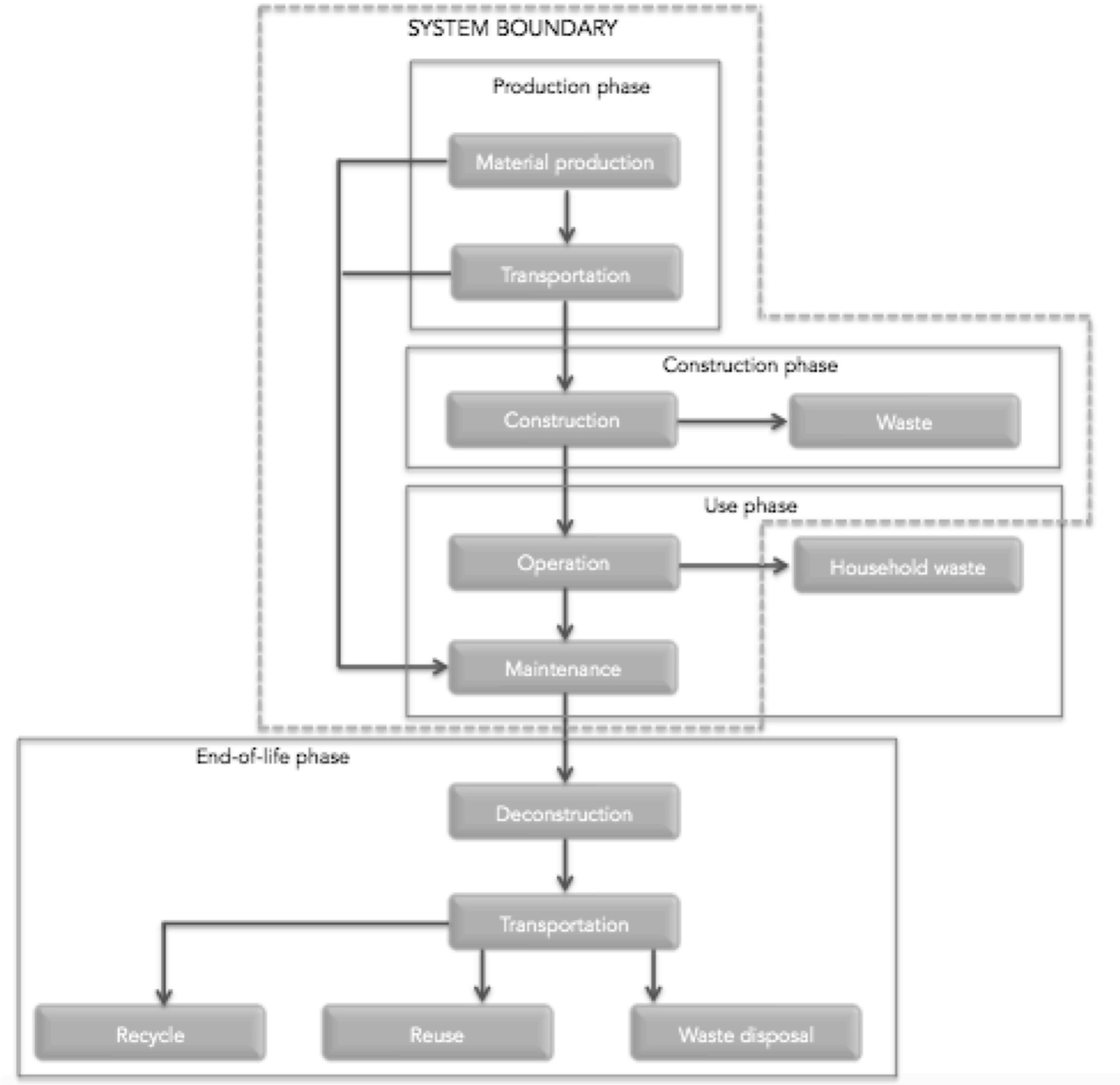


Figure 5.6 System boundary

When performing the LCI, all phases described in this system has to be considered following all the life-cycle process. So, after including all data in SimaPro software, it is possible to obtain the environmental impact produced at each step with a higher lever of accuracy.

Allocation procedures

Allocation procedures are used to distribute the environmental impact when several products or functions share the same process and it is difficult to know the exact contribution of each one of them. For example, when considering waste management, fraction of emissions associated to each component is unknown unless the exact composition of the bulk is known. In this case, allocation procedures are used in order to attribute accurately the pollution from transportation to each component.

According to the standard ISO 14044 (ISO 14040:2006 standard, environmental management, 2006), inputs and outputs shall be allocated to the different products according to clearly stated procedures that have to be always explained and justified. Allocation procedure are divided in three steps, which are the following:

- **Step 1:** firstly, it is necessary to observe if it exists a possibility to avoid allocation, trying to divide the processes in different simpler sub-processes find or calculate more accurate data.
- **Step 2:** if allocation cannot be avoided, inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects a physical relation between them.
- **Step 3:** as a last way to allocate the impacts, if physical relations cannot be found to distribute the outputs obtained, then another type of relation has to be found, for instance, economical value.

Allocation procedures in this study are avoided as much as possible. For instance, this is avoided for all materials considered in the production phase given that detailed calculations are made for all the materials. However, regarding the energy consumption at site from machinery and other equipment use, as only the total amount is available over the entire construction period, the energy has to be allocated proportionally to the weight of each component category. Also allocation procedures are made for some of the material and personnel transportation to the construction site. When calculations are presented in this chapter, it has to be explained when allocation procedures are applied.

Impact categories

As it has been said previously, Life Cycle Impact Assessment (LCIA) is the third stage of LCA methodology. It includes mandatory and optional elements. Choosing impact categories that are going to be studied is the most important of the mandatory elements of this stage and, consequently, also the methodology finally applied for impact assessment. These elements must be consistent with the goal and scope definition already presented. However, selection of impact categories and methodology of impact assessment are not specified in the ISO standards 14040 and 14044 and, therefore, the choice is left to the person that is going to carry out the LCA, who has to take make the decision taking into account the main goals of the study.

Although energy consumption and climate change impacts are often the focus of LCA studies, studying a wider range of impact categories gives a more accurate basis for decision-making. For the impact assessment of the present study, ten impact categories have been selected from the hierarchic version of the ReCiPe method included in SimaPro and these categories are described in the table below. Anyway, it is still useful to limit the study somewhat, and for this reason some ReCiPe impact categories have been excluded. These categories are the following: ozone depletion, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, and fossil fuel depletion. They are considered to be less relevant for various reasons.

Firstly, the first two are indicators of environmental problems that have less relevance for a study of buildings in the Norwegian context. Land use and fossil fuel depletion indicators are not included because of uncertainty for the Norwegian conditions. Finally, as water consumption is not a major issue in Norway, this indicator has been also excluded.

IMPACT CATEGORY	UNIT	DESCRIPTION
Climate change	kg CO_2 eq	Air emissions that contribute to the global warming.
Terrestrial acidification	kg SO_2 eq	Air emissions of inorganic gases (sulphates, nitrates and phosphates) that can be dissolved in water and change its acidity.
Freshwater eutrophication	kg P eq	Phosphate-rich water emissions that can produce adverse ecological effects.
Marine eutrophication	kg N eq	Nitrate-rich water emissions that can produce adverse ecological effects.
Human toxicity	kg 1,4-DB eq	Air emissions in urban areas that can affect human environment, usually consists on heavy metals emissions.
Photochemical oxidant formation	kg NMVOC	Air emissions, usually called *summer smog*, due to the production of ground-level ozone.
Particulate matter formation	kg PM10 eq	Air emissions usually due to the combustion of fossil fuels in the machinery.
Terrestrial ecotoxicity	kg 1,4-DB eq	Soil emissions, which are especially harmful on the land ecosystems because of toxic substances.
Freshwater ecotoxicity	kg 1,4-DB eq	Soil, air and water emissions that may represent an important damage for freshwater bodies.

Marine ecotoxicity	kg 1,4-DB eq	Water emissions that might be harmful for marine ecosystems due to the spill of toxic substances.

Table 5.1 Impact categories included in this study

Initial data quality requirements

Data collection and calculations usually represents one of the most time and energy consuming stages of an LCA study. Data has been collected as much as it has been possible but, in the majority of cases, calculations have been made in order to perform the data inventory. Moreover, it is difficult to determine how accurate must be data in order to give sufficiently precise results. Anyway, the standard ISO 14044 (ISO 14040:2006 standard, environmental management, 2006) gives some specific recommendations explained below:

- Collected data, whether measured, calculated or estimated, is used to quantify the inputs and outputs of a unit process and it has to be included in the data inventory describing each one of the unit processes that has been included in the system boundary.
- When data have been collected from public sources, they have to be referenced. It is important to define the day and the specific source from which data has been taken, as it may suffer changes. On the other hand, sometimes data collected does not fulfill all the necessary requirements to be considered for the study and, if it has not been possible to find better data, this shall be stated.
- Among other things, the major categories of the classified data may be energy inputs, raw material inputs, ancillary inputs, other physical inputs, products, co-products, waste, releases to air, water and soils as well as other environmental aspects.

Data used for this study are mainly directly collected from the different actors involved in the project as well as from the available drawings and other project information. On the other hand, it is important to say that, whenever it has been possible, data has been collected from EPDs, as data is specifically obtainer for each product. Otherwise, data has been collected from EcoInvent database, included in SimaPro software, which calculates the outputs from an average between different similar products.

Assumptions and limitations

Assumptions and limitations are important part of the goal and scope definition. They have to be presented in order to allow the results of study to be considered reliable and enough accurate but avoiding too complex systems. A list of assumptions and limitations is presented below, divided into two categories. The first one is *general assumptions and limitations*, which are valid when carrying out an LCA of any building construction, and *specific assumptions and limitations*, that are related specifically to this project.

General assumptions and limitations:

- **Preparatory works:** all types of work needed before the start of the construction of the building, such as consultancy, administrative and documentation works are not considered in this analysis since data inventory would be very energy and time consuming and uncertain. Moreover, environmental impact produced during this phase is supposed negligible in comparison to the whole building life cycle.
- **Economic and social assessment:** this study only deals with the impact categories stated above, and so no results are obtained regarding economic and social aspects.
- **Carbonation mechanism:** carbonation of the concrete is a very complex mechanism to model as it depends on many factors: concrete composition, porosity, weather conditions and many other parameters. For this reason, the results over a 50-year period have a very inconstant behavior and so this carbon-saving mechanism is not included in this analysis.

Specific assumptions and limitations:

- **Material data limitations:** as it will be explained, some components are not included in the production and construction phases. For instance, the contribution from the production of temporary equipment (scaffolding, machines…) is sometimes not considered.
- **Energy consumption assumptions:** for the construction phase, some assumptions for the energy use have to be realized as it is almost impossible to determine the amount of energy required during each one of the construction activities.
- **Energy consumption limitations:** as stated in the system boundaries, the production phase does not consider the contribution from the manufacturing processes of several products, as they contain a high uncertainty or they are sensible to be reused in other constructions.

Once all these points are defined, the first phase of the Life Cycle Assessment that is being carried out can be considered as finished given that all the basic characteristics has been defined. At this point, all data defined as necessary has to be collected and listed in the Life Cycle Inventory (LCI).

5.4 Life Cycle Inventory (LCI)

The standard ISO 14040 (ISO 14040:2006 standard, environmental management, 2006) provides general specifications that are needed so as to carry out an LCI correctly and with the appropriate accuracy:

- Carrying out an inventory analysis is an iterative process: while data is being collected and more is learned about the system, new data requirements or limitations may be identified and, so, change are needed in the data collection procedures so that the goals of the study will still be fulfilled.

- The two main ways to obtain data are data collection and data calculation. Both cases have specific requirements in order to ensure the reliability of the results, which have been defined in the first stage of this LCA (goal and scope definition).
- It is important to study the necessity of applying an allocation procedure, and use them only when it represents the most accurate solution and always describing the process followed to allocated the impacts. The allocation method is described in the first phase of this LCA study (goal and scope definition).

So, in the following figure is possible to observe the procedure determined in the standard ISO 14040 (ISO 14040:2006 standard, environmental management, 2006)in order to perform an LCI:

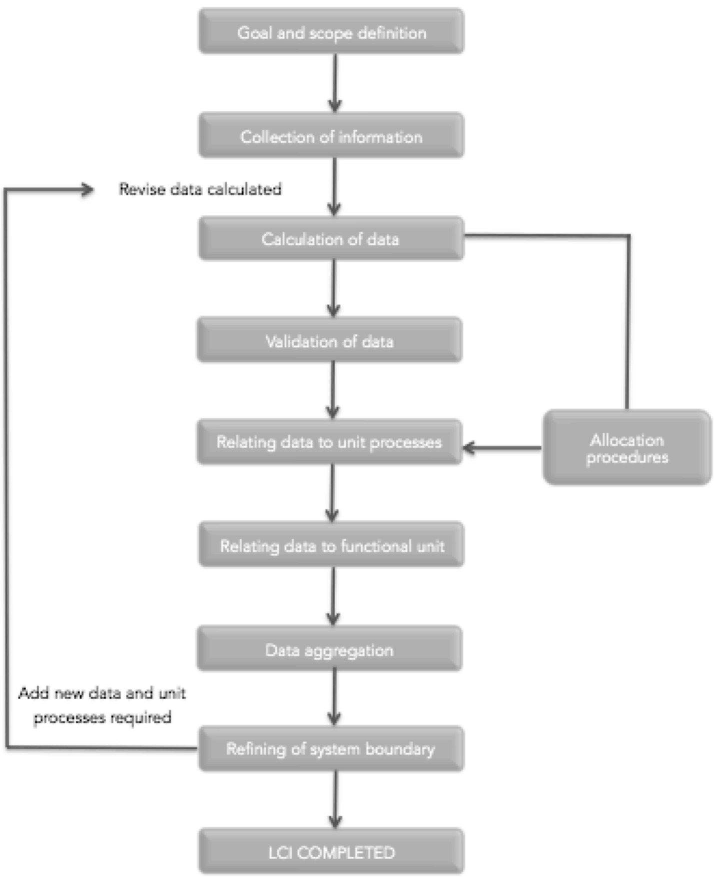


Figure 5.7 Simplifies processes for inventory analysis

LCI of buildings, and construction in general, is a quite complicated task, as in comparison to industrial products the life cycle phases do not follow a linear production line. Each building construction is a unique type of product as the optimal solution is planned depending on the emplacement and function. Moreover, quantification of input flows can be highly uncertain, especially during the construction phase.

The decision-making process that has been followed regarding input data source for the production and construction phases is represented in figure above. Input data collected for the LCA study for the new apartments in Nardovegen are obtained from some specific available information and drawings of the project. When specific data about products is not available, it has been tried to find if an EPD of the specific product or a similar one is available. Finally, when such information cannot be found, generic data from the EcoInvent database is used:

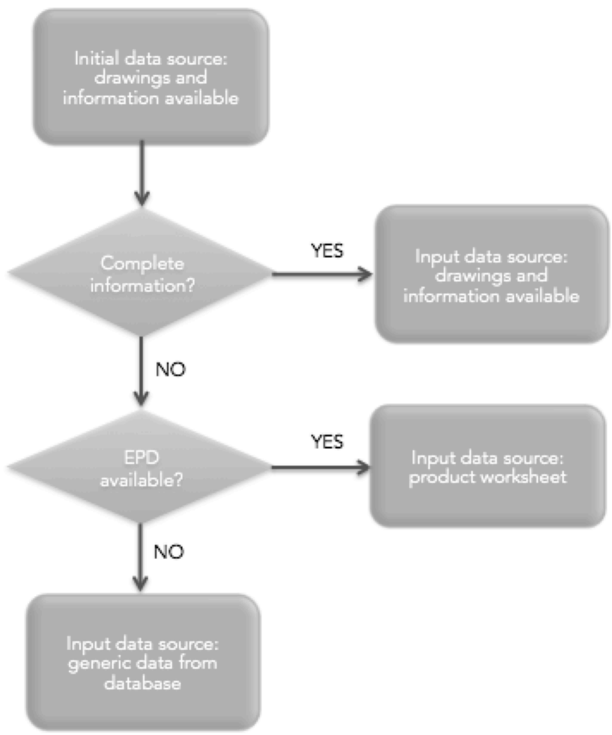


Figure 5.8 Decision-making processes for input data source

As it has been presented, LCA software used so as to perform this assessment has been SimaPro 8, which integrates the EcoInvent v3 database as well as the ReCiPe methodology for Life Cycle Impact Assessment. Then, in this section data inventory for each phase taken into account will be detailed.

5.4.1 Production phase

As it has been established before, the production phase includes mainly concrete and reinforcing steel as well as some specific products. In the following points, a more detailed description of each one of the parts in which the buildings are divided will be performed.

Groundwork and foundations

This first category consists on the addition of spot foundations and foundation walls. Also the amount of soil excavation is calculated in this point but will be considered in the construction phase.

Regarding the foundations, it is also important to remark that this is the part of the buildings that has a higher variation depending the location in which the construction will be carried out. The main reason is that groundwork machinery strongly depends on the properties of the terrain and the same happens with calculations to obtain the measures for the different foundations.

Anyway, in this case the solution proposed is mainly with wall foundations, which have a high between 20 and 45 cm, and are located at the base of the main walls to act as a support system. Isolated foundations are located at specific areas. Steel reinforcement taken into account for the foundations of the three buildings varies between 80 and 90 kg/m^3 of concrete.

External walls

As it has been said, the main structure for these buildings is planned with concrete walls. When calculating the materials for the external walls, they are considered to have a total thickness of 25 cm of reinforced concrete with a ratio of reinforcement of 90 kg/m^3. On the inner part of the wall, a gypsum layer is also added but, regarding the surface painting, it is considered to be part of the operation phase of the building.

On the other hand, there is a different wall for the building A given that is at the basement level. This specific wall has the same thickness of concrete and ratio of reinforcement steel but it needs a drainage board situated in the outer part given that it is in contact with the terrain.

Internal walls

In case of the internal walls, which are the ones separating different apartments, they need a higher level of insulation than the partitions inside every apartment. Specifically, they are considered to have a concrete thickness of 20 cm. In this case, reinforcement ratio can be lower because these walls are not part of the main carrying system and finally it has been considered 80 kg/m^3.

Finally, also a gypsum skimming has been planned but, in this case, is important to say that must be applied on both faces of the wall given that they are located in the interior part of the building.

Partitions

Finally, also partitions have been considered to have a different design considering that they do not carry important loads and can be even demolished in the future to change the interior design of the apartments. Hence, the main material in this case are double hollow bricks with a much lower thickness, in this case finally of 8 cm. As in the previous case, also a gypsum skimming has to be planned on both sides of the wall given that they are inner walls.

On the other hand, also in this case surface finishes are considered to be included in the operation phase of the building.

General flooring

In the following points different types of flooring included in the buildings will be described.

Specifically, this first category includes ground flooring designed for parking areas, situated in buildings A and C, and general flooring designed for the interior of all the apartments for the three buildings.

Regarding ground floors, they need a thicker layer of concrete due to the high loads applied in parking areas. So, finally, this flooring consists on a thickness of 12 cm of concrete with a net K257 acting as the reinforcement. For calculations, is important to know that this net represents 3,6 kg/m^2. Finally, in this case also a plastic layer and an insulation layer of 100 mm has to be considered to ensure the good insulation of the ground floor, which is in contact with the terrain.

For the internal floor, the thickness of concrete is reduced to 10 cm, but with the same reinforcement. Also an insulation layer, which is thicker than the one considered in ground floor, is installed and consists on a 250 mm thick polystyrene slab. In this case, it is necessary to ensure specially the insulation of the wet areas. So, it has been planned to install a waterproof membrane in addition to the necessary slope. Also a special surface treatment consisting of an Ethafoam layer of 10 mm is necessary around concrete walls.

Balcony and terrace flooring

In this case, a thicker layer of concrete is necessary as it has direct contact with the possible external agents acting on the building. Thus, the total concrete thickness for terrace and balcony floors is of 20 cm. Regarding steel reinforcement, it consists on the same net K257 with a weight ratio of 3,6 kg/m^2.

In the case of terraces the insulation layer is thicker, 100 mm against the 80 mm installed in balconies, given that it is installed above apartment areas and so a major insulation is needed. Finally, in both cases it is applied a surface treatment consisting on an Ethafoam layer of 10 mm situated next to the walls to ensure a proper insulation.

Roof

A compact roof is designed for the three buildings. Thus, it has a similar layer distribution than terraces. Specifically, the total concrete thickness is the highest between all the horizontal components of the buildings, with 250 mm. Moreover, reinforcement in this case is not planned with a net, but with a higher weight ratio of 110 kg/m^3.

On the other hand, is especially necessary to take care of the insulation of the roof. With this aim, an insulation layer consisting on 100 mm of high-density polystyrene and also a 10 mm thick layer of Ethafoam around walls and weak points is important to install.

Windows and doors

For the doors, many different models are planned but, as no specific information is available, it has been considered wood doors for both internal and external doors, which is considered to be an enough accurate assumption. On the other hand, for balcony and terrace doors, it has been considered a double-glazing system with an aluminum framework.

Also assumptions have to be made regarding the composition of windows. In this case, double-glazing windows with a maximum U-value of 1,1 W/m^2K are considered for all the different windows.

Formworks

For the calculation of the total amount of formworks required in the construction of the three buildings at Nardovegen, it is considered that they can be reused up to 8 times during all the process. The total surface has been calculated taking into consideration that formworks on both sides are necessary when concreting the walls and only on the bottom side for the floors.

Given that no specific data is available, it is supposed that formwork material is plywood with 18 mm thick panels.

Excluded elements

Taking into account all drawings and information available of the project, it has not been possible to describe accurately all elements of the buildings. However, it is considered that elements described are enough to obtain reliable results when performing the LCA assessment for the buildings at Nardovegen.

Thus, in the following points the main elements that finally are not taken into account in this study are described:

- **Electricity, plumbing and ventilation:** No drawings are available regarding the installations for the buildings. However, it has been observed in other previous researches that it does not represent a high contribution to the total environmental impact.
- **Additional wood:** during the construction phase, also more wood is necessary in order to ensure the security and other uses but it is not possible to estimate the amount.
- **Furniture and other interior elements:** these elements are finally not included as they strongly depend on the final users of the building and its interests regarding interior design.
- **Gardening:** Nardovegen project also includes a big area intended for gardening but it is not considered in this study as it only studies three of the eight buildings included in total in the project. So, it is not possible to define the total gardening surface related with the system considered for the present study.

5.4.2 Construction phase

This section includes a description and categorization of the inventory for the construction phase of the system, from the day work was started on the building lot until the completion of the buildings. This comprises the transportation of all building materials and other components, such as the scaffolding and the tower crane, to the construction site, including excess materials being transported from site as waste and energy used on site for different purposes. So, in this way three categories are taken into account: transportation of components to the construction site, emissions produced at the construction site and waste during construction (WDC).

The transportation to the site is divided in three types of transported unit given that different assumptions have to be made in order to estimate the environmental impact of each one of them: material, equipment and personnel. For instance, the first one is considered only a one-way transportation while the other two need a two-ways transportation and the mean of transportation considered is completely different when considering materials or equipment in front of personnel.

Emissions from construction on the site are due to three main sources, which are electricity, diesel and gasoline. In this case an allocation procedure has to be performed, as it is not possible to know the exact energy consumed in each one of the construction units.

Finally, waste management includes transportation of materials to recycling plant except for mixed waste that is transported to a landfilling area.

Transportation of components to construction site

Transportation is included in the construction phase given that means of transportation and traveling distances are highly dependent on the location of the building considered, and not on the production of the materials. So as to know distances, main assumptions are made regarding the providers and then Google Maps has been used to calculate the distance.

Regarding the means of transport, transportation of material and equipment to the site is mainly performed using transoceanic freight ship and lorry. On the other hand, transportation of personnel is only performed by car. So, the different calculations assessed are presented:

- Transportation of material:

  The following table shows the mean of transportation, route, distance, amount of material transported and amount of kilometer-ton, which means the transportation of one ton of material over one kilometer, of each product category.

  Processes that have been selected from the database are: “Transoceanic freight ship (TFS)”, which includes operation and maintenance of the ship as well as construction and maintenance of port facilities, and “Lorry > 16t, fleet average”, which includes lorry operation and maintenance as well as construction and maintenance of road infrastructures.

For all materials considered except concrete, only one way of transportation is assumed in this point. Indeed, transportation distances for this building are often very important, between 400 and 1000 km, and the products are mainly delivered in once for the entire construction period, so no frequent round-trips are necessary and less environmental impact is produced. In case of concrete, this is different since the concrete factory is based 10 km from the construction site, so round-trips are considered.

Next table presents the main distances taken into consideration for the calculation:

MATERIALS	TYPE OF TRANSPORTATION	ROUTE	DISTANCE (KM)	WEIGHT (TON)	KILOMETER – TONE (TKM)
Concrete	Truck (8 m3)	Nordlang betong – Nardovegen	10,5	3.665,67	38.489,53
Steel for reinforcement	Truck (25 t)	Mo I Rana – Trondheim	486	72,48	35.225,92
	TFS (2400 t)	Germany – Oslo	920	72,48	66.682,80
	Truck (25 t)	Oslo – Trondheim	510	72,48	36.965,47
Formworks	Truck (25 t)	Trondheim – Nardovegen	12	55,23	662,81
Insulation	Truck (25 t)	Askim – Trondheim	565	6,08	3.435,02
Bricks	Truck (25 t)	Lunde – Trondheim	656	200,34	131.424,75
Windows	Truck (25 t)	Moi, Rogaland – Trondheim	945	3,99	3.774,06

Doors	Truck (25 t)	Moi, Rogaland - Trondheim	945	23,38	22.093,44
Others	Truck (25 t)	NR	300	150	45.000,00

Table 5.2 Transportation of the materials

- Transportation of equipment:

  This section considers machinery equipment and temporary products used during the construction phase. Hence, transportation distances are counted twice given that the rented material or equipment will be sent back at the end of the construction phase.

  Next table shows the mean of transportation, route, distance, amount of equipment transported and amount of kilometer-ton per equipment category, taking into account the same elements from the database.

EQUIPMENT	TYPE OF TRANSPORTATION	ROUTE	DISTANCE (KM)	WEIGHT (TON)	KILOMETER - TONE (TKM)
Scaffolding	Lorry	Oslo – Trondheim	510	75	76.500
Tower crane	Lorry	Kjeller – Trondheim	494	200	197.600

Table 5.3 Transportation of the equipment

Regarding the tower crane, it is hard to allocate the impact produced during its transportation between the different categories since the crane helps handling many different elements at site. An allocation based on weight criteria is performed in the table that is attached bellow. So, the total impact due to crane transportation is allocated according to the proportional weight of each component category.

CALCULATED WEIGHTS	TON	%	BLOCK A	BLOCK B	BLOCK C
Total	4.509,53	100,00	1.663,31	1.546,15	1.300,07
Foundations	433,16	9,61	219,40	114,05	99,71
External walls	1.886,66	41,84	645,93	668,38	572,35
Internal walls	433,39	9,61	162,79	142,07	128,54
Partitions	249,32	5,53	86,90	101,72	60,70
General flooring	673,01	14,92	278,18	221,87	172,96
Terrace / balcony flooring	208,35	4,62	108,21	37,97	62,17
Roof	237,06	5,26	25,01	130,03	82,02
Formworks	55,23	1,22	20,37	18,95	15,91
Others	333,36	7,39	116,52	111,12	105,72

Table 5.4 Weight analysis for the allocation procedures

- Transportation of personnel:

  Finally, in this last section regarding transportation to the building site, transportation of personnel during all the construction phase of the building is assessed. This personnel includes all members of the construction site team: workmen, drivers, site managers… They are considered to represent a total of 15 people and to work at an average distance of 12 km from home. An allocation of the total transportation based on the weight analysis presented in the previous point is realized.

  The following table summarizes all the information about transportation of personnel and the result obtained:

PERSONNEL	QUANTITY	UNIT
Hired people	15	p
Travels realized (both ways)	240	p
Travelling distance (one way)	12	km
Kilometer - person	43.200	pkm
Amount / functional unit	15,55	pkm

Table 5.5 Transportation of personnel

Construction on the site

This part of the construction phase is the more complex as it includes many different sources of emission and it must consider the electricity and diesel consumption of some construction units that are difficult to estimate. In such effect, some estimation have been done regarding some aspects of this point always taking into account other studies made in similar buildings.

Therefore, construction on the site includes the emission produced by the machinery during all the construction process, in which the most important sources are groundwork and the tower crane, the electricity and water consumption in the barracks installed in the construction site during all the process and other sources such as the lighting and ventilation that must be installed at the site. So, the different calculations and assumptions made in this sense are presented in the following points:

- Electricity for the tower crane:

  This section includes the energy consumption of the tower crane once placed in the site during all the construction process. Is important to take into account that the transportation has been considered before and must not be calculated at this point.

  As an approximation, it has been established a common value for the electricity consumption of the tower crane in building construction, which is of 12.000 KWh per month. Taking into account that the estimated duration of the construction procedures for these buildings is 13 months finally is obtained a total of 156.000 KWh, which is equivalent to 561.600 MJ.

Moreover, is important to say that an allocation procedure has to be made, as it is not possible to know the amount of energy used in each one of the construction units considered and only the total amount of energy can be estimated.

- Barracks:

As the construction works are currently being carried out it has been easy to count the total amount of barracks installed at the site, which has been finally found out that is a total of 8 units. In order to introduce this consumption to the inventory in SimaPro it is necessary to estimate the water and electricity consumption with general values that has been considered as common values:

BARRACKS	QUANTITY	UNIT
Total offices	8	u
Total people hired	15	p
Area of each office	12	m^2
Average electricity consumption	90	KWh/m^2
Average water consumption	90	l/p
Electricity / functional unit	11,20	MJ
Water / functional unit	0,49	l

Table 5.6 Water and electricity consumption of barracks

As in the previous section, an allocation procedure has to be carried out for this source of emission given that is not directly related with any of the construction categories presented.

- Groundwork:

  In this case, firstly is important to establish that it has been assumed that the site of the property consist of land that is easy to handle, which means that is made for instance of clay and soil. Regarding the volume of soil excavated in each building, it has to be taken into account that the terrain in this area is very irregular, with an important slope, and so finally the total volumes obtained for soil excavation are the following:

EXCAVATION	TOTAL VOLUME	UNIT	TOTAL AMOUNT / FU
Block A	675,00	m^3	0,766
Block B	504,00	m^3	0,544
Block C	504,00	m^3	0,519
TOTAL	1683,00	m^3	0,606

Table 5.7 Groundwork volumes

In this case it is not necessary to calculate the volume of diesel consumed by the excavators, as it is already included when introducing the soil excavation in SimaPro inventory.

- Diesel for machinery:

  All the other construction processes of the building, although knowing that their influence to the total environmental impact during construction phase is lower, also requires energy and causes emissions, waste and noise. In many LCA studies this phase is neglected given that its minimal effect in total environmental impacts of the building life cycle. For this reason, information for construction process from literature is limited. Moreover, it is difficult to make accurate estimations because construction as a process is not static, but it varies from building to building since each has its own function and different engineering characteristics.

The energy data for construction machinery is calculated as electricity and diesel. Primary construction works are determined as fill (not the excavation as it has its own section where diesel is already included), compression, sand and gravel laying, cutting steel bars and concrete pumping and vibrating.

As it is very difficult to know the exact consumption because of the lack of data in this aspect, some estimations have been made taking into account similar studies:

MAIN CONSTRUCTION WORKS	ENERGY / FU	UNIT
Soil filling	50,50	MJ
Compression	0,20	MJ
Sand and gravel laying	1,25	MJ
Steel bar cutting	1,75	MJ
Concrete pumping and vibration	12,50	MJ
TOTAL	**66,20**	**MJ**

Table 5.8 Energy consumption during construction works

- Lighting at the construction site:

Construction site lighting is divided into work, emergency and surveillance lighting. On the construction site and in the work area (job site), there should be even general lighting, and where required for better visibility there should also be additional local lighting. So, it is important that the lighting suits the nature of work.

Emergency lighting is built on independent supply and installed mainly in passages and slopes with a luminosity of not less than 0.2 lux. Lighting of surveillance area begins from 0.5 lux. (J. Sutt, 2013)

The planning and realization of outdoor lighting is made more difficult by the changing construction site and working levels in time and space, which obliges relocation of lighting equipment. In such cases, mobile lighting equipment should be preferred, for example trailer masts on rubber wheels or rail track. This fact also makes more difficult the calculation of the total amount of energy required for the correct lighting of the construction site. However, taking into account the total area of the construction site and previous researches as references, it has been finally estimated a total energy of 40.000 KWh, which is equivalent to 144.000 MJ.

At this point all main sources of emission related with the works at the construction site have been described and other sources are considered as less important or irrelevant for the study that is being carried out.

Waste during construction (WDC)

Firstly, is important to say that waste management on sites is strictly regulated in Norway. Materials are sorted in four main categories regarding the waste treatment: wood, steel, clean cardboard and others.

Main sources of waste are wooden formworks, reinforcing steel and cardboard from packing but in this section is also important to consider the soil transportation.

WDC	TYPE OF TRANSPORTATION	ROUTE	DISTANCE (KM)	WEIGHT (TON)	KILOMETER - TONE (TKM)
Reinforcing steel	Lorry	Nardovegen - waste management site	300	4,35	1.304,66

Clean cardboard	Lorry	Nardovegen - waste management site	300	0,15	45,00
Formworks	Lorry	Nardovegen - waste management site	300	55,23	16.570,20
Concrete	Lorry	Nardovegen - waste management site	300	73,31	21.994,02
Soil from excavation	Lorry	Nardovegen - waste management site	100	1,45	144,92
				TOTAL	17.919,86

Table 5.9 Waste management during construction

It is assumed that steel and clean cardboard are 100% recycled and that mixed waste is landfilled. Since the benefits from recycling shall be attributed to other projects, environmental impact of recycling processes are not considered here and, as the composition of the mixed waste is unknown, landfilling process cannot be considered either. Therefore, processes considered are:

- Transportation of reinforcing steel: a transportation distance of 300 km is considered.
- Transportation of formwork: we consider that 100% of the plywood used as formwork is transported to a recycling plant. It is considered a transportation distance of 300 km.
- Transportation of clean cardboard and mixed waste: As in the previous cases, a distance of 300 km has been considered.
- Transportation of soil from groundwork: the disposal of the excavated soil from the groundwork is carried out in a nearer point, at 100 km from the construction site.

At this point all the processes during the construction phase has been presented and next phase can be assessed.

5.4.3 Operation phase

The operation phase of the building considered is divided in two main parts. The first one makes reference to operation itself of the building and the second one to the maintenance and repair of the main parts. So, in both cases is important to take into account that the life cycle of the building is considered to involve a total period of 50 years.

In the first point, water and electricity consumptions are considered, assuming an average consumption per person or surface unit. On the other hand, when taking into account the maintenance of the buildings, mostly elements that need to be renewed throughout the 50 years period are considered.

Operation of the buildings

The operation phase has been modeled in order to include electricity and water consumption for all the apartments. However, and although also the elevators and common areas such as garden and garage also will produce some consumption, this has not been included in the scope of the study. The main reason for not including these elements to the study is the fact that they are considered to be less important and, moreover, the operation phase will be calculated with less detail than the construction phase given that calculating the environmental impact during construction is the main goal of this thesis.

So, in the next points, water and electricity consumptions for the 50 years life cycle considered for the buildings are assessed.

- Water consumption (WC):

  In this case, it has been taken into account an estimated average water consumption found by Statistics Norway, which is based on reports from the municipal waterworks, and established a consumption of 212 l per person and per day. (SSB, 2010)

  So, in order to calculate the total water consumption, it has been necessary to know the amount of people that is expected lo live in these buildings. With this aim, the number of beds seen in the drawings has been used as an approximation.

Finally, the results obtained for each one of the buildings regarding water consumption are summarized in the following table:

WATER CONSUMPTION	PEOPLE PER LEVEL						AVERAGE WC (L/PERSON·DAY)	TOTAL WC
	0	1	2	3	4	5		
Block A	-	8,0	8,0	8,0	0,0	0,0	212	9,29E+07
Block B	-	12,0	8,0	8,0	8,0	8,0	212	1,70E+08
Block C	-	4,0	4,0	8,0	8,0	4,0	212	1,08E+08

Table 5.10 Water consumption

- Electricity consumption (EN):

  Regarding the electricity consumption for the buildings studied, usually is necessary to have data available in this sense in order to know the exact values. Given that these buildings are currently in construction process, data is not yet obtained. So, as an estimation of the value for the electricity consumption, it has been taken the value of 112,5 KWh/m^2·year.

  Then, in order to calculate the electricity consumption for each one of the buildings is necessary to know the area of each one of them and also take into account that the active life of the buildings is considered to be of 50 years.

  So, final results obtained regarding the electricity are the ones presented in the following table:

ELECTRICITY CONSUMPTION	SURFACE PER LEVEL (M^2)						AVERAGE EN ($KWH/M^2 \cdot YEAR$)	TOTAL EN
	0	1	2	3	4	5		
Blokk A	-	176	176	176	35,8	-	212	9,29E+07
Blokk B	-	222	176	176	176	176	212	1,70E+08
Blokk C	-	81	152	153	153	88	212	1,08E+08

Table 5.11 Electricity consumption

Maintenance and repair of components

First, is important to be able to calculate how many times the main elements of the building will have to be repaired or renewed during the total life cycle of the building. Thus, when considering the maintenance, it is important to know the main lifetimes of the components.

All the elements considered in this point are related with surface finishing given that these elements represent the interface between the building users and the building itself and hence affect the way people interact and perceive their built environment and the atmosphere of the building.

A surface finish should provide durable, visually attractive and low maintenance surface to floors, inner and outer walls, ceiling and roof. So, this section is divided into different elements considering painting, bathroom and floor covers, windows and doors. In the following table attached, service life and number of renewals needed for all these elements are presented.

Regarding surface finishes for year zero, before the house is in operation phase, one coat primer and two topcoats of paint are considered on outdoor walls, two coats of paint on indoor walls and ceilings, complete bathroom covers and wood parquet floor covers.

Other types of finishing such as furniture, kitchen equipment, interior decoration, electronic equipment and others are not included in this study given that all these products are user specific and cannot be standardized. So, these are the results obtained:

ELEMENTS FOR MAINTENANCE	SERVICE LIFE (YEARS)	NUMBER OF LIFE CYCLES	DESCRIPTION
Paint wall (outdoors)	8	7	3 coats per year 0 and 2 coats per cycle
Paint wall (indoors)	10	5	2 coats per year 0 and 2 coats per cycle
Paint ceiling (indoors)	10	5	2 coats per year 0 and 2 coats per cycle
Bathroom	30	2	Panel, wet room plates and tiles are considered to be replaced
Floor covering	20	3	Wood parquet floor is considered to be replaced
Windows and outer doors	30	2	All windows and outer doors are considered to be replaced

Table 5.12 Maintenance of components

In the following points, all the components that need maintenance (and has been presented in the table above) along the life cycle of the building will be described in detail:

- Painting:

  All wall surfaces of the building need to be painted at regular intervals as they are strongly affected by use of the building and time. Outside walls are considered to have a coat of primer and two topcoats at the end of the construction phase and, during the operation of the building, two new topcoats are applied every eight years. Given that inner walls are less exposed to external agents, only two coats are applied at the beginning and also two extra coats every ten years.

Regarding the painting of the ceiling for all the buildings, it has been considered as they have the same exposition than inner walls and so the same number of coats is applied. It has been taken into consideration an outdoor painting that is solvent based and an indoor painting water based.

- Bathroom:

  When calculating the maintenance for the bathroom areas, it has been considered that a general renovation of the surface finishes takes place after 30 years. This means that all ceramic tiles are replaced for all the bathrooms in the three buildings.

- Flooring:

  Parquet floor is used inside all the flats as a finish surface. Specifically, the type of parquet considered in this analysis is three layers engineered wood, with a total 14 mm thickness. Six coats of a water based acrylic varnish create the topcoats and, finally, it is necessary to say that the floor is assumed installed floating, glue free.

  According to general European producers, lifetime of floating multilayer parquet is set to 20 years, and so three life cycles are assumed for this flooring.

- Windows and doors:

  Given that the important exposition of windows and outer doors to external agents and the necessity of the good quality of them for the correct insulation of the buildings, all of them are considered to be replaced after 30 years.

5.4.4 End-of-life phase

Finally, the end-of-life phase has not been taken into account for this study given that it usually does not have relevant importance in building Life Cycle Assessments and, moreover, in this specific case the phase that has been studied in more detail has been the construction phase.

So, other phases have been studied in order to compare with respect to the results obtained for the construction phase, but end-of-life phase is considered to be less important. On the other hand, level of uncertainty related with this phase is the highest between all because it is very difficult to accurately predict the environmental impact of the recycling or incineration processes or the transportation distances that are going to be needed in 50 years. Finally, it should be also taken into account that, even if we consider that the operation phase consists on 50 years, usually buildings are not demolished after that, but usually some rehabilitation operations are performed.

5.5 Life Cycle Impact Assessment (LCIA)

As showed in the description above of the LCI phase, many input and output data constitute the inventory flows. The results of an LCA study cannot just display a list of disaggregated output data, as this would represent a huge number of values and would be neither comfortable to read and nor representative of the global environmental impact. This would also make difficult the comparison between results from different studies and hence make more difficult the results interpretation. For this reason, a first step of the LCIA is to aggregate values in impact categories and obtain one representative value per each.

5.5.1 Category indicators and characterization models

An impact category is a category to which the LCI data will belong and each one of them has a category indicator. Finally, characterization models describe in which context the impact category and the category indicators are defined. Furthermore, as it has been established previously, there are two types of impact categories: midpoint and endpoint. The midpoint approach models assess the impact categories regarding to the baseline impact categories and its impact to the environment, while the endpoint approach evaluates the damage caused to the areas of protection (AoPs), defined as the resources use, human health and ecological impact.

The choice of midpoint or endpoint indicators depends on the scope of the study, since midpoint indicators are easy to calculate but hard to interpret (in terms of effects on the planet), whereas endpoint indicators are hard to calculate but easy to understand. In order to allocate an impact category, a category indicator and a characterization model to all output data from the LCI analysis, different methodologies have been developed but the standards do not advice one specific methodology for the moment.

However, some guidelines and recommendations are given in the ISO 14044:2006 (ISO 14044:2006 standard, environmental management) standard:

- Information and sources used must be referenced when impact categories, category indicators and characterization models are selected in an LCA. This also applies when new impact categories, category indicators or characterization models are defined. Examples of impact categories are given in ISO/TR 14047.
- The selected set of impact categories studies have to reflect a comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration.
- LCI results other than mass and energy flow data included in the LCA (for example, land use) have to be identified and their relationship to corresponding category indicators has to be determined.

In this analysis, as it has been said, a total of 10 indicators have been taken into account but special attention has been paid to the climate change, a midpoint impact category, as it is the only impact category related to greenhouse gases emissions. The only sources of greenhouse gases emissions are related to mass and energy flows. Hence land use is not considered in this analysis (this would be relevant in the impact category abiotic depletion, for example, if this had been finally considered).

The table shown below specifies the characterization model and other information related to the climate change impact category:

IMPACT CATEGORY	EXAMPLE
LCI results	Amount of greenhouse gas emissions per functional unit
Characterization model	Baseline model of 100 years
Category indicator	Infrared radioactive forcing (W/m^2)
Characterization factor	Global warming potential (GWP_{100}) for each greenhouse gas such as kg CO_2 eq
Category indicator result	Kilograms of CO_2-equivalent per functional unit
Category endpoints	Coral reefs, forests, crops
Environmental relevance	Infrared radioactive forcing represents potential effects on the climate, depending on the atmospheric heat adsorption

Table 5.13 Climate change category

5.5.2 Characterisation of LCIA results and other elements

Category indicator results are calculated with SimaPro for each impact categories using characterization factors. These factors are coefficients that are multiplied by each output data related to the impact category selected in order to sum all corresponding data in one single score. The characterization factor values represent the relative importance of each output data compared to a reference output data. The calculation of the characterization factors also depends on the characterization model selected.

Additional elements can be added to the LCIA phase depending on the goal and scope definition of the study. These elements aim on helping the decision makers through the calculation of a unique value to indicate the level of environmental impacts of a project when several impact categories are selected for the study. With this method, all impact category results are aggregated in one single indicator. However, these optional elements are not yet regulated by any standard. Hence, the choice of the factors is often subjective and can lead to misinterpretations of the LCIA results. According to the ISO 14044:2006 standard (ISO 14044:2006 standard, environmental management), the different optional elements are defined as following:

- **Normalization:** this process aggregates the value of all category indicators relative to reference information.
- **Grouping:** this process aims on rating and ranking all impact categories.
- **Weighting:** in this case, in order to aggregate the results of the different impact categories, numerical factors are used.
- **Data quality analysis:** in this last case, the aim of this optional element is not to aggregate all category indicators, but to show the reliability of the LCIA results.

Normalization, grouping and weighting are not relevant in this analysis since only one impact category is deeply studied. However, if in the future another building assessment aims to study many different impact categories, these three optional elements should be taken into account in order to help with a better understanding of the results. Regarding data quality analysis, the last element presented, uncertainty and sensitivity analyses are performed at the end of this chapter. Uncertainty analysis deals with data that are not completely reliable and it aims to observe the variations produced on the output data when changes are applied on the most uncertain inputs. On the other hand, the sensitivity analysis tries to evaluate consequences when applying changes on input data related with the major contributors to the environmental impact.

5.6 Interpretation of the results

The interpretation phase is the last stage of an LCA study. Indeed, as we can see in the third figure *General LCA methodology*, the interpretation phase is not simply coming after the

LCIA phase, but is directly related with all the previous phases. Specifically, this phase takes into account the results from the Life Cycle Inventory and the Life Cycle Impact Assessment together, and establishes a consistent relation with the goal and scope definition.

Moreover, according to the ISO 14040:2006 standard (ISO 14040:2006 standard, environmental management, 2006), the interpretation phase has to show that the LCIA results are based on a relative approach, that they indicate potential environmental effects and that they predict environmental impact for endpoint categories such that they do not represent an excessive risk. According to the ISO 14044:2006 standard (ISO 14044:2006 standard, environmental management), the interpretation phase has to include the following elements:

- Identification of the hotspots of the system based on the results of the LCI and LCIA.
- When necessary, it should include sensitivity and consistency analysis. For the specific case of this thesis only sensitivity analysis is performed.
- Conclusions, including limitations and recommendations.

So, in this section, the results from the LCIA phase are presented and interpreted and, finally, uncertainty and sensitivity analyses are performed. The results are given basically for the climate change impact category and are presented in four different ways: general results, results per life-cycle phase and results per category.

5.6.1 General results

First the overall results have to be presented to obtain a general idea of the environmental impact for the buildings considered. In the next figure, disaggregated results for each one of the ten impact categories initially taken into account are presented in reference to production, construction, maintenance and operation phases:

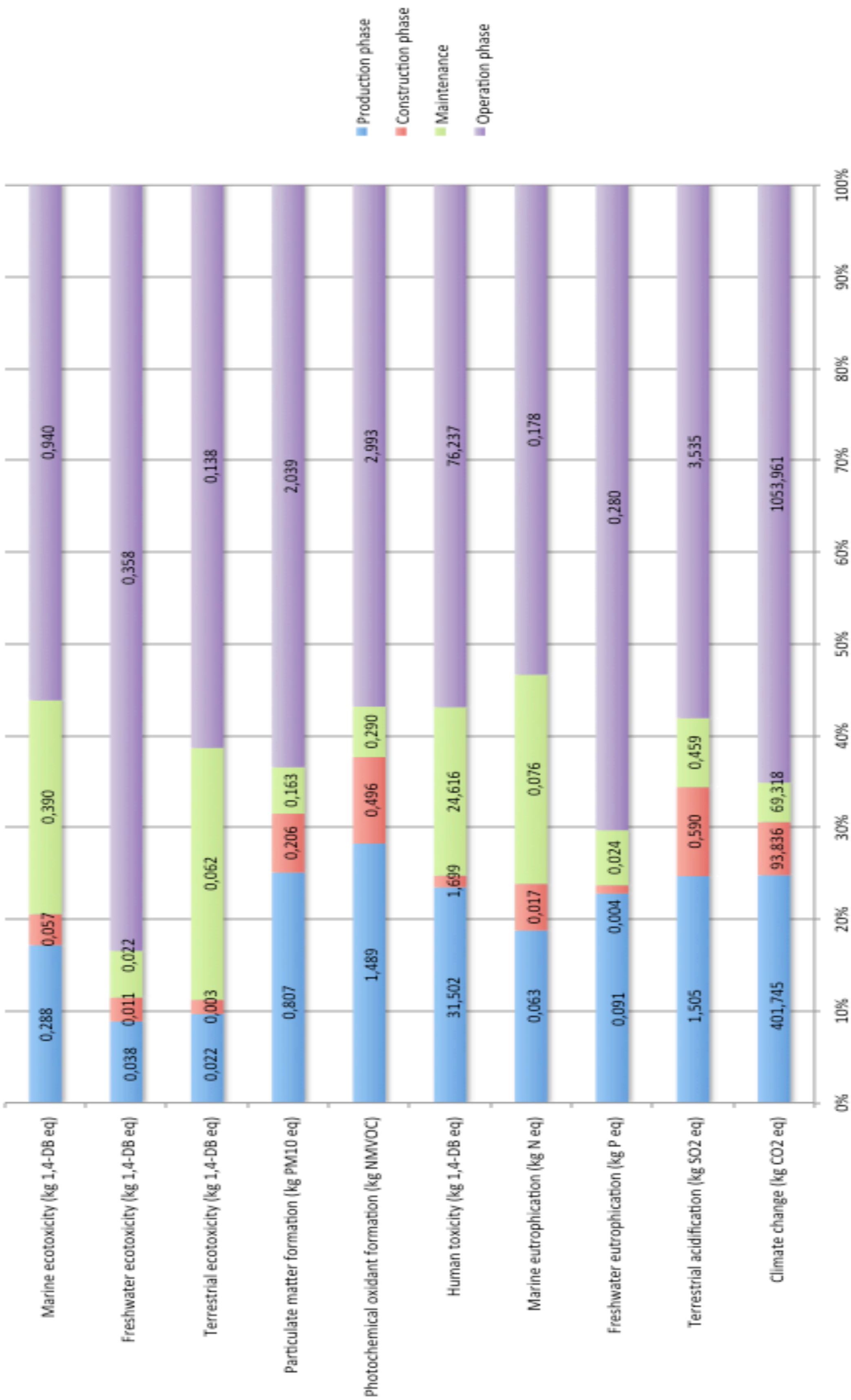


Figure 5.9 Total life cycle environmental impacts

For this study, it has been given special importance to the study of climate change impact category, which is a midpoint indicator, because this is directly related to greenhouse gases emission. So, finally the total global warming impact for the life-cycle phases considered is 1.618,9 kg CO_2-eq per FU, which has been defined in the appropriate chapter as 50 years of 1 square meter of utility floor space of a residential apartment in a block of flats. Taking into account the total surface for each one of the three buildings, the overall impact for the new apartment project in Nardovegen is 4.497,2 ton CO_2-eq.

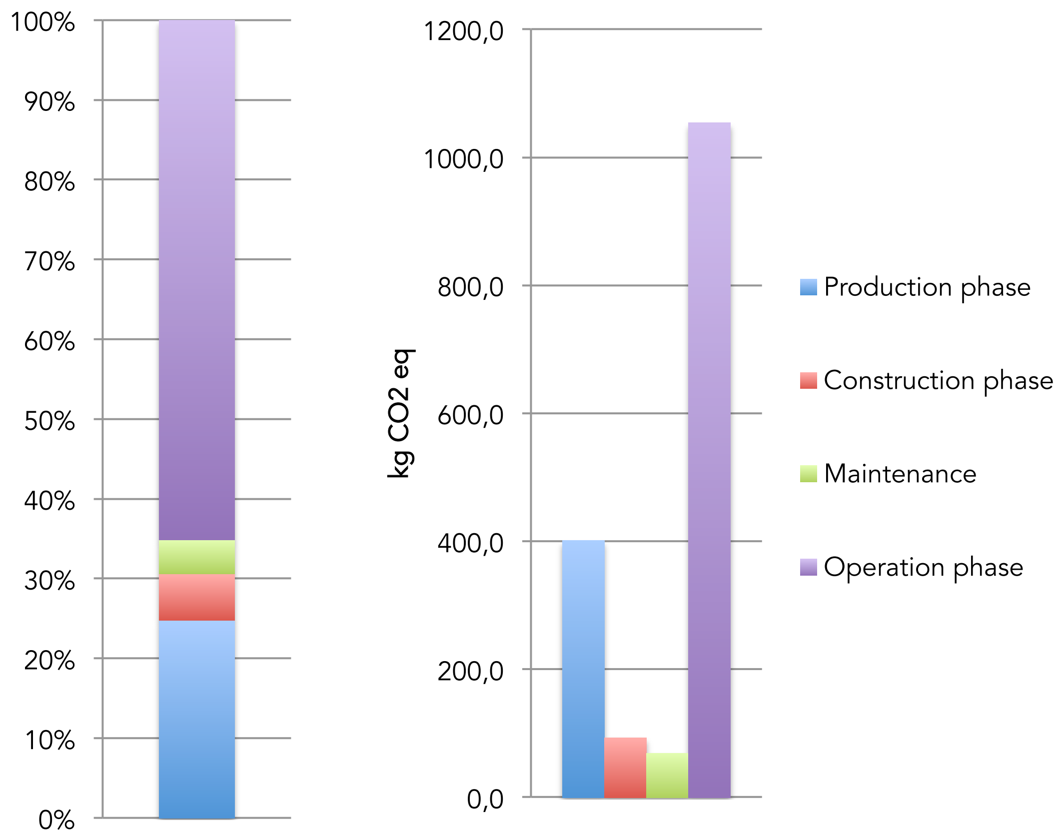


Figure 5.10 Total climate change impact

The first aspect that can be observed from the graphics presented is that the burdens from the operation phase consist on a 65,11 % of the total climate change impact, which is clearly the most harmful life-cycle stage between the ones considered in this analysis. This fact will be studied later in the corresponding point, where the results per life-cycle phase are presented.

Comparing these results with the ones obtained for similar studies, all of them included in the literature review of this thesis, we can observe that the results are in the same range of values. More specific comparisons will be made in the discussion chapter.

In the following points, more specific results will be presented regarding the different life cycle phases studied and the different categories regarding the construction units in which the buildings have been divided when performing the inventory of this LCA. It is important to say that special attention will be paid to the results of the construction phase, as it is the main focus of this study.

5.6.2 Results per life-cycle phase

First, it has to be remembered that a total of four life cycle phases has been considered, excluding the end-of-life phase for this study. So, finally the phases taken into account are material production, construction, operation and maintenance for the three buildings.

As it has been said previously, the operation phase is the most harmful regarding the climate change impact category. After this, the second place regarding this emission is for the material production phase, which represents a 24,82 % of the total impact. However, this value is slightly greater than one third of the impact produced during the operation phase. The resting two phases are decreasingly ordered as construction phase (with a 5,80 %) and maintenance (4,28 %) representing the less harmful phase.

So, next step will be studying separately each one of this life cycle phases in order to analyze the most important sources for the greenhouse gases emission.

Material production phase

Firstly, it is necessary to say that the total contribution of the material production phase is 401,75 kg CO_2-eq per FU. If we divide these emissions into the different categories in which the buildings have been divided, we can obtain the following contributions:

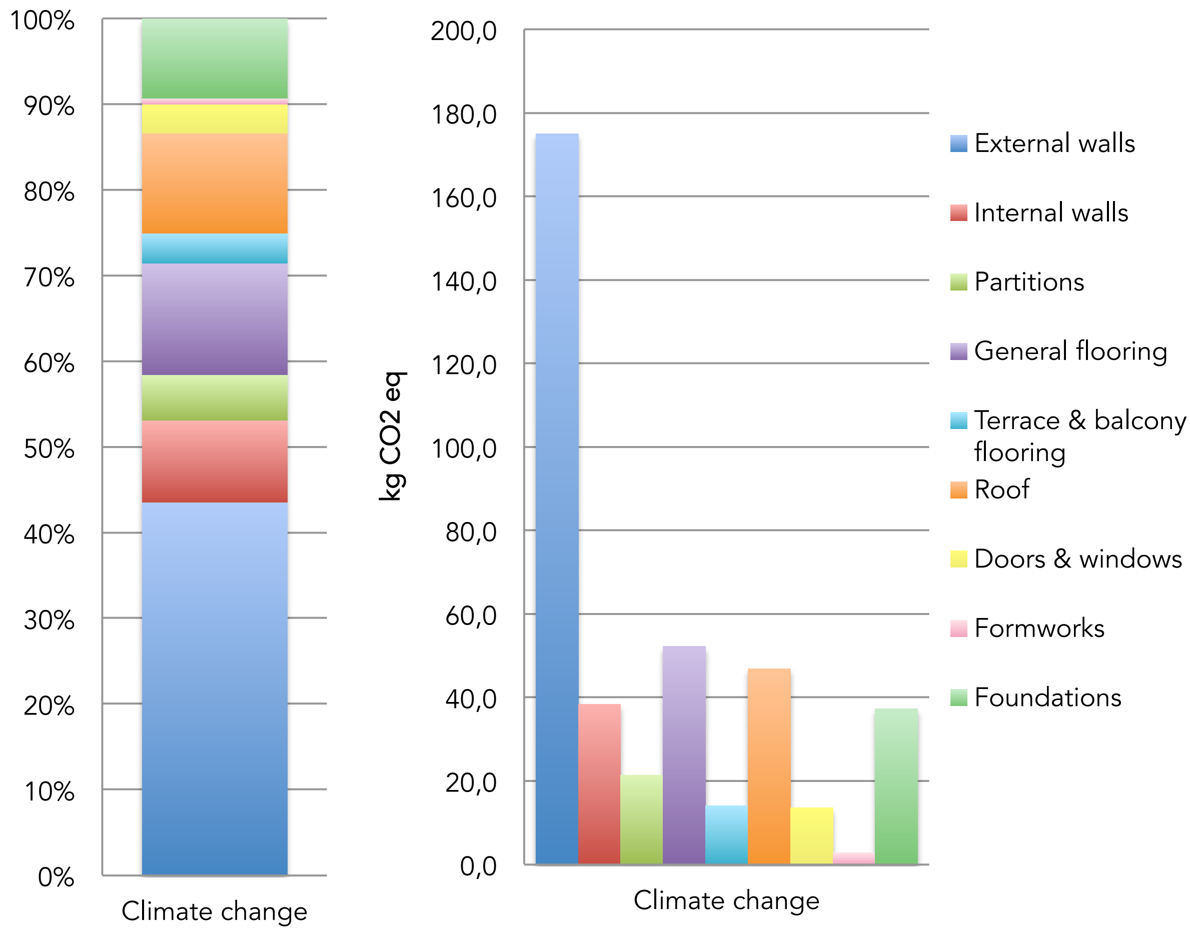


Figure 5.11 Climate change impact during production phase

The first thing that can be observed in this case is that the maximum contribution to the climate change impact category is the production of the materials associated to the external walls, with a 43,55 % over the total emissions. This category is followed by the emissions due to the production of the necessary materials for the general flooring (with a 13,01 %) and the roof (with a 11,68 %). This fact makes it easy to think that the material that produces the most greenhouse gases emissions during its fabrication processes is concrete, as the pointed categories are the ones that use the greatest part of this material.

In order to prove this effect, it has been decided to obtain the graphic with the contribution of the production of the main materials used in the construction of the buildings:

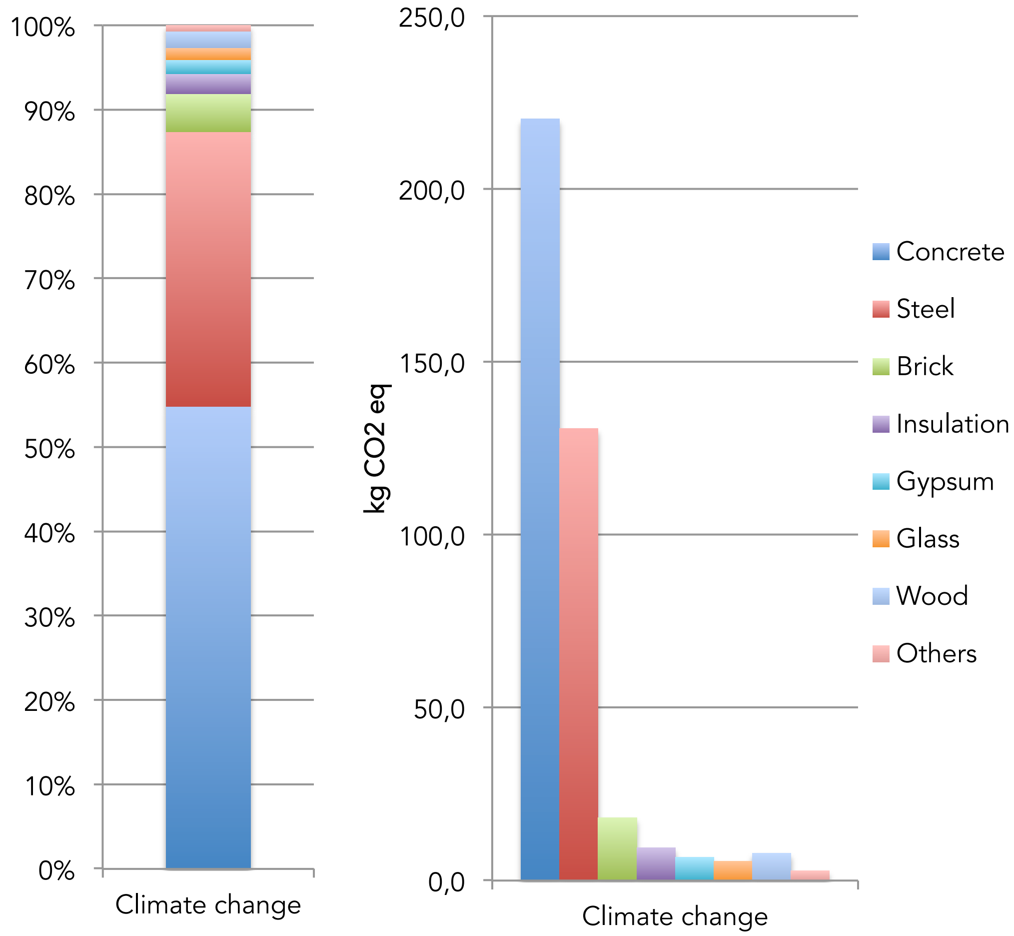


Figure 5.12 Climate change impact by materials

As it was expected, the production of the concrete, with 220,22 kg CO_2-eq per FU, is the most important regarding the emission of greenhouse gases given that it represents more than half of the emissions during this phase. The following material that produces the greatest environmental impact is the steel necessary for the reinforcement with a total of 130,76 kg CO_2-eq per FU, which represents also an important percentage of 32,55 % over the total for the production phase. In order to be able to observe the rest of the materials more precisely, concrete and steel have been removed from the graphic and the results obtained at this point are the following:

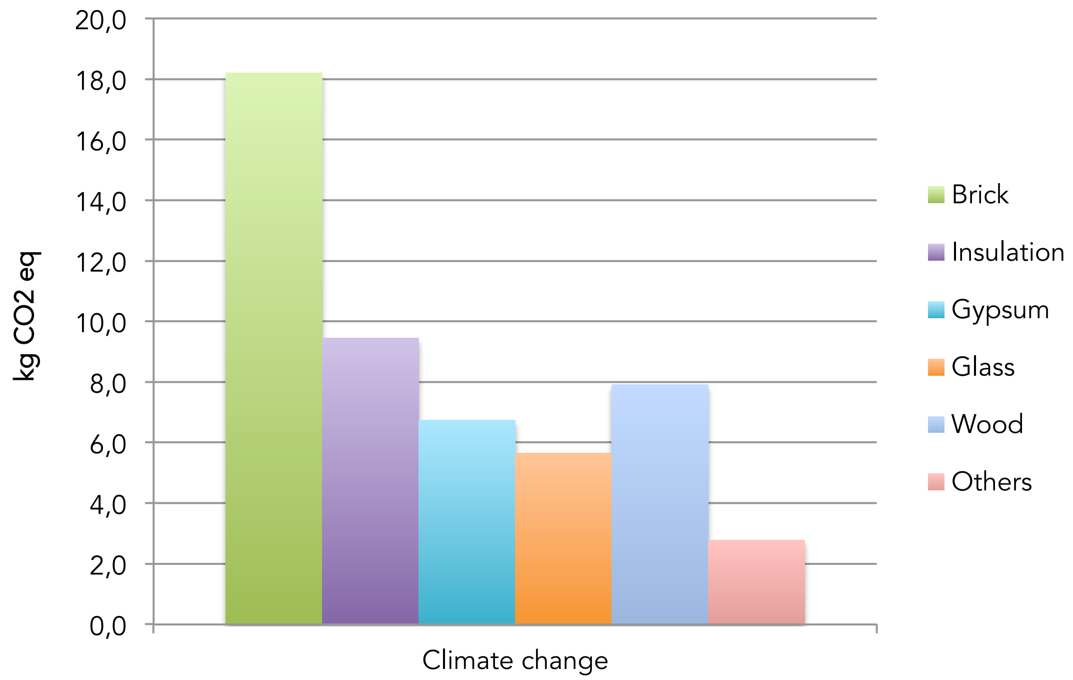


Figure 5.13 Climate change impact by materials (without concrete and steel)

It can be firstly observed how in this case the values for the emissions during the production of the rest of materials are much more lower. Moreover, bricks are the following material regarding this issue due to the big amount necessary for the construction of the partitions but it only represents a 4,53 % of the total environmental impact of the production phase.

Construction phase

This phase of the life cycle of the buildings that are being studied is the central of the study and with this aim it has been analyzed in much more detail than the rest. The total greenhouse gas emission produced during this phase is of 93,84 kg CO_2-eq per FU, which represents a 5,80 % of the overall environmental impact that has been calculated.

If we divide this emissions into the categories already presented, in the same way as it has been done for the material production phase, we obtain again that the most harmful category is the external walls of the building, which represent a 33,67 % of the total environmental impact. This category is followed by partitions (13,53 %) and general flooring (12,04 %).

Graphics showing these results are now presented:

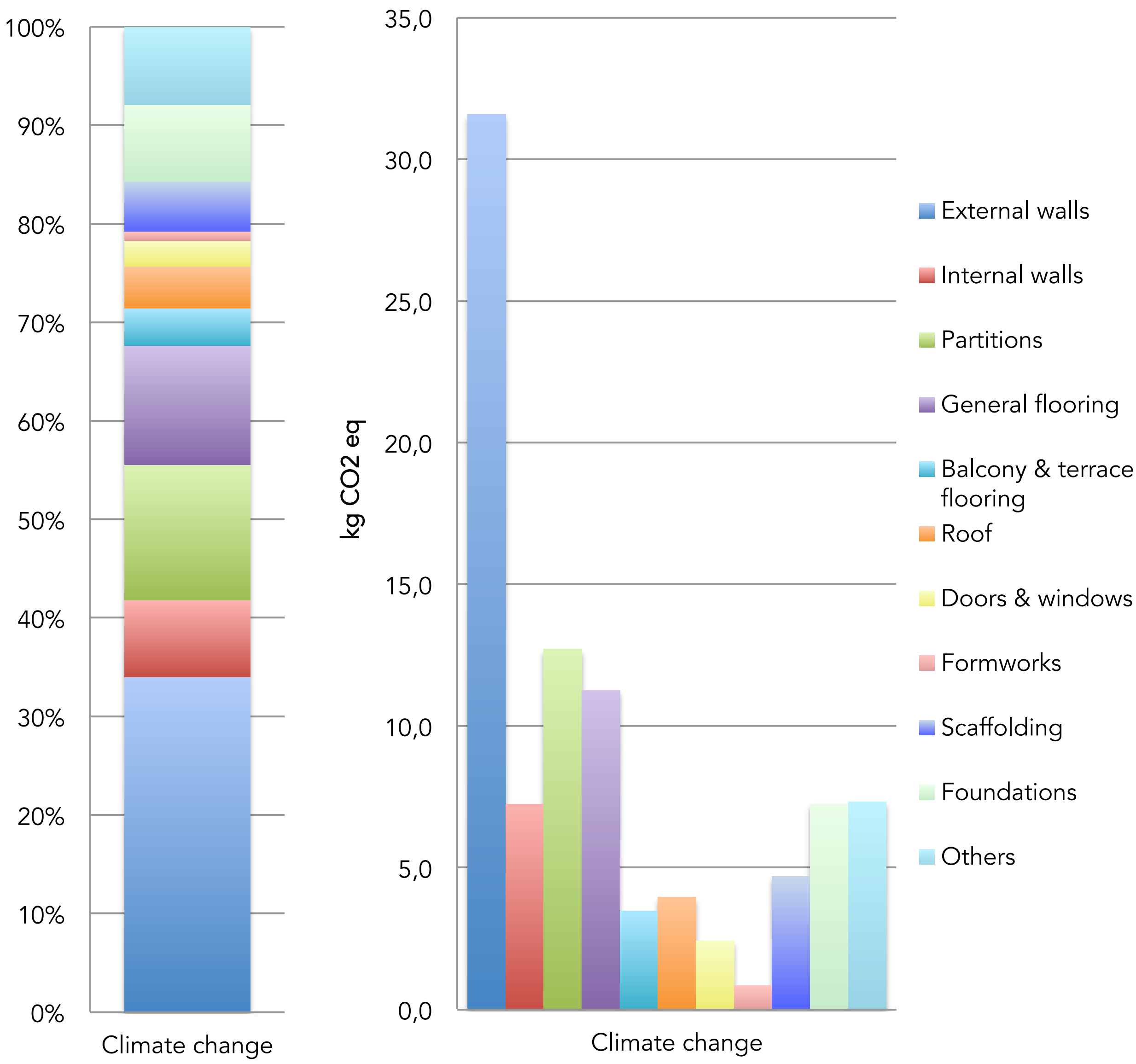


Figure 5.14 Climate change impact during construction phase

For this life cycle is important to take into account that some allocation procedures have been done in order to distribute the environmental impact due to, for instance, the tower crane or the transportation of the workers to the construction site. As it has been established previously, allocation has been done in terms of the weight of the different categories taken into consideration.

On the other hand, it could be interesting to study in more detail the environmental impact that is caused during the transportation of all the materials to the construction site, as it represents a 43,82 % of the total emissions produced during this phase, as it is shown in the following figure:

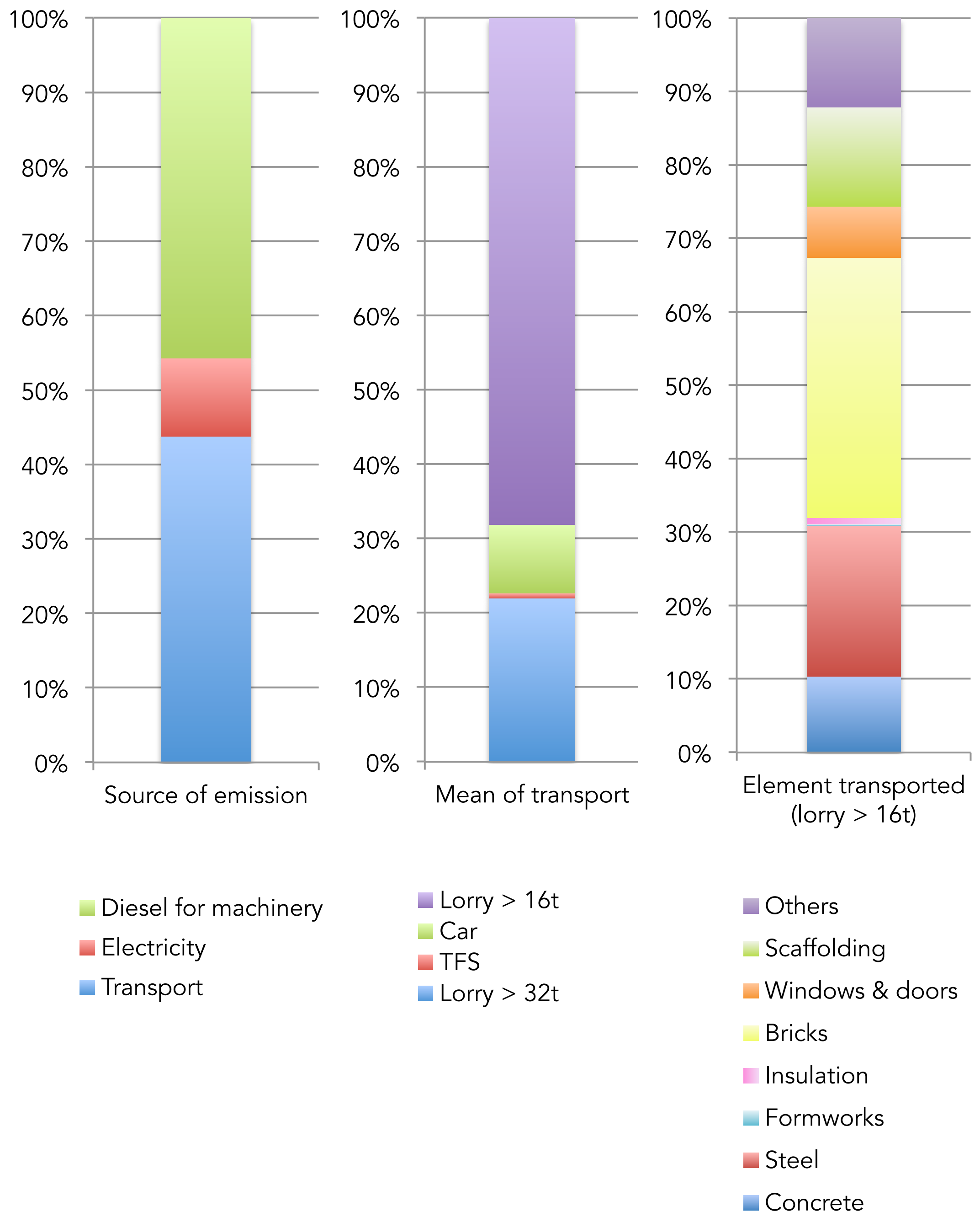


Figure 5.15 Climate change impact due to transportation

So, as it can be seen in the second column of the graphic, the emissions produced during the construction phase have been distributed depending on the mean of transportation used and a clearly dominance of the lorry >16 t is observed with an percentage of 67,51 % of the total emission produced due to the transportation. So, finally it has been decided to study the emissions produced for each ones of the materials carried by this mean of transportation and the results are the observed in the third column. Transportation of bricks is found to be the major contributor to the environmental impact due to the high volume needed in all the partitions.

Operation and maintenance phase

In this case, the total environmental impact is of 1.123,28 kg CO_2-eq per FU, which represents the most important part of the total impact calculated for the building with a 69,39 %. Firstly, it is important to say that the analysis of this phase has not been assessed with the same level of detail, as the main goal of it is to compare with the construction phase. So, first the results obtained dividing the result into the air emissions due to maintenance, water and electricity consumption are the ones represented in the following figure:

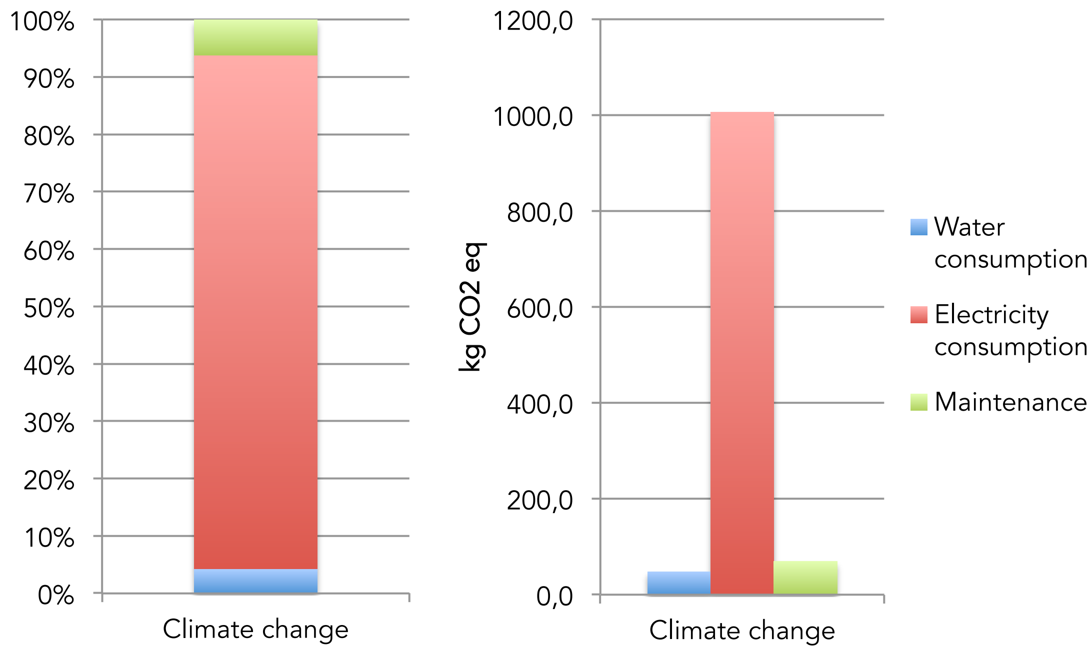


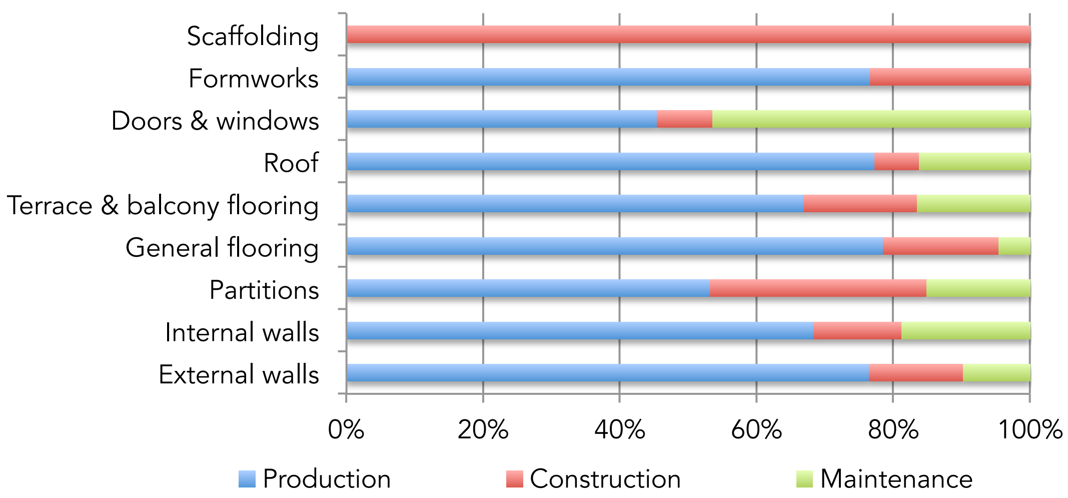
Figure 5.16 Climate change impact during operation phase

The first important point that can be observed in the graphic is that the main source of environmental impact during the construction phase is due to the electricity consumption, with almost 90 % of the total. Given that the relevance of this source of emission, it has been carried out a sensitivity analysis regarding this issue. In the corresponding point, it is analyzed the variation in the contribution of this phase to the overall environmental impact for different possible electricity mixes.

As a final conclusion for this phase, it can be said that after 22 years of use of the building, the impact produced due to the operation and maintenance of the building equals the total impact produced before the year zero, which means during the material production and construction of the building.

5.6.3 Results per category

Once every life cycle phase has been studied separately, the results will be presented in terms of the different categories taken into account, which are the following: external walls, internal walls, partitions, general flooring, terrace & balcony flooring, roof, doors & windows, formworks and scaffolding. To present the results in this point, finally the environmental impact due to water and electricity consumption during the construction phase are not included because they cannot be associated to any specific category. So, finally, representing the distribution of the emissions in each of the phases considered for all the categories mentioned, the following graphic is obtained:



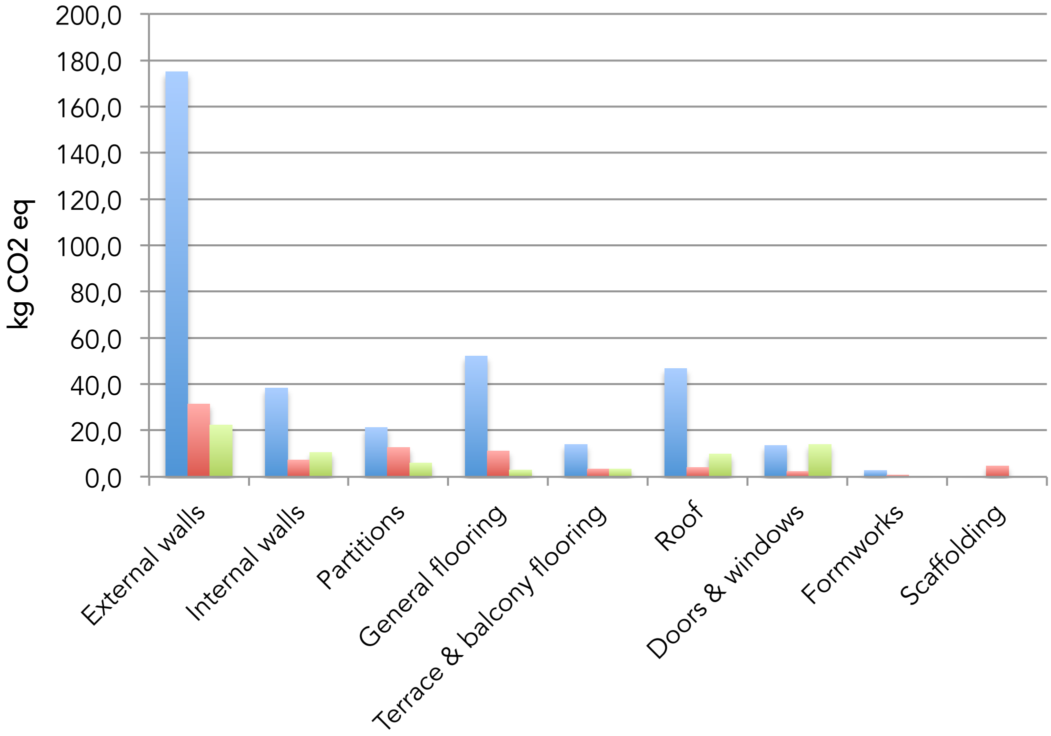


Figure 5.17 Climate change impact by categories

As it can be seen, the maintenance of the different elements does not represent an important contribution on the CO_2 emission in any case. So, it is proved the importance of studying in detail the impact during the construction phase of the buildings.

Moreover, these specific graphics are also useful in order to identify the hotspots for the impact assessment of these buildings. Firstly, it can be concluded that the production of the necessary materials for the external walls is the most harmful regarding the environmental impact. In second and third position there can be observed the production for the material of the general flooring and the roof, which are also two of the categories that include the most production of a high quantity of concrete.

So, the main conclusion that can be made is the fact that it would be much more favorable for the construction to plan a bigger building, which would involve less volume of concrete for the external walls, than three smaller buildings as it has been finally planned.

5.6.4 Sensitivity analysis

The main goal when performing a sensitivity analysis is to obtain the reaction of the system considered for the LCA when some changes are made on different input parameters. In this case, the main hotspots have been studied. Hence, variations have been applied with respect to the electricity and the concrete since it has been found that the electricity consumption and the concrete production are the most important sources of environmental impact. The results obtained for each one of these cases are presented in the following point.

Electricity mix for the operation phase

Since Norway is connected to Scandinavia and Europe via international electricity grids, NordPool (2011), the electricity mix used for the assessment of the LCA must be chosen carefully. Finally, the three following electricity mix have been taken into account:

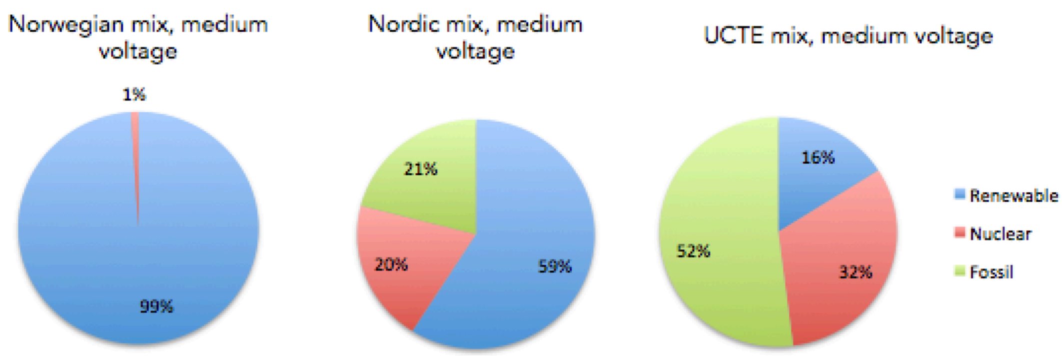


Figure 5.18 Different electricity mix

So, the above figure shows the different shares of renewable, nuclear and fossil energy sources, which are considered the most relevant electricity sources for Europe and Norway (EcoInvent, 2007). Climate change impacts are calculated per kWh produced when carrying out the LCIA and there is a significant difference between the Norwegian and European production mix. It is important to first make clear that the Norwegian mix is the electrical production mix, and does not reflect the mix that is consumed in Norway.

As Norway is connected to the Scandinavian and European grids, the amounts of hydropower produced vary throughout the season, and thus imports and exports will also vary the same way. In periods with no import of electricity, power would be generated by 99% hydropower. On the other hand, when Norway imports electricity, then some of that electricity could be generated from nuclear or fossil fuels somewhere else in Scandinavia. For this reason, the Norwegian consumption mix varies through the season and using the Norwegian production mix for the calculations of the environmental impact would produce less impact than what actually happens.

Hence, one could argue that the best option is then to calculate electricity impacts with the Union for the Coordination of the Transmission of Electricity (UCTE) production mix. This is the annual average production mix of the Continental European countries, with a reasonable share of renewable, nuclear and fossil fuel electricity production. In this case, at the contrary than the Norwegian mix, the results obtained would be highly conservative and, therefore, higher impact than the actually produced would be obtained from the calculations. As a result, Norway and Scandinavia in general, with its high share of renewable energy generation could lose its competitive superiority as producers of renewable electricity.

For example, if aluminum production in Norway were calculated with European electricity mix instead of Nordic mix, there would not be any advantage on producing aluminum in Norway, with hydropower electricity, than any other place in Europe.

There is also a difference that should be considered when choosing electricity mixes for construction or use phase. For the house construction and production of all the necessary materials, an electricity mix based on the electricity mix produced nowadays is reasonable. Thus, the results will reflect the actual situation today. For the use phase, it would be a worse approach to consider the today’s production mix as relevant for the next 50 years. If the European Union reaches its goals of more renewable energy in 2020, emissions per produced kWh would actually be lower than the calculated scenarios. (T. Ekvall, 2005)

So, for the first results presented, the electricity mix used is the Nordic mix, but in this point also the other two mixes presented will be assessed in order to show the possible range of results. For the three cases, the overall results obtained are the following:

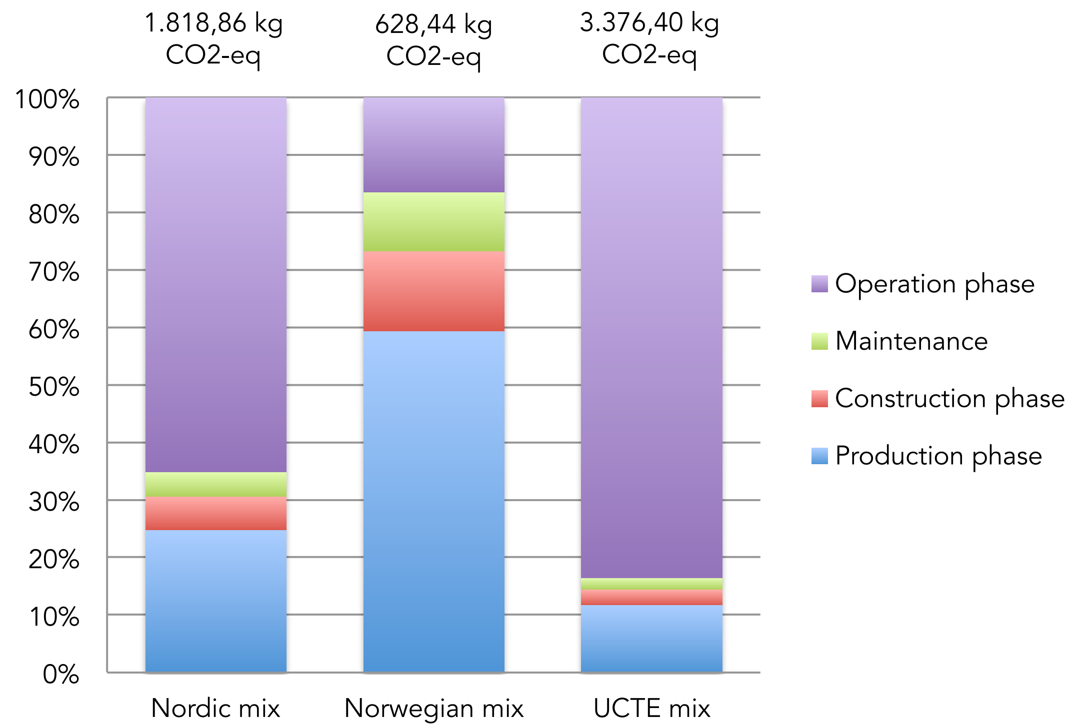
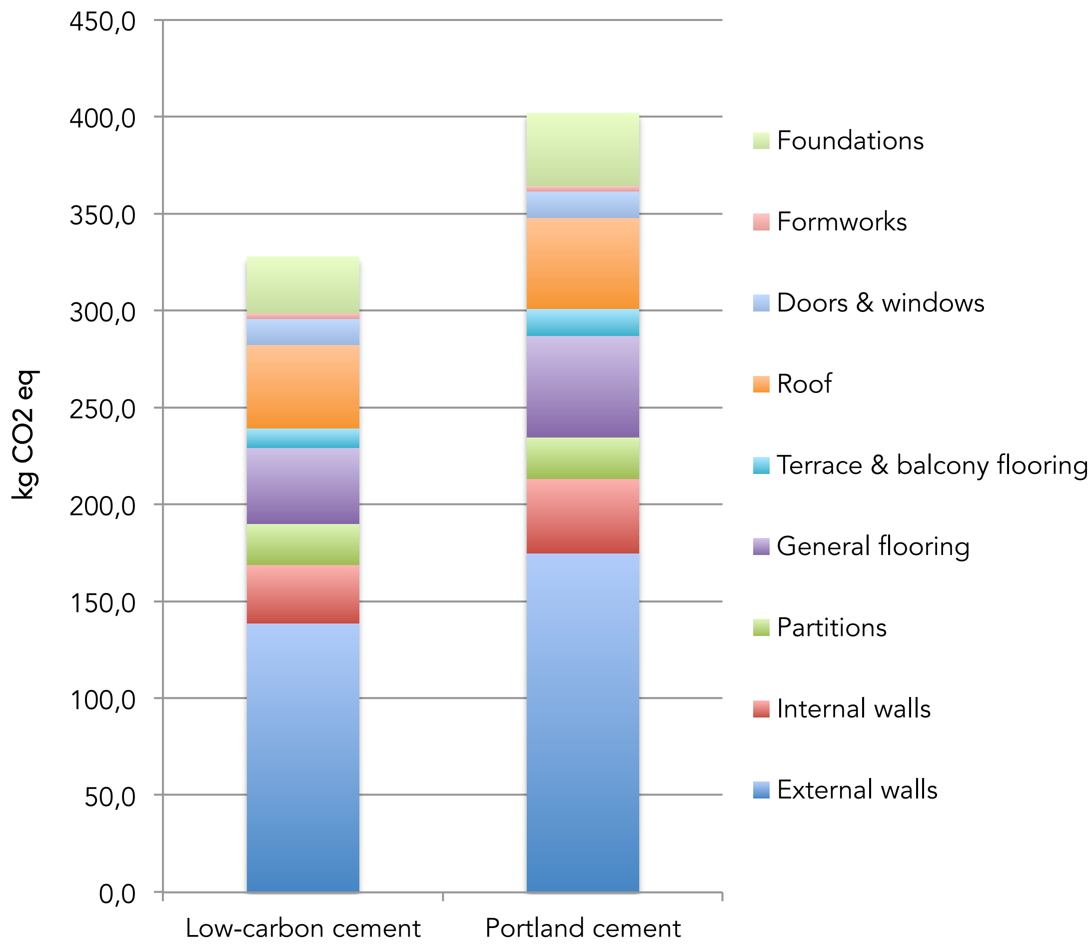


Figure 5.19 Climate change impact variation due to different electricity mix

So it is clearly observed how the results can suffer high variations depending on the electricity mix considered.

Use of low-carbon concrete

As a second sensitivity analysis, it has been studied the possibility of replacing the Portland cement, which is the most common solution and the one considered in this study, with special low-carbon cement. Data about the environmental impact of this type of cement has been taken from the EPD assessed by Norcem. The principal difference is that, for the low-carbon cement, the global warming potential calculated is of 503 CO_2-eq/ton cement (Norcem AS, 2013) while for the Portland cement was of 758 CO_2-eq/ton cement (Norcem AS, 2013). So, it is observed a reduction on the environmental impact of a 34%. In the following figure it can be observed the variation of the total environmental impact for the material production phase:



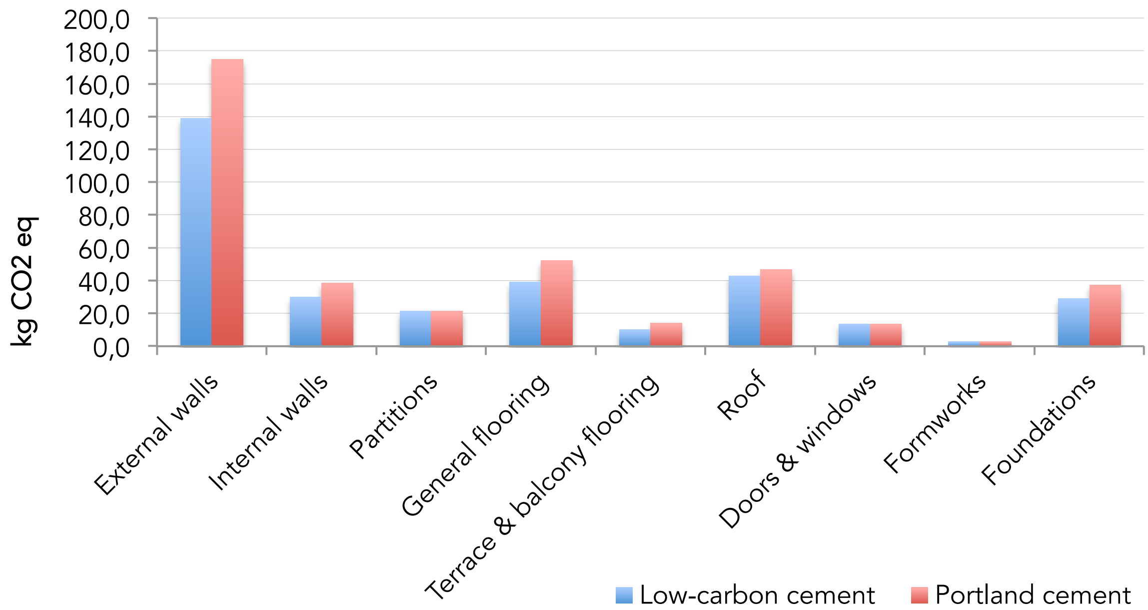


Figure 5.20 Climate change impact variations due to low-carbon concrete

As it can be observed, there is an important reduction of the environmental impact of the production of the different categories of the building studied, which is around 20-25 % for each one of the categories that include the production of concrete and 18,42 % if we consider the impact of the whole phase.

Thus, it can be concluded that the use of low-carbon concrete leads to a considerable reduction of the environmental impact produced during the initial phase of a building.

5.6.5 Uncertainty analysis

When performing LCA models regarding building, most of the possible uncertainties are due to the following aspects:

- **Quality of data:** data may be incomplete, inaccurate, obsolete or not appropriate.
- **Description of the building:** the description available for the building can be, as in the previous point, incomplete or inaccurate.
- **Building life cycle span:** life cycle span taken into account for the calculation is assumed in advance as well as life cycle for different components.
- **Building operation:** consumptions during operation phase are clearly influenced by the user and also by many other external factors that cannot be known in advance.

Moreover, other uncertainties are produced by the fact that inventories of material and energy are highly influenced by the geographic location of the buildings considered. So, for all this reasons is interesting to perform an uncertainty analysis in which the main uncertainties for this LCA are presented and it is justified the reliability of the results presented.

First, there is an uncertainty regarding the lifetime considered for the set of buildings, as it is assumed that the operation phase is of 50 years. This is a general accepted value for the lifetime, which used in many of the previous studies presented in the corresponding chapter of this thesis and so it is used in order to make the results more comparable.

Others uncertainties can be divided into the four different life cycle phases that have been taken into account:

Production phase

Amounts of materials have been accurately calculated from the available drawings of the building. Bill of quantities (BOQ) of the project was not available for the performance of this LCA but it is considered that data used is reliable enough and special attention has been paid on the measurements of concrete volumes. However, drawings and other data available of the project usually contained too low detail in order to establish the exact amounts for some of the materials. Hence, the establishment of the material inventory required making a large number of assumptions regarding material dimensions, quantities and compositions. The availability of technical drawings meant that qualified assumptions were possible, thus reducing the uncertainty somewhat, but the uncertainty of the material inventory is still significant.

All impacts are based on materials and generic data from the Ecoinvent 3.0 database but some modifications have been done when a specific EPD was available for the material used. So, in these specific cases the uncertainty is clearly reduced but this type of eco-labels are not usually available for the construction materials.

Construction phase

Energy consumed during construction may carry a high uncertainty but, as it has been seen, it is not a key aspect when calculating the overall environmental impact during construction.

Transportation distances have been estimated based on assumed production locations. Although uncertainty has been reduced by research on probable production locations, and also comparing to other previous constructions carried out in the same area, there is still significant level uncertainty related with the transportation. So, distances are only rough estimates and real values may differ.

Maintenance

Regarding the surface finishing and its life cycle, it exists a clearly high uncertainty given that it cannot be known in advance the maintenance frequency necessary in each case. So, it has been assumed taking into consideration previous researches and general accepted values.

Moreover, taking into consideration that 50 years is a general assumption that usually does not correspond with the actual length of time for the operation phase, the number of life cycles considered for the maintenance of the elements is even more uncertain.

Operation phase

There is a lot of uncertainty associated with estimating energy demand based on simulations or statistical data. Even though measured data is generally preferable, in this case was not available given that the project is still in its construction phase and there would be a high uncertainty associated with using measured annual values to predict consumption for the whole lifetime of a building. Energy consumption depends on many factors and varies significantly over time. Climate and temperature are obviously important influential factors, but the individual behavior of house residents is also very important and represents a factor that is not possible to take into account.

Moreover, climatic variations over time are difficult to predict, and they have an essential influence on electricity consumption. Hence, extrapolation of average nowadays consumption over the entire lifetime can be somewhat misleading, especially when taking into consideration that global average temperature is raising. Finally, as it has been seen with the sensitivity analysis, there is a strong dependence between the electricity mix used for the assessment and the results obtained for the environmental impact for the operation phase.

So, it can be concluded that there is always a significant uncertainty associated with the Life Cycle Assessment of a building, and the present thesis is not an exception. Using reliable data and contacting the responsible person in the construction have reduced uncertainty. However, uncertainties are still significant, especially regarding processes occurring during the use phase, as the future behavior of the occupants of the buildings is very difficult to predict.

6

Discussion of the results

6.1 Introduction

In this chapter the results obtained from the LCA assessment for the new project of apartments in Nardovegen will be discussed and compared with other previous studies already presented in the chapter *Previous researches* of this same thesis. This chapter will go over all the main points of this thesis, starting with the LCA methodology presented and then analysing the results: first with a comparison with relevant studies presented in the literature review and then looking into all the phases considered to pay special attention on the hotspots of the study. So, the main purpose of this discussion is to summarize the most important points revealed with the results of this thesis and to check the consistency of the overall work.

6.2 LCA methodology

Among the first chapter of this thesis there has been carried out a complete description of LCA methodology but focused on performing a robust framework of study for the application of this methodology to buildings, and specifically to the new project of apartments in Nardovegen. So, in the following points, a discussion regarding each one of the different phases assessed in this study is conducted.

6.2.1 Goal and scope definition

As it has been established, the main reason for performing this LCA was to calculate the environmental impact for a new project of apartments in Nardovegen. Concretely, it has been paid specially attention on the construction phase, including the production of all the materials needed. So, these results will be available in the future to be compared with other building LCA assessments. Finally the end-of-life phase was not included due to the high uncertainty related with this phase, as is very difficult to know the recycling processes that will be used in 50 years and, moreover, it is not considered an interesting phase if we want to put the focus on the construction period.

The definition of the functional unit was made taken into account the general used in this type of LCA assessments, as it allows an easy comparison of the results in the future and gives enough consistency when adding the results obtained for each one of the buildings.

In reference with the system boundaries that were specified, apart from the end-of-life phase exclusion that has been already justified, also other uncertain elements were excluded from the study, such as the repair and rehabilitation processes during the use phase.

6.2.2 Life cycle inventory (LCI)

For this study, this stage of the LCA had a higher complexity than in other assessments consulted given that a bill of quantities (BOQ) of the project was not available. So, with the help of the drawings and the main information that was available from the project, all the measurements were made in order to know the amount for each one of the materials. On the other hand, when this was not possible, also the main responsible of the construction was contacted to receive more specific information.

In reference to the output flows, they are obtained using EPD declarations or similar instead of generic processes for all the cases it has been possible. So, for the rest of the materials and processes, outputs are obtained using the EcoInvent database, which is considered enough accurate and reliable.

6.2.3 Life cycle impact assessment (LCIA)

In this case a ReCiPe method has been applied in order to transform all the list of outputs of the system into a reduced list of mid-point indicators, which are easier to interpret. Between all the impact categories considered, finally it has been paid special attention on the global warming, with kg CO_2-eq per FU units. Finally, weighting, grouping and normalization processes were not applied in order to maintain the transparency of data obtained.

On the other hand, some allocation procedures have been done in order to distribute the environmental impact of specific material or processes into the different categories taken into account. The aim of this is avoiding the creation of more subcategories that would make more difficult the interpretation of the results and their comparison with the results of other previous studies.

Finally, uncertainty and sensitivity analysis were carried out to ensure the reliability of the results and show the consequences when changing data that was sensible to be modified along time.

6.2.4 Interpretation phase

In this last phase, results obtained were analyzed and presented in different ways in order to find the most important sources of emissions when considering different life cycle phases, different categories and different materials. So, finally it has been identified the operation phase as the major contributor to the environmental impact and, regarding the different categories, the external walls are the most harmful. Specifically, the main cause of this is the high amount of CO_2 released to the environment during the production of the concrete.

6.3 Previous researches

Looking at the different previous studies presented in this thesis, finally it has been found out that one of them deal with a really similar problem to the one here assessed and another one has been chosen in order to compare what happens when planning buildings with different main materials. However, it has to be said that in these cases the main goal of the studies was to compare the results between different buildings and not to make a specific study for a phase of the life cycle. The most common comparison that has been observed is between similar buildings but planned following different standards such as TEK10 or passive house standard. Thus, in order to compare the results with this study, it is important to look at the results of buildings that follow the TEK10 standard, as it is the one followed in the planning of the apartment buildings in Nardovegen.

First, R. Spiegel carried out a LCA assessment for two new school buildings but, as it has been said, for the comparison it will only be taken into account the results for the new building planned with the Norwegian building code, TEK10 (Spiegel, 2014). In this case it is important to say that the functional unit used is the same than the one of this theses, even taking into account the same life cycle phases for the assessment.

In this study the overall impact that was found for the TEK10 school was 1.525,5 kg CO_2-eq per FU, which is very similar than the environmental impact found for the dwellings studied in this thesis. One of the main reasons for which the resultant impact of the present study is slightly higher is the important contribution of the production of the materials for the external walls of the three buildings. Moreover, for the operation phase of the school only the electricity consumption was taken into consideration.

The next study compared with the present LCA assessment is the one carried out by O. Dahlstrøm, which also performs an assessment with the aim of comparing a project of a building that follows the TEK10 standard with the same project when following the passive house standard (Dahlstrøm, 2011). So, again the results taken into account for this chapter are the first ones. The main goal to compare this assessment with the results of this thesis is to observe the differences when using wood as the main material of the walls instead of concrete, which has been found to be the major pollutant in the Nardovegen project. On the other hand, although the function of building is also residential and so it gives better results to compare with the present study, it takes into consideration all the phases of the building life cycle, including the end-of-life phase.

So, results finally obtained for this study are an overall environmental impact of 1.587 kg CO_2-eq per FU, also below the impact calculated for the study of the set of buildings in Trondheim. It is very interesting to see how the environmental impact of the material production phase is reduced to less than half of the impact of the Nardovegen project. Anyway, the overall impact is very similar given that it includes the end-of-life phase.

Finally, if we make a graphic comparing these cases and the results of the present study we obtain the following:

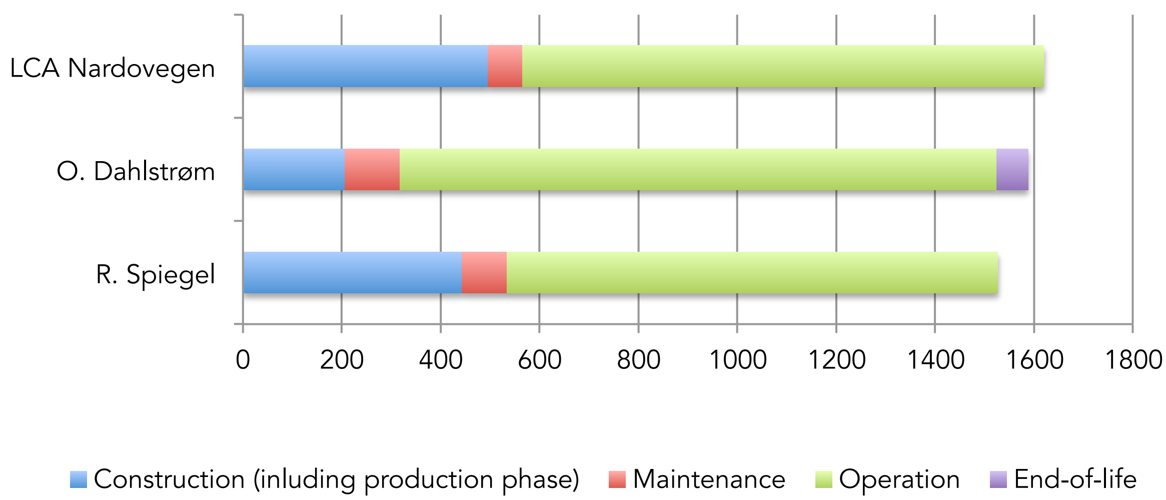


Figure 6.1 Comparison of climate change impact for different studies (I)

So, in this graphic, differences that have been presented and justified in this point are clearly seen. The results obtained from both reviews are so quite consistent with the results of the present study, as the differences are not really elevated and the most important ones are easily justified.

As an extension, the results have been finally also compared with the results from a LCA of a building that follows the passive house standard. In this case, the assessment carried out in the same thesis by O. Dahlstrøm has been chosen given that it studies a building that has a residential function (Dahlstrøm, 2011). As it has been said, for this study also the end-of-life phase was considered, which will be taken into account for the comparison of the results. The following graphic compares this building with the present project:

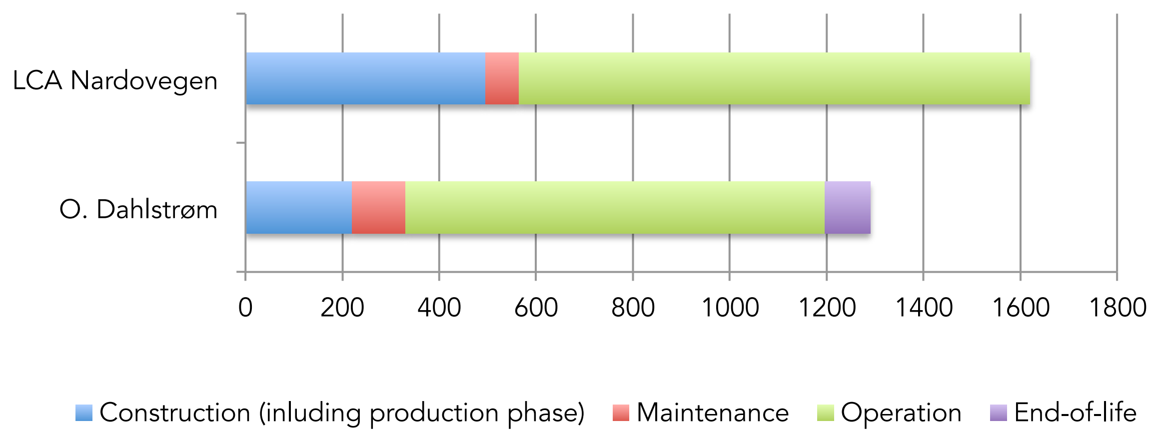


Figure 6.2 Comparison of climate change impact for different studies (I)

Hence, the overall impact for the passive house was of 1.290 kg CO_2-eq per FU, clearly below the impact produced during the life cycle of the Nardovegen apartments. If we look at the distribution of this impact between phases, we observe a considerable difference for the construction phase, as wood is used as a principal material. However, comparing with the wooden house that follows the TEK10 standard analyzed in the same study, the impact during the construction phase has increased due to the higher input of materials for insulation. Anyway, it allows significantly reducing the impact for the operation phase and, therefore, it provides better long-term results.

6.4 Results per life cycle phase

In this point there will be discussed the results obtained for each of the life cycle phases considered and some improvements will be proposed in order to reduce the environmental impact of the project. In each one of the phases considered, it has been chosen the main points that are though that need special attention, for instance, for the production phase these main points are concrete and reinforcing steel production.

6.4.1 Material production phase

This first phase considered was clearly the most difficult to assess given that it includes many processes and all the measurements had to be done from the beginning with the only help of the available drawings and the possibility to contact the construction responsible in case of specific needs. As this phase was known to be the most harmful regarding the impact burdens, the input data included was needed to be the most accurate and precise possible. So, for this reason special attention was paid on the measurements in order to make the least general assumptions.

Concrete production

As it has been shown, concrete production is the highest contributor to the CO_2 emissions of this project. In this direction, a lot of studies have been made and the following table made with the results obtained by T. Häkkinen and S. Vares (T. Häkkinen, 1998) shows the different contributions of the different stages of the concrete life cycle to the overall impact regarding energy and main emissions (CO_2, NO_X and toxic heavy metals):

	FUEL AND ELECTRICITY	CO_2 EMISSIONS	NO_X EMISSIONS	TOXIC HEAVY METALS
Cement	69%	83%	71%	88%
Gravel	3%	1%	1%	1%
Raw materials transportation	5%	3%	8%	< 1%
Concrete production	16%	8%	5%	10%
Product transportation	7%	5%	15%	< 1%
TOTAL	100%	100%	100%	100%

Table 6.1 Main emissions during concrete production

As it can be seen, cement is clearly the principal polluting agent. This represents more than 70 % of the total emissions and energy used during the concrete production processes and the main cause is the elevated temperatures needed for the decomposition of the calcium carbonate. So, the total amount of environmental burdens produced during the production of the concrete strongly depends on the cement content, which is usually in a weight proportion between 10 and 15 %.

Reinforcing steel production

In reference to the steel used for this assessment, it is important to remark that the its environmental impact has been calculated taking into account that the production process is carried out through an electric arc furnace (EAF), which considerably reduces the total amount of air emissions.

So, even considering the higher transportation distance needed by the steel produced in Germany, it is still less pollutant than the steel produced in Norway (which approximately produces double amount of CO_2 emissions).

6.4.2 Construction phase

This phase was given special attention and the principal source of air emissions was found to be the transportation of the materials to the construction site. On the other hand, also a study of the energy consumption on the site was made to know in detail the pollution effect during this phase.

It is important to say that many processes that take place during this phase need an allocation process in order to distribute the effect on the environment onto the different categories considered. This is, as it has been already said, because in some cases it is not possible to assign all the effects to the same category or to exactly distribute it.

Transportation

Between all the means of transport that are considered in this study, the main pollutant is found to be the lorry, specifically the >16t lorry takes 67,51 % of the total amount of emissions produced because of the transportation. In this case the ratio of emissions depending on the mean of transportation has been taken from the EcoInvent database as it is though to be accurate enough and it provides reliable data for the current means of transportation.

Regarding the transportation of the tower crane, the scaffolding and the personnel, it has been necessary to allocate the environmental burdens and it has been done in terms of the weight of the different categories. On the other hand, the transportation of personnel is very difficult to determine exactly given that even the mean of transportation is uncertain.

Special attention has to be paid on the transportation by lorry >16t of the bricks, reinforced steel and scaffolding because they are the most contributors to the environmental impacts. In order to reduce these emissions, maybe it could be found local suppliers for the bricks and the scaffolding. However, it has been shown that is not favorable to find a local supplier for the reinforced steel, as it would increase the CO_2 emissions during the production phase. Finally, in reference to the concrete, the total emissions are lower given that, in spite of the big amount of volume needed, it is produced locally with only around 10 km of transportation needed.

Energy consumption

During the construction phase, it has been also studied the energy consumption on the site. It was found a high level of uncertainty because many general assumptions had to be made and the environmental impact regarding the energy consumption was approximated through general data. However, given that the impacts due to the transportation described in the previous point are higher than the impact produced by the activities carried out on the site, the uncertainties are finally considered assumable.

Nevertheless, as diesel burnt for machinery also represents an important source of emissions during the construction phase, some alternatives should be considered in this way. For instance, use of other sources of energy for machinery such as electricity and low carbon diesel could be studied.

6.4.3 Operation and maintenance phase

This final phase considered includes maintenance activities for the main elements of the building and water and electricity consumption along the 50 years considered for the use phase. The principal conclusion found from the result obtained for this phase is that after 22 years of normal use of the building, the impact produced due to the operation and maintenance equals the impact produced before the year zero, which means during the phases of the production material and construction.

The main points that need special attention because of the importance contribution to the overall impact and the high level of uncertainty are the electricity consumption and the maintenance operations.

Electricity consumption

The electricity consumption during the 50 years considered as the normal length for the use phase of the building has been found to be the major contributor to the environmental impact of the system considered, with a total percentage of 62,14 % of the overall air emissions. So, a more detailed study has been carried out with a sensitivity analysis, as it is possible to consider different energy mixes depending on the data used in the assessment.

So, with the sensitivity analysis it has been found the importance of using eco-friendly sources of energy, as with the Norwegian current mix of production (that unfortunately does not reflect the current mix that is consumed in Norway) the overall environmental impact is reduced to less than half of the calculated impact in this study.

Maintenance activities

Regarding the maintenance of the main elements considered, it has been observed an important level of uncertainty when considering the frequency and so the service life of the different materials or elements. Moreover, in general there is not a common agreement regarding the operations that should be included when it comes to maintenance of a building given that it strongly depends on the user. For instance, some users could be really environmentally conscious when choosing materials or others could be more interested in interior design current fashions and so make more changes in the surface finishes even if it has not elapsed the service lifetime assumed.

So, in order to have an overview of the impact produced due to the maintenance operations, the usual technical service life of the products has been consulted. In this way a reasonable result is found because the real lifetime is though to be into a similar interval. On one hand some material will be changed before because of design reasons but, on the other hand, usually products can be used for longer than the technical service life.

7

State of art of LCA and possible improvements

7.1 Introduction

Nowadays, it can be clearly observed the low application of the "life cycle thinking" in the building construction industry. For this reason, is really limited to some specific buildings such as the ones used as pilot buildings in the framework of R&D projects, representative buildings and big company headquarters. The application of LCA studies in the building industry is developed only in specific cases and mainly thanks to R&D research centres, universities and some specialized consultant companies.

On the other hand, if we take a look at the application of LCA assessments in the production industry, it can be observed that it has been increasingly used during the last years but in really concrete occasions. Manufacturer product industries are carrying out this kind of studies in order to elaborate Environmental Product Declarations, which give the essential information about the environmental impact of the manufacture of a specific product.

However, and in spite of the clearly important opportunities that a unification of the LCA use would represent, it exists some barriers and obstacles to deal with before it can be widely implemented in the building construction industry. Above all things, the principal barriers are technical, related with the availability of the appropriate tools and database related with this specific industry, formative, related with the availability of a group of technicians enough qualified and expert on this field, and economic, given that the high price of the implementation of the LCA methodology in the building industry produced by lack of appropriate tools and the amount of time needed to carry out this kind of studies (I. Zabalza, 2012).

For this reason, some agents of the construction industry generally consider LCA studies as a complicated methodology. Thus, this produces high difficulties in the comprehension of the results.

However, maybe the most important barrier that has to be beaten in order to generalise the use of LCA above the building industry is the lack of legislation and incentives, which entails to a low demand of this type of assessment. For instance, nowadays practically it does not exist a link between the LCA assessments and the energetic certificate procedures that has been developed during the last decade. For this reason, in some cases it can even produce some contradictions, as the fact that a better energetic qualification can be sometimes obtained even if it includes higher primary energy consumption. The main reason is that the energy certification does not take into account the energy consumption during the production or transportation of the materials (I. Zabalza, 2012).

Hence, the incorporation of LCA assessments to the energy certificate procedures for buildings would allow an important improvement in the reliability of the results, as it would also include the energy used during the production, the transportation and the final disposition. A better approach of the overall environmental impact of the building would be obtained and, therefore it would be promoted a more sustainable way of building construction. Also the innovation in the building industry would increase and more building rehabilitations would be carried out in order to increase the service lifetime, which would obviously reduce the high environmental impact associated with the construction of a new building.

7.2 Recommendations for future assessments

Bearing in mind all the points presented in this thesis, the principal actions that could be recommended in order to improve the reliability of the results obtained and overcome the current barriers are the ones now presented:

- **Training:** It is really important the training of professionals in order to perform LCA with reliable results, as it is a powerful tool in order to assess the environmental impact of a building taking into account its whole active life. Moreover, training is more important in building construction given that it leads to more complex systems, including many types of materials and components.
- **Awareness in the importance of LCA for building industry:** the construction industry represents between 30 and 40 % of the total CO_2 emissions, which makes very important the accurate study of the environmental impact in building construction. Moreover, it provides reliable information in order to make easier the decision-making processes.
- **Recommendations for future comparisons:** If future studies want to compare the results with the ones obtained with this thesis is very important to compare first that there exist enough connections and similarities regarding some aspects of the input data such as the main materials. Moreover, in this case it will be important to pay special attention on the hotspots of this study, which are the concrete production and the electricity consumption during the operation phase.
- **Choice of impact categories:** In this thesis it has been given more importance to impact on the climate change, which means the CO_2 emissions, but many other impact categories have been also presented and are specifically studied in other similar studies.
- **Promotion of EPDs:** Using Environmental Product Declarations is highly recommended to get much relevant, verified and compared results, as they are calculated in detail for specific products and not from a general average as results obtained from databases.

- **Economic and social impacts:** Although climate change is the main focus of this thesis, it is also important in some cases to make a more complex study including also economical and social issues. In this way, the existing tools that can be applied would be Life Cycle Cost Analysis (LCCA) and Social Life Cycle Assessment (SLCA).

On the other hand, some measures that have been found as very useful in order to build more eco-friendly dwellings and reduce the environmental impact during building constructions are the following:

- **Promotion of low-carbon concretes:** the concrete production has been found to be the principal hotspot for the building construction, specifically the cement production. Therefore, changes towards the use of low-carbon concrete are highly recommended in order to reduce the environmental impact.
- **Promotion of recycled steel:** this point is already very common for reinforcing steel and is very important to reduce CO_2 emissions due to the steel production. Moreover, it is proved that steel does not loose its resistance properties during the recycling process.
- **Use of renewable energy sources:** the other principal hotspot found for the system studies is the energy consumption during the operation phase. It is highly recommended to develop and promote the use of renewable energy sources, as it would drastically reduce the environmental impact during this phase.

8

Conclusions

The ideal building would be that one that was inexpensive to build, could last forever with low level of maintenance and finally could return completely to the earth at the end of the active life (Bainbridge, 2004). However, it is an idealistic point of view, which is not achievable nowadays and, thus, is very important to continue working on the study of life cycle environmental impact of buildings.

First, it is important to remark the powerful tool that represent the Life Cycle Assessment (LCA) when studying the environmental effect for building constructions. The application of this methodology should be an essential task when assessing sustainability issues.

It has been also seen that there exist some important barriers when implementing this methodology for buildings, as they represent a very complex product and there is an important lack of specific databases related with this industry. For this reason, it is though that is really important to promote the training of professionals in order to carry out LCA with reliable results and aware in the importance of performing Environmental Product

Declarations (EPD) so as to get much relevant and verified results.

This thesis contributes to increase the literature available regarding LCA of buildings located in Norway. Specifically, a set of three buildings included in the new apartment project situated at Nardovegen (Trondheim) has been considered in this study. Special attention has been paid on the study of the environmental impact produced before the year zero, which includes all the impacts produced during the material production, their transportation to the construction site and all works during the construction process.

A difficult stage of the LCA was the performance of the Life Cycle Inventory (LCI), as it represents the basis for all the calculations. So, it was necessary to accurately use all drawings and information available related with the project. Finally, the overall results showed that the total environmental impact of the system considered is 1.618,9 kg CO_2-eq per FU and, contrasted with appropriate previous researches, it is found that the most contributor are the concrete production processes and the energy consumption during the operation phase. Therefore, specific sensitivity analysis were carried out in this sense to finally encourage the change into the use of low-carbon concrete and more renewable energy sources for future constructions.

9

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10

Appendices

The following appendices are attached to this study:

A) Input data

B) Examples of EPDs

C) Output data

Moreover, also the Excel files *"LCI"* and *"Interpretation"* are attached, which show all calculations needed for the establishment of the measurements of the Life Cycle Inventory and how output information from SimaPro has been treated in order to get the results.

A) Input data

The excel file LCI attached to this thesis shows the detailed measurements that have been done with the drawings and information available related with the new project of apartments in Nardovegen, Trondheim.

All these measurements have been divided into different parts (one in each excel sheet) in order to make easier the comprehension. The different parts are the following:

Functional unit	Transportation
Walls	Construction on site
Floors	Allocation
Doors & windows	Water & electricity consumption
Foundations	Maintenance

In the following pages, tables regarding the measurements of walls are attached in order to show how the calculations have been made.

BLOKK A	MEASURE													UNIT	MATERIAL LAYERS	THICKNESS OF THE LAYERS (m)	TOTAL MEASURE	UNIT	AMOUNT / FU
	THICK	HIGH						LENGTH											
		Level 0	Level 1	Level 2	Level 3	Level 4	Level 5	Level 0	Level 1	Level 2	Level 3	Level 4	Level 5						
External wall (basement level)	0,31	3,20	-	-	-	-	-	86,67	-	-	-	-	-	m	Drainage board	0,050	2579,30	kg	2,66
															Reinforced concrete	0,250	69,34	m3	0,07
															Reinforcement (90 kg/m3)	-	6240,24	kg	6,43
															Gypsum skimming ($1000 < \rho < 1300$)	0,010	3050,78	kg	3,14
External wall	0,26	-	3,30	2,85	2,85	2,85	0,85	-	73,72	73,72	73,72	25,72	25,72	m	Reinforced concrete	0,250	189,66	m3	0,20
															Reinforcement (90 kg/m3)	-	17069,49	kg	17,58
															Gypsum skimming ($1000 < \rho < 1300$)	0,010	8345,08	kg	8,59
Internal wall (thick)	0,22	3,20	3,30	2,85	2,85	2,85	-	14,31	28,38	28,38	28,38	6,75	-	m	Gypsum skimming ($1000 < \rho < 1300$)	0,010	3524,94	kg	3,63
															Reinforced concrete	0,200	64,09	m3	0,07
															Reinforcement (80 kg/m3)	-	5127,19	kg	5,28
															Gypsum skimming ($1000 < \rho < 1300$)	0,010	3524,94	kg	3,63
Internal wall (thin)	0,10	3,20	3,30	2,85	2,85	2,85	-	38,59	54,44	54,44	54,44	57,00	-	m	Gypsum skimming ($1000 < \rho < 1300$)	0,010	8534,88	kg	8,79
															Double hollow brick partition (60 mm < thickness < 90 mm)	0,080	69830,82	kg	71,92
															Gypsum skimming ($1000 < \rho < 1300$)	0,010	8534,88	kg	8,79

BLOKK B	MEASURE													UNIT	MATERIAL LAYERS	THICKNESS OF THE LAYERS (m)	TOTAL MEASURE	UNIT	AMOUNT / FU
	THICK	HIGH						LENGTH											
		Level 0	Level 1	Level 2	Level 3	Level 4	Level 5	Level 0	Level 1	Level 2	Level 3	Level 4	Level 5						
															Reinforced concrete	0,250	269,08	m3	0,29
External wall	0,26	-	4,75	2,85	2,85	2,85	2,80	-	68,12	66,32	66,32	66,32	66,32	m	Reinforcement (90 kg/m3)	-	24216,80	kg	26,15
															Gypsum skimming (1000 < ρ < 1300)	0,010	11839,32	kg	12,79
															Gypsum skimming (1000 < ρ < 1300)	0,010	3804,11	kg	4,11
Internal wall (thick)	0,18	-	4,75	2,85	2,85	2,85	2,80	-	21,48	21,48	21,48	21,48	21,48	m	Reinforced concrete	0,160	55,33	m3	0,06
															Reinforcement (80 kg/m3)	-	4426,60	kg	4,78
															Gypsum skimming (1000 < ρ < 1300)	0,010	3804,11	kg	4,11
															Gypsum skimming (1000 < ρ < 1300)	0,010	9990,20	kg	10,79
Internal wall (thin)	0,10	-	4,75	2,85	2,85	2,85	2,80	-	55,00	57,00	57,00	57,00	57,00	m	Double hollow brick partition (60 mm < thickness < 90 mm)	0,080	81738,00	kg	88,27
															Gypsum skimming (1000 < ρ < 1300)	0,010	9990,20	kg	10,79

BLOKK C	MEASURE													UNIT	MATERIAL LAYERS	THICKNESS OF THE LAYERS (m)	TOTAL MEASURE	UNIT	AMOUNT / FU
	THICK	HIGH						LENGTH											
		Level 0	Level 1	Level 2	Level 3	Level 4	Level 5	Level 0	Level 1	Level 2	Level 3	Level 4	Level 5						
															Reinforced concrete	0,250	230,42	m3	0,26
External wall	0,26	-	3,20	2,85	2,85	2,85	2,80	-	67,72	67,02	67,02	67,02	47,12	m	Reinforcement (90 kg/m3)	-	20737,37	kg	23,54
															Gypsum skimming (1000 < ρ < 1300)	0,010	10138,27	kg	11,51
															Gypsum skimming (1000 < ρ < 1300)	0,010	3441,81	kg	3,91
Internal wall (thick)	0,18	-	3,20	2,85	2,85	2,85	2,80	-	21,48	28,64	21,48	21,48	14,32	m	Reinforced concrete	0,160	50,06	m3	0,06
															Reinforcement (80 kg/m3)	-	4005,02	kg	4,55
															Gypsum skimming (1000 < ρ < 1300)	0,010	3441,81	kg	3,91
															Gypsum skimming (1000 < ρ < 1300)	0,010	5961,24	kg	6,77
Internal wall (thin)	0,10	-	3,20	2,85	2,85	2,85	2,80	-	35,35	40,82	40,82	40,82	28,50	m	Double hollow brick partition (60 mm < thickness < 90 mm)	0,080	48773,79	kg	55,36
															Gypsum skimming (1000 < ρ < 1300)	0,010	5961,24	kg	6,77

B) Output data

The software used in this thesis, SimaPro, includes the ReCiPe methodology in order to carry out the LCIA. Then, it is possible to obtain the contributions to the different impact categories of each one of the units and processes that have been introduced.

All these results have been grouped and treated in the *Interpretation* excel file, which is attached to this study. In the following page, as an example, the table obtained from SimaPro for some of the materials related with the production phase of the building A is shown.

SimaPro 8.0	Impact assessment	Date:	30.04.2015	Time:	11:21
Project	Nardovegen apartments				

Calculation:	Analyze
Results:	Impact assessment
Product:	1 p Production phase - Blokk A (of project silvia)
Method:	ReCiPe Midpoint (H) V1.08 / Europe Recipe H
Indicator:	Characterization
Skip categories:	Never
Exclude infrastructure processes:	No
Exclude long-term emissions:	No
Sorted on item:	Impact category
Sort order:	Ascending

Impact category	Unit	Total	Concrete, normal {RoW}| production | Alloc Def, S	Reinforcing steel {RoW}| production | Alloc Def, S	Gypsum, mineral {RoW}| citric acid production | Alloc Def, S	Polystyrene foam slab for perimeter insulation {RoW}| processing | Alloc Def, S	Concrete, normal {RoW}| production | Alloc Def, S	Reinforcing steel {RoW}| production | Alloc Def, S	Gypsum, mineral {RoW}| citric acid production | Alloc Def, S	Brick {RoW}| production | Alloc Def, S	Door, inner, wood {RoW}| production | Alloc Def, S	Glazing, double, U<1.1 W/m2K {RoW}| production | Alloc Def, S	Plywood, hardwood, raw, debarked {RoW}| market for | Alloc Def, S
Climate change	kg CO2 eq	255,7098076	106,4524791	59,92432377	2,121934652	12,00130259	27,59879087	13,17786045	1,312201497	18,28955948	6,991221284	5,054756672	2,785377186
Ozone depletion	kg CFC-11 eq	7,31065E-06	2,01E-06	2,23E-06	4,03E-07	2,69E-07	5,21E-07	4,90E-07	2,49E-07	3,53E-07	2,77E-07	3,68E-07	1,44E-07
Terrestrial acidification	kg SO2 eq	0,966596882	0,346324485	0,243353522	0,01445298	0,042393831	0,089787829	0,053515477	0,008937703	0,064517815	0,043084029	0,039503645	0,020725566
Freshwater eutrophication	kg P eq	0,054806886	0,010564948	0,026963756	0,000771529	0,00117742	0,002739061	0,005929556	0,000477113	0,001893432	0,002227057	0,001301277	0,000761737
Marine eutrophication	kg N eq	0,03943243	0,013588451	0,009836178	0,001719357	0,001240262	0,003522932	0,002163058	0,001063248	0,002003141	0,00205349	0,001286854	0,000955459
Human toxicity	kg 1,4-DB eq	18,97888401	4,14745931	8,767587913	0,397418286	0,225868642	1,075267228	1,92806598	0,245762926	0,686758573	0,749016987	0,48737618	0,26830198
Photochemical oxidant formation	kg NMVOC	0,945012055	0,328320089	0,280261565	0,006879049	0,041398005	0,085120023	0,061631864	0,004253994	0,056157087	0,029285167	0,024693402	0,02701181
Particulate matter formation	kg PM10 eq	0,498001639	0,134946376	0,199459004	0,004799573	0,01410157	0,034986098	0,043862705	0,002968049	0,022365652	0,016465687	0,013388399	0,010658526
Terrestrial ecotoxicity	kg 1,4-DB eq	0,012942651	0,002344096	0,003269687	0,002366562	0,000258155	0,000607729	0,000719032	0,001463479	0,000352614	0,001022919	0,000232384	0,000305994
Freshwater ecotoxicity	kg 1,4-DB eq	0,024274651	0,005315854	0,007607529	0,001535557	0,001925303	0,001378184	0,001672959	0,000949587	0,00142154	0,001258473	0,000765379	0,000444286
Marine ecotoxicity	kg 1,4-DB eq	0,178189872	0,052838641	0,059796543	0,00545513	0,004136765	0,013698907	0,01314976	0,003373445	0,007448193	0,009091682	0,005276798	0,003924008
Ionising radiation	kBq U235 eq	11,48348865	3,80518199	3,044328388	0,266792348	0,340833459	0,986528664	0,669473298	0,164984024	0,741633206	0,704527634	0,42467974	0,334525896
Agricultural land occupation	m2a	73,33079284	0,876312942	0,859026966	0,33011686	0,16447632	0,227192244	0,188907221	0,204143816	0,782161522	17,1815877	0,19836273	52,31850452
Urban land occupation	m2a	3,299061264	0,989895363	0,756794447	0,029592246	0,043052606	0,256639539	0,166425434	0,018299805	0,113463309	0,252890068	0,064973926	0,607034521
Natural land transformation	m2	0,034208432	0,012314093	0,006367274	0,000246903	0,000383488	0,003192543	0,001400217	0,000152684	0,002369013	0,002526235	0,000974178	0,004281804
Water depletion	m3	440,2668117	126,3579798	174,8958403	5,009247387	7,266288989	32,75947625	38,46105942	3,097711757	15,60660595	16,48472588	13,47020874	6,85766721
Metal depletion	kg Fe eq	63,17878601	2,406560057	47,35340448	0,153098908	0,16001056	0,623922978	10,41341007	0,094676156	0,501984676	0,447868242	0,752926246	0,270923639
Fossil depletion	kg oil eq	46,63551717	12,9165708	12,92558368	0,50164816	5,829821246	3,348740578	2,842444058	0,310218539	3,891939199	1,912507873	1,345363134	0,8106799

C) Example of EPD

For the performing of this Life Cycle Assessment, it has been used as many EPDs as it has been possible given that they lead to more reliable results than the ones obtained from generic databases. In this appendix, an example will be shown. Specifically, it is the one that analyses the low-carbon concrete that has been presented in the sensitivity analysis.

Ver 1713

ENVIRONMENTAL PRODUCT DECLARATION

ISO 14025 ISO 21930 EN 15804

epd-norge.no
The Norwegian EPD Foundation

Eier av deklarasjonen	Norcem AS
Program operatør	Næringslivets Stiftelse for Miljødeklarasjoner
Utgiver	Næringslivets Stiftelse for Miljødeklarasjoner
Deklarasjonens nummer	00151N rev1
Godkjent dato	16.10.2013
Gyldig til	16.10.2018

Lavkarbonsement

Produkt

Norcem AS

Produsent

Generell informasjon

Lavkarbonsement
Produkt

Norcem AS
Produsent

Program operatør:
Næringslivets Stiftelse for Miljødeklarasjoner
Postboks 5250 Majorstuen, 0303 Oslo
Tlf: +47 23 08 80 00
e-post: post@epd-norge.no

Eier av deklarasjon:
Norcem AS
Kontakt person: Liv Margrethe Hatlvik Bjerge
Tlf: +47 22 87 84 38 (Oslo)
+47 35 57 24 99 (Brevik)
e-post: liv.bjerge@norcem.no

Deklarasjon nummer:
00151N rev1

Produksjonssted:
Brevik

Deklarasjonen er basert på PCR:
CEN Standard EN 15804 tjener som kjerne PCR Requirements on an Environmental Product Declaration (EPD) for Cement, Bau-Umwelt

Kvalitet/Miljøsystem:
Miljøstyringssystem ISO 14001-sertifisert (NO-0001003)

Deklarert enhet:
1 tonn sement fra råvareuttak til port

Org. no.:
NO 934949145 MVA

Deklarert enhet med opsjon:

Godkjent dato:
16.10.2013

Funksjonell enhet:

Gyldig til:
16.10.2018

Miljødeklarasjonen er utarbeidet av:
Mie Vold
Østfoldforskning

Sammenlignbarhet:
EPD av byggevarer er nødvendigvis ikke sammenlignbare hvis de ikke samsvarer med EN 15804

Årstall for studien:
2013

Verifikasjon:
Uavhengig verifikasjon av data og annen miljøinformasjon er foretatt etter ISO 14025, 8.1.3.

eksternt ☑ internt ☐

Seniorforsker, Cecilia Askham
(Uavhengig verifikator godkjent av EPD Norge)

Godkjent i tråd med ISO 14025, 8.1.4

Dr. ing Sverre Fossdal
(Verifikasjonsleder i EPD-Norge)

Deklarert enhet:
1 tonn sement fra råvareuttak til port

Nøkkelindikatorer	Enhet	Lavkarbonsement A1 - A3	Transport Produksjonssted til sentrallager i Norge
Global oppvarming	CO_2 -ekv	503	3
Energibruk	MJ	3853	37
Farlige stoffer	*		

* Produktet inneholder ingen stoffer fra REACH Kandidatliste eller den norske prioritetslisten

Produkt

Produktbeskrivelse:
Grå portland flyveaskesement

Produktspesifikasjon
Kalkstein fra eget dagbrudd og gruve samt dagbrudd i Verdal er viktigste råvare i tillegg til flyveaske.
Råvaresammensetningen i lavkarbonsement er som følger:

Materialer	Enhet	Lavkarbonsement
Klinker	kg/DE	599
Flyveaske	kg/DE	300
Kalkmel	kg/DE	50
Gips	kg/DE	47
Annet	kg/DE	4,3

Tekniske data:
Lavkarbonsement (EN 197-1, CEM II/B-V)
Ytterligere informasjon finnes på: Link til Teknisk datablad eller på WEB: http://www.heidelbergcement.com/no/no/norcem/sementtyper/index.htm

Markedsområde:
Norge

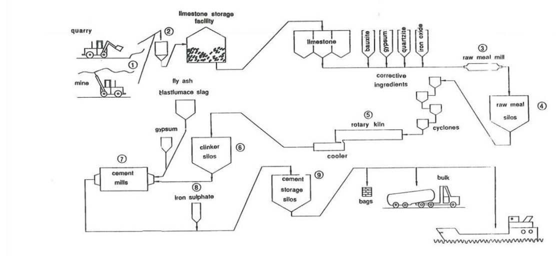
Levetid:
Avhenger av bruksområde

LCA: Beregningsregler

Deklarert enhet:
1 tonn sement fra råvareuttak til port

Systemgrenser:
Fra råvareuttak til marked

Produksjonsfasen for produktet
• Hovedprosessene ved Norcem Brevik er uttak av kalkstein fra to felt i nærheten av bedriften: Dalen gruve og Bjørntvet dagbrudd, i tillegg til dagbrudd i Verdal.
• Kalksteinen tilsettes korreksjonsmaterialer, som kisavbrann, kvarts, oxiton, bauxitt og gips, og males og brennes ved høye temperaturer (1450^{o}C) til klinker.
• Klinkeren finmales til sement. I maleprosessen tilsettes mindre mengder gips, jernsulfat og flygeaske i blandingssement.



1. Mining of limestone from quarries or mines
2. Limestone crushing
3. Grinding of limestone and additives to produce raw meal
4. Silos for storage and homogenisation
5. Burning of clinker in a rotary kiln where the temperature of the materials reaches up to a 1450°C
6. Silos for clinker storage
7. Grinding of clinker with gypsum and other additives to produce cement
8. Addition of iron sulphate to dechromatise the cement
9. Storage, dispatch of cement

Datakvalitet:

Råvaregruppe	Datakvalitet	Kilde	Alder for data
Klinker	Spesifikke data	Norcems egne tall	2012
Flygeaske	Ikke relevant	eMaterial AS	2013
Kalkmel	Spesifikke data	Norcems egne tall	2012
Gips	Databasedata	EcoInvent	2006
Annet	Under Cut-off		

Spesifikke data er brukt for de materialer som utgjør vesentlige bidrag til miljøpåvirkning.

Allokering:
For produksjonen hos Norcem er totalt forbruk for 2012 registrert og fordelt på produserte produkter på vektbasis .
I de tilfeller det benyttes et avfallsprodukt fra annen produksjon, allokeres forhold knyttet til framstilling til den opprinnelige produksjonen.
Alternativ brensel anses som avfallsprodukter fra annen produksjon. Påvirkninger knyttet til framstilling er allokert til den opprinnelige produksjonen, mens påvirkninger ved forbrenning er allokert til virksomheten som drar nytte av energien.
Alt utslipp og forbruk av ressurser knyttet til produksjonen av elektrisitet og fremstilling av andre energibærere som er benyttet i produksjon ved råvarene i produktet er allokert til råvarene og derved produktet i neste omgang.

Cut-off kriterier:
Masser som utgjør mindre enn 1% er ikke tatt med.

LCA: Scenarier og annen teknisk informasjon

Følgende informasjonen beskriver scenariene for modulene i EPDen.

Tilleggsinformasjon: Transport fra Produksjonssted til sentrallager i Norge 50 km
Transporten skjer med Norcems egen bulkbåt for sement

Annen teknisk informasjon
Ikke relevant

LCA: Resultater

I modul A1 inngår produksjon av råvarer fra uttak av ressurser. A2 inkluderer transport av råvarer til Norcem, A3 inkluderer produksjonsprosessen hos Norcem.

Systemgrenser (X = inkludert, MID = modul ikke deklarert, MIR = modul ikke relevant)

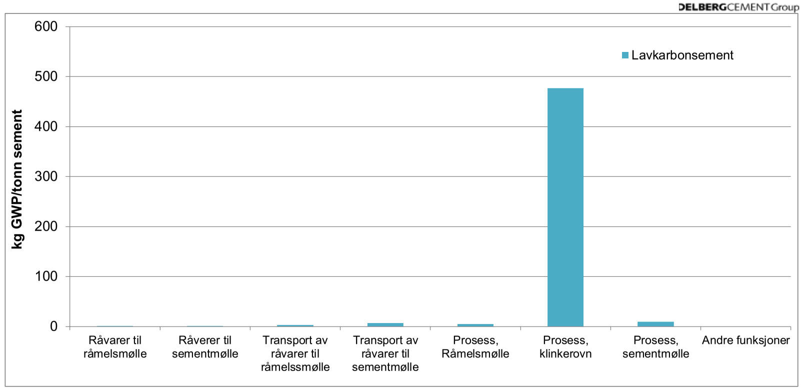
Produktfase			Konstrusjon installasjon fase		Bruksfase							Sluttfase				Etter endt levetid
Råmaterialer	Transport	Tilvirkning	Transport	Konstrusjon installasjon fase	Bruk	Vedlikehold	Reparasjon	Utskiftinger	Renovering	Operasjonell energibruk	Operasjonell vannbruk	Demontering	Transport	Avfallsbehandling	Avfall til deponi	Gjenbruk-gjenvinning-resirkulering-potensiale
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
X	X	X	MID	MID	MID	MID	MID	MID	MID	MID	MID	MID	MID	MID	MID	MID

Miljøpåvirkning

Parameter	A1	A2	A3	A1-A3
GWP	2,14	10,12	490,98	503,25
ODP	6,67E-08	1,14E-06	2,02E-06	3,23E-06
POCP	0,012	0,015	0,040	0,068
AP	0,07	0,18	0,71	0,96
EP	0,02	0,02	0,22	0,25
ADPM	2,66E-05	1,25E-05	1,29E-04	1,68E-04
ADPE	22,62	152,14	1 951,76	2 126,53

GWP Globalt oppvarmingspotensial (kg CO_2-ekv.); **ODP** Potensial for nedbryting av stratosfærisk ozon (kg CFC11-ekv.); **POCP** Potensial for fotokjemisk oksidantdanning (kg C_2H_4-ekv.); **AP** Forsurningspotensial for kilder på land og vann (kg SO_2-ekv.); **EP** Overgjødslingspotensial (kg PO_4^{-3}-ekv.); **ADPM** Abiotisk uttømmingspotensial for ikke-fossile ressurser (kg Sb -ekv.); **ADPE** Abiotisk uttømmingspotensial for fossile ressurser (MJ)

Lese eksempel: 9,0 E -03 = 9,0 * 10^{-3}



Ressursbruk

Parameter	A1	A2	A3	A1-A3					
FPEE	11,60	2,25	604,88	618,73					
FPEM	-	-	-	-					
TFE	11,60	2,25	604,88	618,73					
IFPE	24	155	2 023	2 202					
IFPM	-	-	-	-					
TIFE	35	157	2 628	2 820					
SM	304,30	-	0,00	304,30					
FSB	-	-	-	-					
IFSB	-	-	1 032,37	1 032,37					
V	16,17	11,01	967,76	994,93					

#

FPEE Fornybar primærenergi brukt som energibærer (MJ); **FPEM** Fornybar primærenergi brukt som råmateriale (MJ); **TFE** Total bruk av fornybar primærenergi (MJ); **IFPE** Ikke fornybar primærenergi brukt som energibærer (MJ); **IFPM** Ikke fornybar primærenergi brukt som råmateriale (MJ); **TIFE** Total bruk av ikke fornybar primærenergi (MJ); **SM** Bruk av sekundært materialer (kg); **FSB** Bruk av fornybart sekundært brensel (MJ); **IFSB** Bruk av ikke fornybart sekundært brensel (MJ); **V** Netto bruk av drikkevann (m^3)

Livsløpets slutt - Avfall

Parameter	A1	A2	A3	A1-A3					
FA	1,60E-04	7,80E-05	7,03E-04	9,41E-04					
IFA	1,89E+00	3,55E-01		2,25E+00					
RA									

FA Avhendet farlig avfall (kg); **IFA** Avhendet ikke-farlig avfall (kg), **RA** Avhendet radioaktivt avfall (kg)

Livsløpets slutt - Utgangsfaktorer

Parameter	A1	A2	A3	A1-A3					
KG									
MR									
MEG									
EEE									
ETE									

KG Komponenter for gjenbruk (kg); **MR** Materialer for resirkulering (kg); **MEG** Materialer for energigjenvinning (kg); **EEE** Eksportert elektrisk energi (MJ); **ETE** Eksportert termisk energi (MJ)

Lese eksempel: 9,0 E -03 = 9,0 * 10^{-3}

Spesifikke norske krav

Elektrisitet
Nordisk produksjonsmiks

Klimagassutslipp 0,0458 kg CO_2 ekv/MJ

Farlige stoffer
Produktet er ikke tilført stoffer fra REACH kandidatliste (pr.16.10.2013) over stoffer av svært stor bekymring, stoffer på den norske Prioritetslisten (pr.16.10.2013) og stoffer som fører til at produktet blir klassifisert som farlig avfall. Det kjemiske innholdet i produktet er i samsvar med den norske produktforskriften.

Transport
Transport fra Produksjonssted til sentrallager i Norge er 50 km

Inneklima
Materialet har ingen relevant påvirkning på inneklima

Klimadeklarasjon
Foreligger ikke

Bibliografi

NS-EN ISO 14025:2006 *Miljømerker og deklarasjoner - Miljødeklarasjoner type III - Prinsipper og prosedyrer.*

NS-EN ISO 14044:2006 Miljøstyring - Livsløpsvurderinger - Krav og retningslinjer

NS-EN 15804:2012 *Bærekraftig byggverk - Miljødeklarasjoner - Grunnleggende produktkategoriregler for byggevarer*

ISO 21930:2007 *Sustainability in building construction - Environmental declaration of building products*

Vold Mie: 2013 *Oppdaterte EPDer med 2012-tall for Norcem Brevik, Bakgrunnsrapport for verifisering. Mie Vold, Østfoldforskning, Fredrikstad, Mai 2013*

Institut Bauen und Umwelt e.V. (2012-1) *Requirements on an Environmental Product Declaration (EPD) for Cement*

Institut Bauen und Umwelt e.V. (2012-2) *Calculation Rules for the Life Cycle Assessment and Requirements on the Background Report*

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Østfoldforskning	**Forfatter av Livsløpsrapporten** Mie Vold Østfoldforskning as Gamle Beddingsvei 26, 1671 Kråkerøy	Tlf: Fax e-post: web	+47 41 46 98 00 +47 69 34 24 94 mie@ostfoldforskning.no www.ostfoldforskninh.no