Master's thesis

NTNU
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Evaluation of BIM-based LCA in the early design phase (low LOD) of buildings

Master's thesis in Civil and Environmental Engineering
Supervisor: Rolf André Bohne
June 2019

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Kunnskap for en bedre verden

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Preface

This report has been written as a master thesis at the Norwegian University of Science and Technology (NTNU). The thesis is conducted during the spring of 2019 under the Department of Civil and Environmental Engineering and counts as 30 credits. This work represents the final work enrolled in *TBA4910 Project Management, Master's Thesis*.

The research evaluates the feasibility of Building Information Modeling (BIM) as the sole data for conducting Life Cycle Assessments (LCAs) in early design stages, using the Level of Development (LOD) in the BIM model. The thesis contains a case study that conducts LCAs at different LOD levels using One Click LCA (OCL). This LCA tool is capable of using quantity take-off generated by BIM to obtain environmental impacts, and by selecting available information in OCL to compile LCAs. Both procedures are compared. Finally, a suggestion to the Architecture, Engineering and Construction (AEC) professionals in how to use LOD as the direction-setting process in OCL, is proposed.

I would like to thank my supervisor at NTNU, professor Rolf André Bohne, for guidance and meetings regarding the master thesis. Also, thanks to Ingvil Arntzen and Terje Andersen at NCC for directness into the ongoing project, Valle Wood, and ability to use OCL.

During the spring of 2019, I wrote an article in collaboration with my supervisor of this master thesis with the same title. My contribution was accepted and chosen for an oral presentation at the SBE19 conference.

Summary

Building Information Modelling (BIM) is a convenient tool that is capable of collecting information throughout the whole life cycle of a building in one platform. The evolution in the digital BIM model in early design stages is not standardized, but Level of Development (LOD) is a concept that systematically structures the design processes divided into five levels. LOD is assessed in this master thesis as an opportunity to enhance the calculation of the environmental impacts in different early design stages more efficiently, using the methodology Life Cycle Assessment (LCA). Enlightening the building elements that contribute to the highest release of CO_2, permits early building material selection. This facilitates a pathway towards sustainable and environmentally friendly buildings.

This study evaluates BIM based LCA in early design stages (low LOD). Valle Wood by NCC, is the building project appearing as the thesis' case study, employed for executing LCAs at different LOD levels using the LCA software One Click LCA (OCL). The scope of this master thesis, as well as the conducted LCAs, is limited to the production stage (A1-A3), which will be considered as the system boundary for this study. An LCA framework determined by LOD levels is proposed to systematize a sustainable decision process in the early design stages.

Qualitative and quantitative methods are the basis of this thesis' results. The qualitative methods investigate the findings regarding the interactions between BIM and LCA, as well as how BIM based LCAs can be advantageously rendered through comprehensive literature reviews. BIM models were deliberated this study through document reviews, received from NCC. The quantitative LCA calculations on the BIM models are based on using quantity take-off generated by BIM, as well as one LCA using input data retrieved from designers in Valle Wood, to obtain environmental impact in OCL.

Central findings of this master thesis indicate feasible integration of the LCA methodology inside BIM. There are three main approaches ranging from the use of several software, the inclusion of LCA information in BIM, and quantity take-offs generated by BIM to conduct BIM based LCAs. Results from the LCAs using OCL designated more accurate assessments in higher LOD. Nevertheless, results based on quantity take-offs generated by BIM were not trustworthy as the take-offs do not correspond to OCLs format. Consequently, an improvement of 66% with respect to CO_2 emissions at the same LOD level (LOD 350), occurred when the right quantity of materials were selected, according to the project description.

The conclusion to this master thesis is a concretized suggestion where today's unpredictable development of BIM becomes part of a LOD framework. This will enable reliable and trustworthy LCAs during the early design stages. Interaction of BIM and LCA tools entitle an automated LCA process as the accessibility to the requisite information is located on the same platform.

Suggestions for further work is the development regarding a standardized methodology accounting both BIM and LCA. Environmental data on various building materials is still absent and needs development. This information is required with respect to the compilation of LCAs using undocumented and unverified data.

Sammendrag

Bygningsinformasjonsmodellering (BIM) er et nyttig digitalt verktøy som samler informasjon om alle byggeprosjekters faser på én plattform. I de tidlige stadiene av prosjekteringsfasen er ikke utviklingsgraden av den virtuelle BIM modellen standardisert, men begrepet Level of Development (LOD) er et konsept som strukturer beslutninger fordelt på fem nivåer. I denne masteroppgaven sees LOD på som en mulighet til å effektivisere miljøberegninger i ulike stadier av prosjekteringen, gjennom metoden livssyklusanalyse (LCA). Tidlige miljøanalyser i prosjekteringsfasen vil gi tydelig oversikt over hvilke bygningselementer som bidrar til høyest utslipp av CO_2, som igjen vil bevisstgjøre materialvalg og vil påvirke utformingen mot bærekraftige og miljøvennlige bygg.

Denne studien evaluerer BIM-basert LCA i tidlig prosjekteringsfase av byggeprosjekter. Byggeprosjektet Valle Wood av NCC er en case benyttet for å gjøre LCA i forskjellig nivåer av LOD ved bruk av LCA-programvaren One Click LCA (OCL). Omfanget av denne masteroppgaven, og miljøanalysene, er systembegrenset til produksjonsfasen (A1-A3). Et LCA-rammeverk betinget av LOD-nivåer er foreslått, med hensikt å strukturere miljøvennlige beslutningsplaner i prosjektering-stadiene.

Arbeidet er basert på kvalitative og kvantitative metoder. De kvalitative metodene undersøker litteraturens svar på samhandlingen mellom BIM og LCA gjennom en litteraturstudie, og hvordan BIM-baserte LCAer fordelaktig kan utføres. Tilgjengeliggjorte dokumenter i form av BIM-modeller er studert gjennom oppgavens dokumentstudier. De kvantitative LCA-beregningene på caset baserer seg på informasjon uthentet fra tre BIM-modeller, samt én LCA ved bruk av inndata bestemt av de prosjekterende i Valle Wood.

De viktigste resultatene og funnene i denne masteravhandlingen tilsier at LCA-metodikken bør og kan integreres i BIM. Det er i hovedsak tre innfallsvinkler mot en BIM-basert LCA som benyttes i dag. Disse innfallsvinklene spenner fra bruken av flere dataprogrammer til å gjennomføre LCA i BIM, til uthenting av informasjon i BIM til å utøve LCAer. Funnene i casestudiet og miljøanalysene i OCL viser at en høyere LOD i BIM utgjør mer nøyaktige LCA-resultater. Likevel er disse resultatene ikke troverdig, da uthentingen av data i BIM ikke samsvarer med formatet i OCL. En forbedring på 66% i klimagassutslipp, CO_2-eq, i tilsvarende LOD-nivå (LOD 350) inntraff da riktige mengder og materialer fra prosjektbeskrivelsen ble benyttet.

Konklusjonen i oppgaven er et konkret tiltak der dagens uforutsigbare utvikling i BIM blir satt inn i et LOD-rammeverk basert på informasjonsnivå, for å muliggjøre troverdige LCAer underveis i tidlig prosjekteringsfase. Sammenkobling av BIM- og LCA-verktøyer gjør miljøanalyser mer automatisert og enklere fordi tilgjengeligheten til nødvendig informasjon er på samme plattform.

Videre anbefaler masteroppgaven mer utvikling i standardiserte metoder som hensyntar både

BIM og LCA. Miljødeklarasjoner som oppsummerer miljøprofilen til bygningsmaterialer, er en mangel hos flere komponenter. Disse dataene er nødvendige for å utføre korrekte og nøyaktige LCAer.

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Abbreviations

AEC Architecture Engineering and Construction

AIA American Institute of Architects

BCF BIM Collaboration Format

BIM Building Information Modeling

CAD Computer Aided Design

EPD Environmental Product Declaration

FU Functional Unit

GHG Greenhouse Gas

GlobalABC Global Alliance for Buildings and Construction

GWP Global Warming Potential

HVAC Heating Ventilation and Air Conditioning

IDM Information Delivery Manual

IEA International Energy Agency

IFC Industry Foundation Class

IPCC Intergovernmental Panel on Climate Change

IPD Integrated Project Delivery

ISO International Organization for Standardization

LCA Life Cycle Assessment

LCC Life Cycle Costing

LCI Life Cycle Inventory

LCIA Life Cycle Inventory Assessment

LOD Level Of Development

MVD Model View Definitions

NDC Nationally Determined Contribution

NTNU Norwegian University of Science and Technology

OCL One Click LCA

PCR Product Category Rules

UN United Nations

ZEB Zero Emission Building

Chapter 1: Introduction

In this chapter, a reflection on the importance of the environmental assessment with respect to enhancing the global warming potential (GWP) caused by building projects, will be presented. Several initiatives regarding this topic have been proposed earlier, but with a wider focus than what will be presented in this thesis. The scope of this study will only include the design stage and what the building industry can do to improve the environmental assessment, regarding Building Information Modeling (BIM) and Life Cycle Assessment (LCA).

1.1 Background

There are several basic, well-established scientific links that constitute the background for this master thesis. The UN Intergovernmental Panel on Climate Change (IPCC) states that the human fingerprint on greenhouse gases (GHGs) have risen to record levels not seen in three million years (UN 2018a). The quantities of GHGs in the atmosphere is, among other things, caused by industrialization, deforestation and large scale agriculture. The building industry is an important factor regarding the densification of GHGs in the atmosphere, specifically 39% of total energy and process-related emissions (UN 2018a; IEA 2018).

In the past, the development of sustainability for buildings mainly focused on the energy demand and emissions during the use phase. Since the emergence of low energy buildings, the literature shows the importance of embodied energy and emissions during building constructions and production of materials (Häfliger et al. 2017).

During the past decades, there has been a growing interest in the building sector for the use of BIM. This is due to many benefits and resource savings during design, planning and construction (Volk, Stengel, and Schultmann 2014). With the use of BIM, the building can first be constructed virtually on a computer before it is actually built, which enables the assessment of the building performances before the building is finished (Jrade and Jalaei 2013). There are various advantages that BIM modeling introduce, for example preplanning, clash detection, visualization, quantification, cost estimates, facility management, deconstruction and data management. However, the integration of LCA is not available yet (Najjar et al. 2017; Volk, Stengel, and Schultmann 2014; Shadram et al. 2015; Basbagill et al. 2013; Soust-Verdaguer, Llatas, and García-Martínez 2017; Jrade and Jalaei 2013; Antón and Diaz 2014; Durão et al. 2019; Santos et al. 2019a; Soust-Verdaguer, Llatas, García-Martínez, and Gómez de Cózar 2018).

Development of 3D modelling was introduced for the building industry in the 1970s, and it was the forerunner for BIM in the early 2000s (Volk, Stengel, and Schultmann 2014). To structure the process of constructing a building within a BIM software, there is a non-standardized method called Level of Development (LOD). LOD separates the level of completeness, which depends on the level of the graphical features and the detail within the BIM objects. Moreover, the use of LCA methodology was established in the second half of the 1990s (Najjar et al. 2017). LCA is a tool for evaluating the environmental performance of a product or service. It is a time-consuming process, largely because of the huge amount of data gathering required to map the quantities of materials and its emission flows throughout the life cycle.

1.2 Purpose, Objectives and the Knowledge Gap

Due to the demand for environmental actions in the building industry, this thesis' main purpose is *to investigate which features that are required in an interaction between BIM and LCA in the early design stage (low LOD), to evaluate the environmental performance of a building.* Clarification of this main purpose is partitioned into three research questions. The knowledge gap between LCA and BIM, and not knowing the actual life cycle emissions from a building in the early design stages, initiated the development of the following research questions based on this thesis' main purpose:

1. *How is the environmental assessment treated in a building project today?*
2. *What is the interaction between BIM and LCA, and how is this interaction used to evaluate environmental performance in building projects?*
3. *How can an early design LCA framework correspond to LOD with respect to One Click LCA (OCL)?*

By finding answers to these questions, the knowledge gap between BIM and LCA will be reduced, and early design stages for both fields will be improved. Due to this, a quantitative hypothesis for this master thesis is that the more environmentally detailed BIM becomes, the more reliable LCAs occur in early design stages of building projects. Trustworthy results that display the actual GWP, are directly associated with fewer errors in the layer between BIM and LCA. The author believes that the decision-making process can reasonably exclude materials that contribute the most to GWP. Additionally, a framework that includes LCA and LOD requirements, would enhance the field of BIM and LCA towards a unification.

1.3 Scope and Limitations

The sustainability of buildings is depending on several aspects. This master thesis is evaluating one of them, namely the environmental impact of buildings regarding GHG emission, and its GWP. This study focuses on the LOD in the design stage using BIM, and how a BIM-based LCA can help improve the environmental impacts, limited to buildings. To evaluate the environmental performances in early design stages, this thesis is using LCA methodology.

To narrow the scope of this study, only the production stage (A1-A3) is included. Cradle to gate processes for materials and services used in construction are considered (Fufa et al. 2016):

- Raw material extraction and processing (A1)
- Transport of raw materials to the manufacturer (A2)
- Manufacturing of products and packaging (A3)

1.4 Structure of the Report

The introduction to this master thesis proves the importance of contributing to a better and environmentally friendly building sector. Section 1.1 gives reasons for implementing BIM and LCA, and the potential to integrate both fields is achievable. Chapter 2 presents a theoretical framework for this study.

This master thesis consists of qualitative results, as well as quantitative. The state-of-the-art and best practice in the field of BIM-LCA are mainly based on literature reviews, while the executions of LCAs are based on document reviews and measurements in the LCA software tool OCL. The author of this thesis utilized a project by NCC, Valle Wood (see Chapter 4) as the case study. The results are presented with an ongoing discussion and a conclusion, that answer the research questions based on the findings. Finally, suggestions for further work is declared based on lessons from this study.

At the end of Chapter 2 and 5, tables are conducted to systematically withdraw the most important findings related to the research questions and assist the reader throughout the report.

In Appendix A, the SBE19 conference paper is attached. The conference paper is an independent product that was conducted during the compilation of the thesis and will not appear as a part to this master thesis.

Chapter 2: Theory

This chapter is divided into three main areas. Firstly, a section regarding climate change will be presented, where it will be discussed how the building industry can help to intersect global warming. Then, BIM and LCA will be introduced, where there will be presented a general section and a detailed section. The general section contains requirements and standards, as well as tools to provide a clear overview. The detailed section intends to provide a theoretical and contemplate overview that builds on the general section.

To systematically evaluate the BIM-based LCA in the early design phase of buildings, it is necessary to include the procedural background in this theory chapter, to address the BIM model that is capable of translating Industry Foundation Class (IFC) files into an LCA software. IFC files can easily be confused with *.smc*. However, the only difference is that IFC is an open file format that works across any BIM software, and .smc is only compatible with Solibri Model Checker (ISO 2018). The purpose of this chapter is to find the linkage between BIM and LCA, and explore how they interact. The motivation for finding the linkage between BIM and LCA is to lower the GWP in the building industry, which accounts for a major part of GHG emissions. GWP is a measure of how much energy the emissions of an amount of a gas will absorb over a period of time, relative to the emissions of the same amount of CO_2 (EPA 2017). With the intention of reducing consequences of climate change, an introduction to climate change and its impacts is presented in Section 2.1.

The state-of-the-art and best practice are presented in Section 2.6. This part covers how environmental assessments are treated in a building project. This section aim to collect and discuss the theory. Moreover, trends and approaches toward an integration of BIM-based LCA in early design stages is presented based on the foregoing sections and subsections.

2.1 Climate Change and Buildings

This section intends to explain issues related to some of the most important impacts that climate change is causing. The building industry's environmental impact will be discussed, as well as the share of buildings' and constructions' final energy and emissions. Furthermore, areas of opportunities to achieve pathways to sustainable buildings and constructions will be listed and shortly commented.

Allen et al. (2019) and IPCC (2018) state with high confidence that warming induced by humans has already reached approximately 1 °C (between 0,8 °C and 1,2 °C) above pre-industrial levels in 2017, with an increasing rate of 0,2 °C per decade. This proves that there is a change in the global climate. Warming greater than the average temperature has been experienced in many regions and seasons, both over land and oceans (Allen et al. 2019).

Actions regarding sustainable development in partnership with all United Nations (UN) members, is an urgent call to handle climate change, as well as working to preserve the oceans, land, forests and human health (UN 2018c). The Brundtland Commission's definition of sustainable development is: to ensure that the population today meets the needs of the present, without compromising the ability of future generations to meet their needs (Brundtland 1985; Robert, Parris, and Leiserowitz 2005). Figure 2.1 which is obtained from UN (2018c) shows the 17 sustainable development goals.

Figure 2.1: 17 sustainable development goals

The building industry can contemplate with several of these sustainable development goals. The listed goals that directly consider the building industry are:

- 11) Sustainable cities and communities
- 12) Responsible consumption and production
- 13) Climate action

These goals are related to the embodied energy consumption, as well as the in-use energy of buildings (see Subsection 2.1.3). In addition, goals that indirectly contemplate the building industry are:

- 6) Clean water and sanitation
- 7) Affordable and clean energy
- 8) Decent work and economic growth
- 14) Life below water
- 15) Life on land

Buildings are products of several actions relate to the impacts of economy, energy, water, land use and production. All of these aspects have to be developed in a sustainable way, to achieve UN's sustainable goals and balance the present climate change.

UN (2018a) defines climate change as:

> "The defining issue of our time and we are at a defining moment. From shifting weather patterns that threaten food production, to rising sea levels that increase the risk of catastrophic flooding, the impacts of climate change are global in scope and unprecedented in scale. Without drastic action today, adapting to these impacts in the future will be more difficult and costly".

Climate changes are problematic in many ways. For example, the changes threaten food production, cause catastrophic weather events and bad air quality due to pollution, as well as causing climate refugees (Christina Nunez 2019). Ice sheets are melting and the water that was once held in glaziers is now causing sea level to rise. Observed trends of heavier floods, storms and more frequent droughts in different seasons and land area, pose challenges regarding food. Where animals can live and where vegetation can grow is now shifting. These changes in climate directly affects human health. Ozon, which is a major contributor to urban smog, increases rapidly with higher temperatures. This can cause human health problems, such as cancer and asthma (Christina Nunez 2019).

GHGs cause climate change by trapping heat. In addition, GHGs contribute to respiratory diseases from air pollution and smog (Christina Nunez 2019). Some of the GHG that contribute the most to climate change impacts, according to Christina Nunez (2019) are shown in Table 2.1.

The Paris Agreement

The Paris Agreement, established in 2015, is the first global accord on climate change that contains policy obligations for all countries (Dimitrov 2016). This is a climate deal among 185 parties that have ratified out of 197 parties that attended the convention where the agreement was made. The convention reached an awaited agreement to combat climate change, and to accelerate the actions and investments needed for a sustainable low carbon future (UN 2018b; UN 2018d).

Tundra and Permafrost

At higher latitude, owing to cold season warming, appraise warmer than the average temperature and impacts are projected to be large (Hoegh-Guldberg et al. 2018). Woody shrubs are encroaching into tundra and this will not stop until the elevated days with the mean air temperature above 0°C terminates. Areas of frozen ground are called permafrost, and these areas are twice the size of the atmospheric carbon store (Dolman et al. 2010). Permafrost and the tundra

Table 2.1: Some GHGs

GHGs	**Sources**
Carbon dioxide (CO_2)	Primary GHG that is responsible for 75% of emissions. CO_2 mainly come from burning fossil fuels like coal, oil and gas.
Methane (CH_4)	Methane is a natural gas that is released from landfills, petroleum industries and agriculture. CH_4 is at least 84 times more potent than CO_2 which make this natural gas important to address to effectively reduce the impact of climate change because it accounts for about 16 % of all GHG emissions.
Nitrous Oxide (N_2O)	This gas accounts for about 6% of GHG emissions, but it is 264 times more powerful than CO_2. The biggest sources of N_2O are burning fuels, agriculture and livestock.
Industrial gases (SF_6, NF_6)	Fluorinated gases accounts for about 2% of GHG emissions and is used in manufacturing processes and they are extremely powerful as the heat trapping potential is thousands of times greater than CO_2.
Ozone (O_3)	GHG that include water vapor is the most abundant GHG, but water vapor is not emitted by human activity directly. Ozone in the troposphere absorb infrared radiation emitted by the heated earth.

are vulnerable to decomposition, as the frozen ground contains a huge amount of methane and carbon. Thawing tundra represents a potential tipping point, as a decrease in the permafrost and tundra constitute a gigantic release in GHGs (Burke et al. 2018; Hoegh-Guldberg et al. 2018).

Ocean Acidification, Ocean Circulations, Deoxygenation and Storms

Numerous risks from changes associated with ocean acidification, ocean circulations, intensifying storms and deoxygenation has been observed impacts on ocean systems caused by increasing atmospheric CO_2 and other GHGs (Hoegh-Guldberg et al. 2018). Ocean acidification has a direct association with sea surface temperature. Gattuso et al. (2015) show that the temperature in the sea surface has increased by approximately 0,9°C and decreased by 0.2 pH units since the pre-industrial period (1870-1899). Identified risks and impacts have been observed as the sea temperature and CO_2 concentration in the sea increases, for instance bacterial assemblages and processes, coral reefs reduction and changing ecosystems (Hoegh-Guldberg et al. 2018). Concentrations of oxygen in the ocean are declining, due to different temperatures of stratification in the ocean, reduced oxygen solubility (higher temperature in the ocean) and impacts of warming in biological processes that consume oxygen (photosynthesis and respiration) (Breitburg et al. 2018; Hoegh-Guldberg et al. 2018). Deoxygenation has created "dead zones" where waters have been replaced by hypoxic conditions, and displacement of oxygen dependent organisms like fish is present in these areas (Hoegh-Guldberg et al. 2018). Ocean movements and circulations are changing along with the climate change, which influences the biology and ecology in the oceans (Hoegh-Guldberg et al. 2018). The frequency of storms and wind speed has increased and the wave height is getting bigger. All of these changes lead to increased exposure to impacts, such as bad water quality, flooding periods and sediment runoff occurs (Anthony 2016).

Sea Level Rise and the Loss of Sea Ice

From 1901 to 2010, the global sea level rose by 19 cm due to warming and melted ice. In addition, it is predicted to rise by 40-63 cm by 2100 relative to the reference period of 1986-2005 (UN 2018a). Compared to global warming of 2 °C to 1.5 °C by 2100 (according to the Paris Agreement), the global sea level rise is projected to be around 0,1 metre lower with the temperature rising at 1.5 °C (IPCC 2018). A slower rate of sea level rise enables adaption in the human ecological systems in low lying coastal countries and areas (IPCC 2018). Furthermore, limiting the global warming to 1.5 °C, lower the impacts on terrestrial, freshwater, coastal ecosystems and biodiversity (IPCC 2018).

Adaption

Adaption takes place at global and local levels to manage impacts from climate changes, by reducing vulnerability and exposure to its harmful effects and exploiting any potential benefits (Allen et al. 2019). There are limitations to adaption and adaptive capacity for human systems and natural systems, but most adaptation needs will be lower for global warming of 1.5 °C compared to 2 °C (IPCC 2018).

Adaption options that mitigate emissions can also provide synergies and cost savings in several sectors and industries, as well as system transitions (Allen et al. 2019). In the construction industry, deeper emission reductions in production and more efficient design systems regarding cooling/heating, as well as overall low carbon transitions, is required to lower the electricity supply. Trade-offs between adaptation and mitigation can undermine aspects of sustainable development in the building sector (Allen et al. 2019).

The building industry is large and appear as a major contributor to global warming. Therefore, in Subsection 2.1.1, 2.1.2 and 2.1.3, the focus will be on the construction industry in particular. The global status is presented and possible pathways towards a sustainable building industry are submitted.

2.1.1 Global Status

The building and construction sector is a key contributor to the challenges related to climate change. This appears from the fact that the building industry accounted for 36% of final energy use and 39% of energy and process related emissions in 2017, according to Global Alliance for Buildings and Construction (GlobalABC) report conducted by UN Environment Program and International Energy Agency (IEA) (IEA 2018). The distribution can be seen in Figure 2.2, obtained from IEA (2018), which confirms that the building industry is one of the major emitters of GHGs (Shadram et al. 2015). The distributions show a need for resilient buildings.

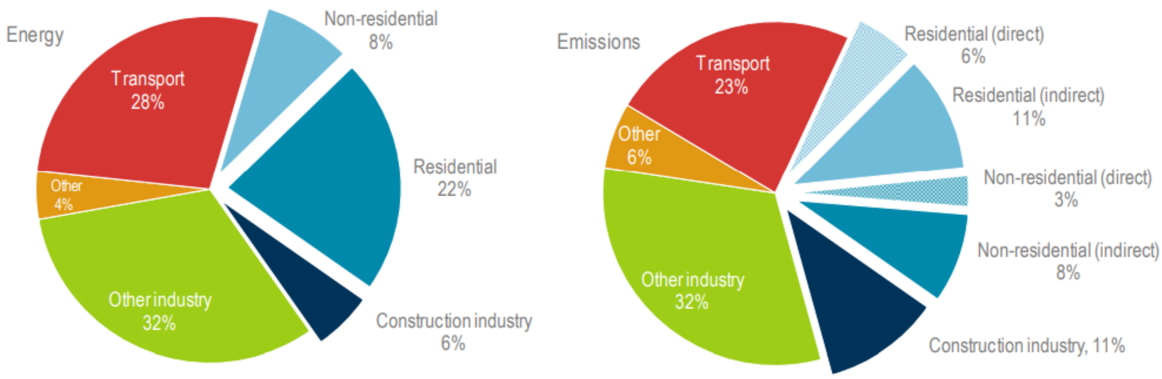

Figure 2.2: Global share of buildings and construction final energy and emissions, 2017

In the case of energy demand, the trends since 2010 are negative. Final energy demand in the building sector has risen by 5%, where the impact of growth in floor area and population, outpacing the impact of energy efficiency improvements (IEA 2018).

Ensuring a global strategy to curb emissions from the building sector, is it important that countries include the sector in their nationally determined contributions (NDCs). A lack of coverage in emissions relative to specific actions related to energy efficiency, renewables, energy codes or energy certifications in buildings by NDCs, is present today (IEA 2018). Many developing economies do not have mandatory building codes related to energy, despite high construction rates (IEA 2018).

2.1.2 Pathways to Sustainable Buildings and Construction

In line with the Paris Agreement, energy use per m^2 in buildings needs to be reduced by 30% by 2030 (IEA 2018). IEA (2018) mentions multiple areas of opportunities to achieve a sustainable pathway for the building and construction sector:

- Human factors - user control and human skills.
- Technology solutions - enhance system technology and the building envelope.
- Architecture solutions - design to achieve passive or Zero Emission Buildings (ZEB).
- Material solutions - the use of recycled materials and materials with low embodied energy

demand.

- Resilient buildings - a building that has the same functionality and durability for extreme weather events and climate change.
- Urban solutions - local jurisdictions through urban planning and district solutions.
- Clean energy transition - decarbonising energy.
- Circular economy - life cycle loop throughout the lifespan of a building from cradle to grave (see Figure 2.15).

All of these pathways are able to intersect, improve and achieve, in the integration of a BIM-based LCA in the early design stage of building projects. By designing a project in BIM, the ability to re-design is an advantage. All of the listed pathways should be considered and optimized in the BIM.

2.1.3 Embodied Energy versus In-Use Energy in Buildings

The built environment has the highest potential to reach the target to limit global warming (Change et al. 2014). The embodied energy is the energy required to produce the building materials, and it is related to the production stage of the life cycle stages of buildings, shown in Figure 2.11. The in-use energy is energy consumption related to the use stage.

The incidence of embodied energy in building energy analyses account for the major part of the whole primary energy demand, compared to the operational energy stages in the use stage (Giordano et al. 2017). Moreover, the share of embodied energy in low energy buildings increases due to the large number and sizeable amount of materials (Koezjakov et al. 2018). Additionally, the total energy use of buildings decreases due to renewable energy sources in the use stage.

According to Y. L. Langston and C. A. Langston (2008), assessing embodied energy is more time consuming than measuring the operational energy in the use stage. Therefore, a digital method of using LCA in accordance with BIM can reduce time when assessing complex buildings. Due to data limitations to perform embodied energy analyses, this thesis speaks to the feasibility to use BIM as the sole data to conduct LCAs.

It is assumed in this master thesis that a building is complex in content and design, and the energy demand is high, to be able to satisfy thermal comfort to the users. The next sections are comprehensive in content, but everything substantiates this master thesis' main topics: BIM and LCA.

2.2 BIM in General

This section gives an overview of the properties of BIM and what standards BIM are determined by. The concept of BIM is broad in content and a definition by NBIMS (2015) explains this:

> "BIM is a digital representation of physical and functional characteristics of a facility. As such, it serves as a shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life cycle from inception onward." (NBIMS 2015)

BIM can represent a digital model, a process of modelling and the guide for cost management, time, risk management and material exchange (see Section 2.3 for details). BIM can be seen from a narrow and a broader perspective. Consequently, BIM in narrow sense comprises solely the digital building model itself, in the sense of a central information management repository and its model creation issues (Volk, Stengel, and Schultmann 2014). Commercial BIM platforms offer integrated data management, component libraries and general functionality. However, widespread differentiations of BIM are given in Section 2.3. BIM in the broader sense can be divided into interrelated functional, informational, technical and legal issues. Depending on the stakeholders' needs and the project requirements, a BIM model is used to support and perform expert services of buildings, such as energy or environmental analyses (Volk, Stengel, and Schultmann 2014). From this statement, two types of software might interact with BIM. The first is data input applications providing services of import, data capture and monitoring, data processing or transformation of captured data into BIM (Volk, Stengel, and Schultmann 2014). The second type of software is data output applications that provide reports and technical analyses, such as structural and energy analyses, as well as clash detection (Volk, Stengel, and Schultmann 2014).

2.2.1 BIM Standards

BIM requires standards for creating a sustainable and common understandable digital model. Figure 2.3 gives an overview of today's five methodology standards (buildingSMART 2014).

What it does	Name	Standard
Describes Processes	IDM Information Delivery Manual	ISO 29481-1 ISO 29481-2
Transports information / Data	IFC Industry Foundation Class	ISO 16739
Change Coordination	BCF BIM Collaboration Format	buildingSMART BCF
Mapping of Terms	IFD International Framework for Dictionaries	ISO 12006-3 buildingSMART Data Dictionary
Translates processes into technical requirements	MVD Model View Definitions	buildingSMART MVD

Figure 2.3: BIM standards

One can read from Figure 2.3 that the methodology is first to describe the processes according to ISO 29481-1 and -2, before conducting a transportation platform of data called IFC, which is determined by ISO 16739. *BuildingSMART* is a standardized process and deliverance of specifications that describe stakeholders, procedures and requirements for a building project (buildingSMART 2016). According to the buildingSMART methodology, the next step related to coordination regards BIM Collaboration Format (BCF). Furthermore, it is crucial to map the terms used in BIM according to ISO 12006-3. Finally, the methodology requires Model View Definitions (MVD) for translating processes into technical requirements. All of these standards are explained in detail in Section 2.3.

2.3 BIM in Detail

There are several BIM applications and tools for creating a digital representation of a building in 3D. The wide variety of BIM has extended to involve 4D, 5D, 6D, 7D and nD. Kamardeen (2010) argues that the content of a 7D building is:

- "3D: Computer Aided Design (CAD) platform that generates a digital representation of the physical and functional characteristics of a facility.
- 4D: planning the process to link the construction activities represented in time schedules with 3D models to develop a real-time graphical simulation of construction progress against time.
- 5D: enables the instant generation of cost budgets and genetic financial representations of the model against time. This reduces the time taken for quantity take-off and estimation from weeks to minutes improves the accuracy of estimates, minimizes the incidents for disputes from ambiguities in CAD data, and allows cost consultants to spend more time on value improvement.
- 6D: 6D allows extending the BIM for facilities management. The core BIM model is a rich description of the building elements and engineering services that provide an integrated description for a building.
- 7D: Incorporating sustainability components to the BIM model generates 7D models, which enable designers to meet carbon targets for specific elements of the project and validate the design decisions accordingly or test and compare different options.
- nD: nD model is an extension of BIM, which incorporates multi-issues of design the information generated and required throughout a building project lifecycle, such as accessibility, sustainability, energy savings, costing, crime-prevention, acoustic, thermal, etc." (Kamardeen 2010)

2.3.1 Information Delivery Manual (IDM) Methodology

ISO 29481-1 sets out a methodology for the provision of an integrated reference document that narrates the processes and data required in the development or management of a constructed facility (ISO 2016b). It describes how to identify and mark out the processes undertaken within that context, the information required for their execution and the results. This part also describes in general terms how IDM methodology can further be provided by software developers, enabling reuse of products and how IDM can be configured to meet national, local and project needs (ISO 2016b).

Figure 2.4, obtained from ISO (2016b), shows the elements of the overall information scheme that are used in a BIM model. Within a BIM model, there are objects that are moulded by classes, which are defined by a standard scheme that contains all of the project information needs for all business processes at life cycle stages (ISO 2016b).

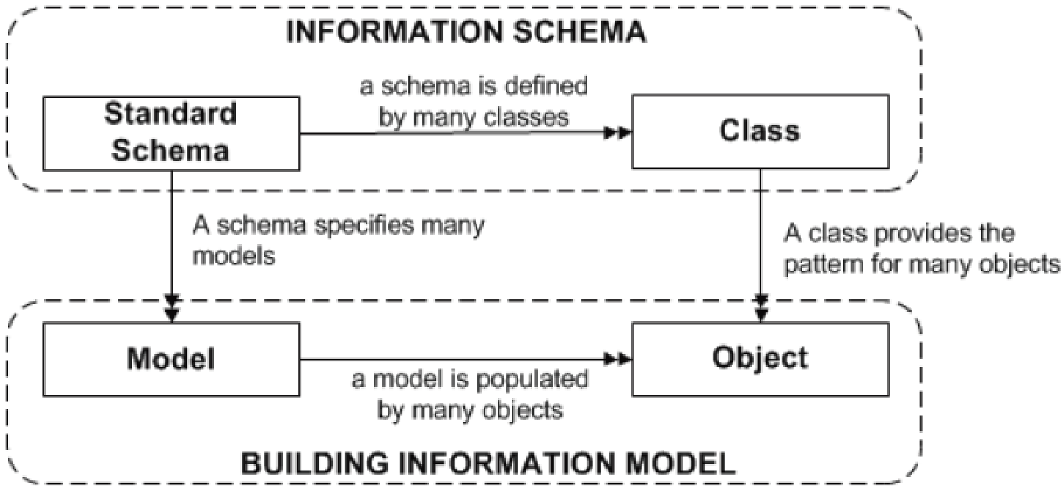

Figure 2.4: information schema towards a building information model

2.3.2 IDM Interaction Framework

"The IDM framework defines the functionality related exchange of process information in BIM" (Volk, Stengel, and Schultmann 2014). ISO 29481-2 focuses on aspects of the construction process that refer to the management and coordination of the involved parties (ISO 2016a). The IDM interaction framework provides the coordination determined by communication, which should be well structured, unambiguous, explicit, and prompt (ISO 2016a).

Within the IDM methodology, ISO (2016a) presents two perspectives. The zones within the *user requirements perspective* are:

- Interaction maps related to the roles and interactions between them.
- Process maps, describing the overall process in which information exchange occurs.
- Information delivery related to the information exchange needs.

- Reference processes.
- The project schedule.

Within the *technical solution perspective* includes:

- The business objects comprising the exchange requirement model.
- The information specification, describing the scheme on which the information exchange is based on.
- The BIM itself.

The zones shown in Figure 2.5, described in ISO (2016a), map the various components of IDM. The process maps describe the flow of activities within a particular topic, the actors' roles and the information required. In addition, the interaction maps define roles and transactions for a specific purpose or functionality (Volk, Stengel, and Schultmann 2014).

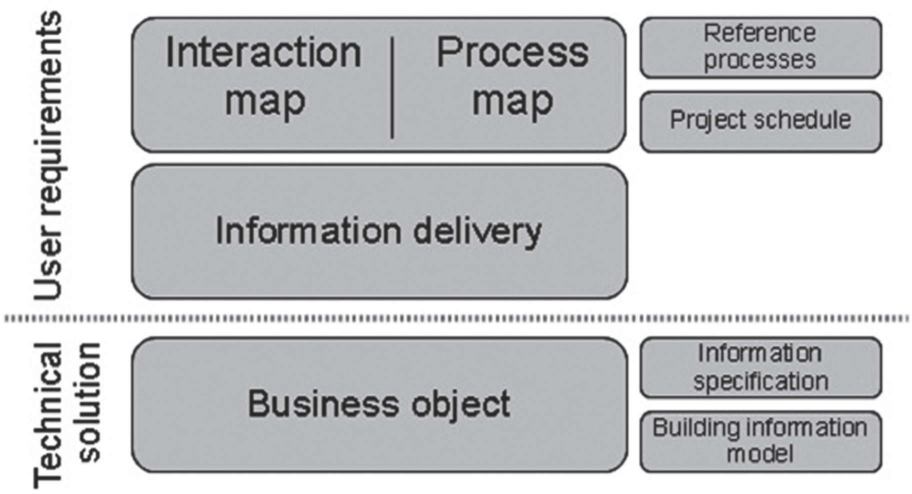

Figure 2.5: IDM perspectives: user requirements and technical solutions

2.3.3 IFC

"The Industry Foundation Classes is an open international standard for BIM data that are exchanged and shared among software applications used by the various participants in the construction, or facility management industry sector" (ISO 2018). ISO 16739 includes definitions of data required for buildings over their life cycle. The ISO 16739 standard release, and upcoming IFC releases, intend to extend the scope to include data definitions for infrastructure assets over their entire life cycle, from cradle to grave (ISO 2018).

Volk, Stengel, and Schultmann (2014) argue that data exchanges are possible either directly or through proprietary or non proprietary exchange formats. IFC defined in ISO 16739 is the dominant non proprietary exchange format of building information between Architectural Engineering and Construction (AEC) software. It was developed to represent building information over the whole buildings' life cycle (except deconstruction), and to facilitate data transfer between BIM modelling software, IFC viewers and expert software applications (e.g. 'Model Checker' from Solibri) (Eastman et al. 2011). Data exchanges between the source and receiving software systems are performed through mainly proprietary translators with its own data structures (Eastman et al. 2011).

2.3.4 Open BCF

BuildingSMART has adopted the Open BCF as a BuildingSMART standard. BCF provides the ability for change management through issue tracking and allows a fully managed cycle (buildingSMART 2014). BCF is an open file format that allows the addition of textual comments, screenshots and more on top of the IFC model layer for better communication between coordinating parties, e.g AEC professionals. It separates the communication from the actual model (BIMcollab 2018).

2.3.5 Framework for Object-Oriented Information

The main part of ISO 12006-3, Framework for Object-Oriented Information, consists of the specification of a taxonomy model. This provides the ability to define concepts by means of properties, to group concepts, and to define relationships between concepts (ISO 2017a). Moreover, the standard defines the use of objects along with NS 8360, but ISO12006-3 states that objects are divided into subject, activities, actors, units, values and measures with units and properties. ISO 12006-6 is a propose of a terminology standard for BIM libraries and ontologies. It is an object-oriented database of multi lingual terms, which defines concepts used in the construction industry related to IFC characteristics (Volk, Stengel, and Schultmann 2014).

2.3.6 Model View Definition

An IFC View Definition, or MVD, defines a subset of the IFC scheme needed to satisfy one or many exchange requirements in the AEC industry. The method used is propagated by buildingSMART to define such exchange requirements (buildingSMART 2018). In addition, a MVD structures relevant information for efficient information flow between stakeholders in building related processes, for instance energy or structural analyses. By this, a MVD definition depends on the required functionality, the referred BIM objects and attributes in processes, as well as interaction maps (Volk, Stengel, and Schultmann 2014).

In Figure 2.6, obtained from Pinheiro et al. (2018), the development in IFC technologies and MVD improvement is shown. Today, IFC4 is released and contains two model views: reference view and design transfer view. These model views support the exchange direction and promote collaboration between multiple disciplines, which enhance the building structure, Heating Ventilation and Air Conditioning (HVAC) zoning, daylighting etc. (Pinheiro et al. 2018).

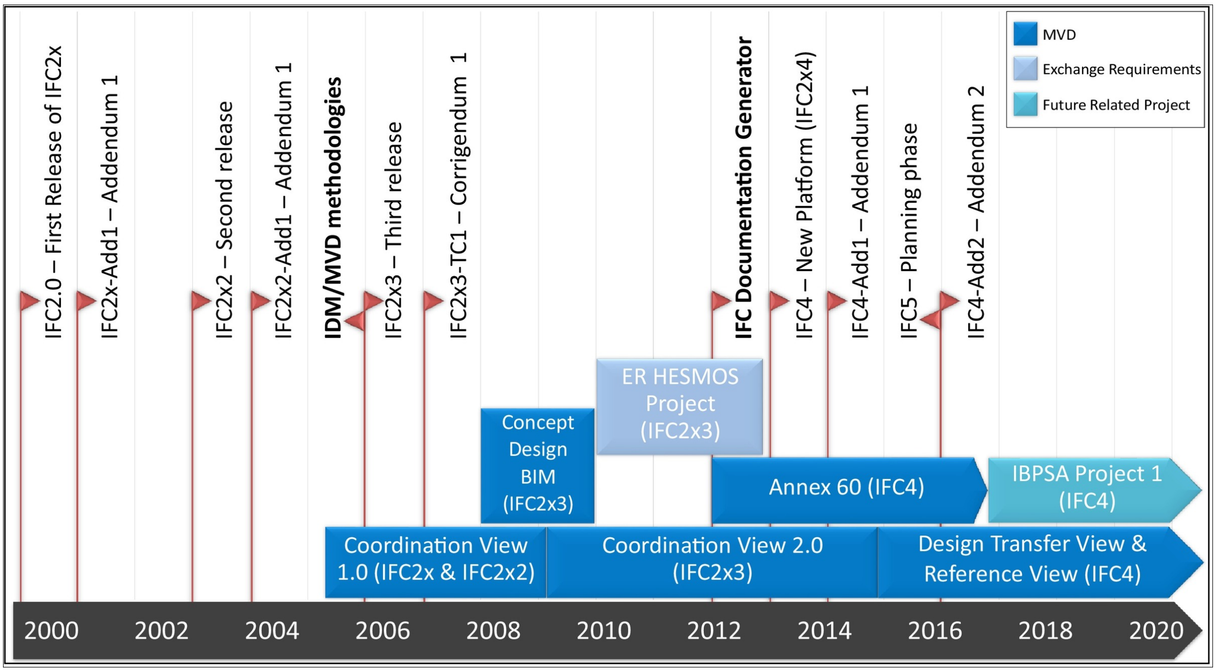

Figure 2.6: Summary of the IFC releases with key enabling technologies for IFC implementation together with MVD development over the years

2.3.7 Naming, Type Encoding and Properties for BIM Objects

"NS 8360:2015 - BIM objects - Naming, type encoding and properties for BIM object libraries for construction works" is the first Norwegian BIM standard that contains the requirements the users of BIM software have to follow. The standard also contain a classification of objects and the connection of features and values to IFC models (Vik 2018; NS 2015). This Norwegian standard differ from ISO 12006-3 in the way that NS 8360 helps to develop an efficient workflow based on released BIM standards.

2.3.8 LOD

The United States AIA document "E202" defines LOD for model elements. To define the term LOD, one can think of it as the overarching requirement for both the graphical level of object's geometry and of how much details included in the model element, which is called the *level of detail*. The non graphical data in BIM objects is called the *level of information*. These two levels in combination form the concept of *level of development*, which is the degree to which the element's geometry and attached information have been thought through in the BIM (Mordue, Swaddle, and Philp 2015; BIMforum 2015). In summary, LOD is the degree to which a receiver of the model can rely on the information (Ramaji et al. 2017).

The advantage of implementing LOD into building projects is especially the ability to use the model for on site instruction and specification. By different stages in the project, the model evolves to match final decisions made by the client and determined digitally in the BIM and on site. This concept is called *level of definition* (Mordue, Swaddle, and Philp 2015).

To restrict misunderstandings in the development of the BIM model and the progress, there has been made a LOD specification by BIMforum (2015) as a reference standard. The specification intends to evolve as the use of BIM develops. Referring to the same sets of specifications, enables consistency in communication and execution for all parties involved (SrinSoft 2018). This is done by facilitating a detailed definition of BIM milestones and deliverance. Table 2.2 presents six LOD levels that define the modelling progress from *conceptual* to *as built* (BIMforum 2015; BIMforum 2018). This table is located at the end of this chapter.

By today, Norway has no standard that covers LOD requirements, but several organizations among the building industry characterize LOD as a great aid for better coordination and interaction between project owners, stakeholders, designers and engineers (Håkon W. Fløisbonn 2018).

The level of BIM was defined by the American Institute of Architects (AIA) for the purpose of making a standard for the embodied environmental impact (Lee et al. 2015), and the results from this can be seen in Figure 2.7. The dashed line around LOD 300 represents the level of the BIM model when environmental assessments should be executed, targeting the embodied energy, A1-A3 in Figure 2.11, according to Lee et al. (2015).

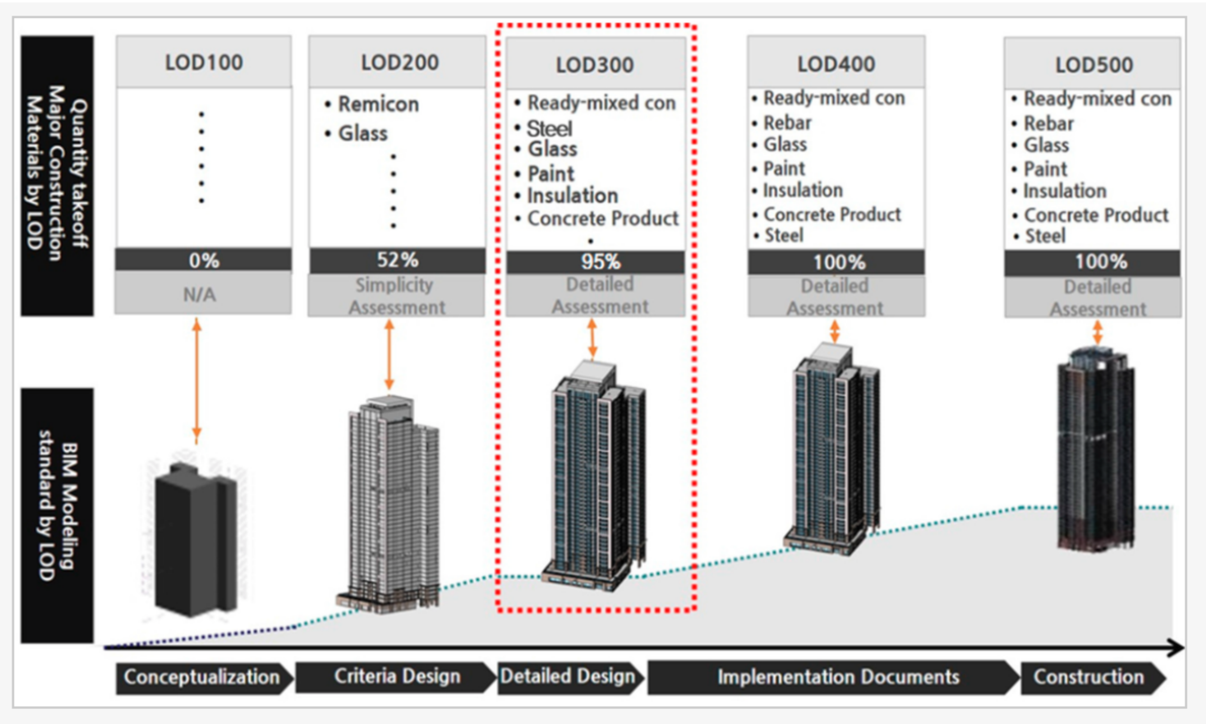

Figure 2.7: LOD levels showing major construction materials and development of BIM modelling

Sustainable buildings have been defined as both structural and environmentally responsible to its processes throughout a building's life cycle (Ding et al. 2018). LOD and BIM enable better early design stage management, and by assessing the environmental impacts of a building, the building itself can be certified according to different green building rating systems.

LCA allows quantifying the environmental impact at all levels and it provides easy comparisons of the final results, in terms of the effective reduction of the overall environmental impact (Mattoni et al. 2018). Moreover, Mattoni et al. (2018) have executed a comparison among five green building rating systems in order to highlight similarities and differences in BREEAM, LEED, Green Star, ITACA and CASBEE. The results are shown in Figure 2.8, obtained from Mattoni et al. (2018).

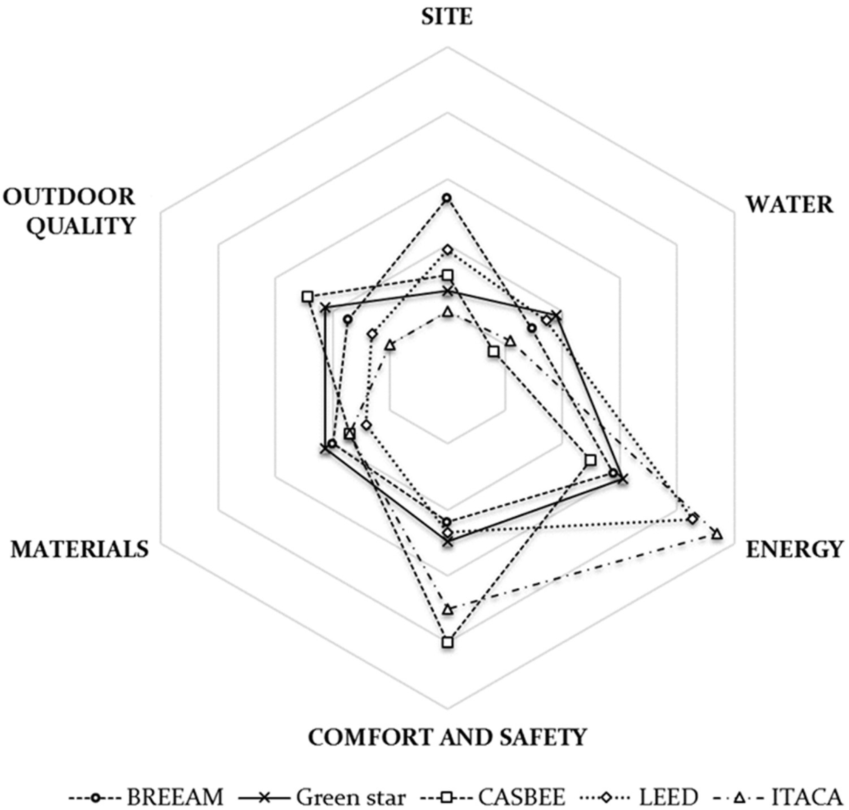

Figure 2.8: Comparison among six macro areas of rating tools

In order to represent a building in a BIM model, the feasibility of early design decisions and assessment according to different rating systems are possible. LCA is a technique that enables such quantifications of impacts that suite green building rating systems. Therefore, LCA will be presented in Section 2.4 and 2.5 due to its capabilities, broad spectre of standards, and its ability to be included in several green building rating systems.

2.4 LCA in General

LCA can be either dynamic or static. As opposed to static LCA, dynamic LCA includes the variable of time and how inventory data and impact results change over time (Bilbao 2018a). This thesis assesses a static LCA and the embodied environmental impacts. There are a variety of definitions of LCA in the literature, and this study uses this definition:

> "Life cycle assessment (LCA) is an emerging methodology that attempts to quantify the overall impacts of a product or service from a holistic perspective that consider

all material and energy inputs as well as human health and ecological impacts over the entire lifecycle" (Rist 2011).

LCA can be utilized as a field of study, a technique or as a specific study. The concept of LCA was developed in the 1970s, focusing on the quantification of energy and material use along with the environmental impacts associated with the material production (Shadram et al. 2015). There is a lot of reasons for doing LCAs. Mainly LCA is used to prevent problems from shifting to other life cycle stages, substances, environmental problems, countries or to the future.

ISO 14040 provides an overview of the LCA framework, shown in Figure 2.9. The flow of the major elements in an LCA is the ongoing iterative process, where goal and scope definition, inventory analysis, impact assessment and interpretation are the main elements. LCA standards and procedures for inventory analysis will be covered.

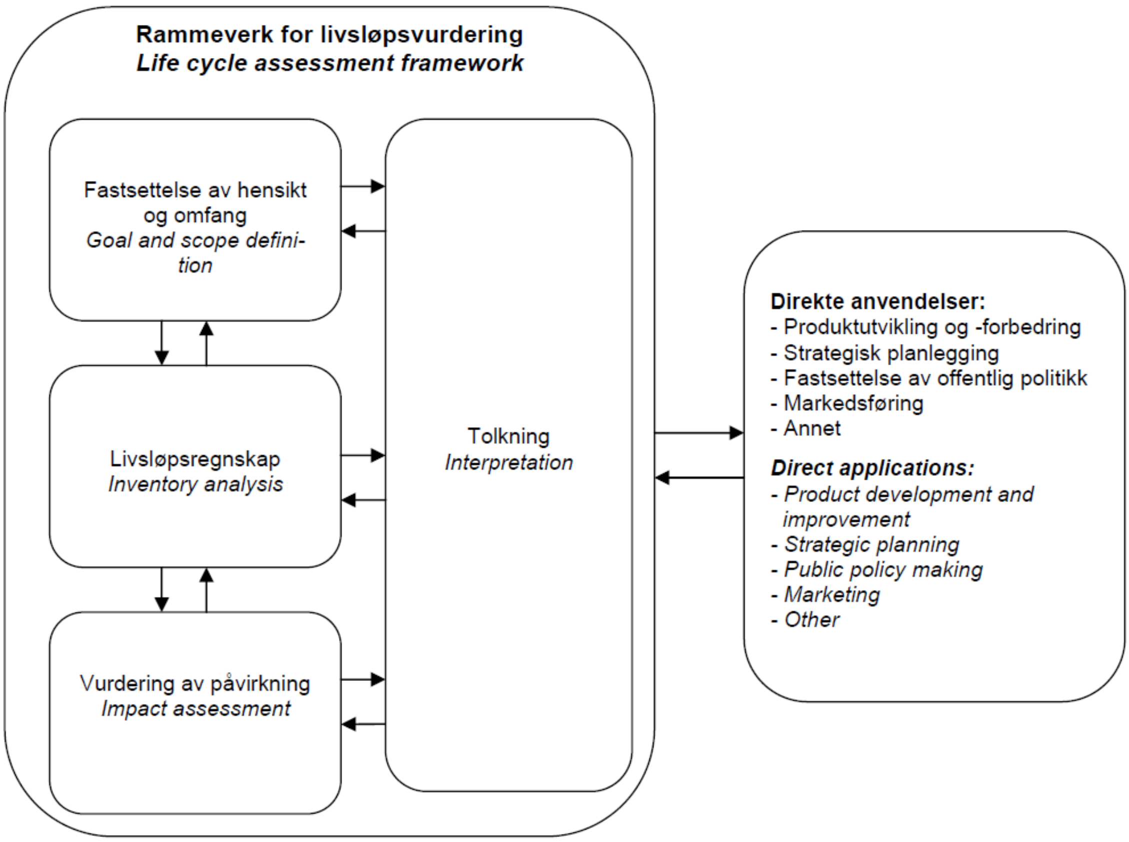

Figure 2.9: LCA Framework

The arrows between the elements shown in the boxes in Figure 2.9 are repeated when more data has become available. The more complete the BIM becomes, the more accurate will the LCA be. Using LOD (see Section 2.3.8), makes it possible to control and check to which level the BIM is developed at a certain time. The iterative arc of revision is repeated to achieve precise assessments.

2.4.1 International Organization for Standardization (ISO) Standards

ISO is an independent international organization with a membership of 164 national standards bodies that give specifications for products, services and systems, to ensure quality, safety and efficiency (ISO 2019).

There are two ISO standards that form the international basis for creating LCAs. ISO 14040 purpose the framework and the principles of an LCA, while ISO 14044 defines the requirements and guidelines. Figure 2.10, obtained from Bilbao (2018a), gives an overview of the ISO 14000 standards that deal with different aspects of environmental management.

Figure 2.10: ISO 14000 standards

Structuring the LCA, needs environmental data of the inventory as Environmental Product Declarations (EPDs) to feed the LCA with material properties and relevant data. The procedure for creating such environmental declarations needs guidelines and standards, which will be covered in this thesis.

2.4.2 LCA Principles and Framework and LCA Requirements and Guidelines

LCA Principles and Framework

ISO 14040 contains definitions and terms used in an LCA. Principles, phases, features and the general concepts of the product system are explained in "General description of life cycle assessment" within the ISO 14040 standard. Moreover, the methodological framework, namely the goal and scope definition, Life Cycle Inventory analysis (LCI), Life Cycle Impact Assessment (LCIA) and the interpretation phase are stated. This international standard covers life cycle assessment studies and life cycle inventory studies (ISO 2006b). It does not describe the LCA technique in detail, nor does it specify methodologies for the individual phases of the LCA (ISO 2006b).

ISO 14040 considers the awareness and the importance of reporting: "Report the results and conclusion of the LCA is an adequate form to the intended audience, addressing the data, methods and assumptions applied in the study, and the limitations thereof" (ISO 2006b). Additionally, a critical review is the process to verify whether an LCA has met the requirements for methodology, data, interpretation and reporting and whether it is consistent with the principles (ISO 2006b).

LCA Requirements and Guidelines

ISO 14044 specifies the requirements and guidelines for an LCA and its phases, covered in Section 2.4.2 (ISO 2006c).

2.4.3 Type III Environmental Declarations

Type III environmental declarations, proposed in ISO 14025, present quantified environmental information on the life cycle of a product, to enable comparison between products fulfilling the same function (ISO 2006a). This international standard establishes principles for the use of environmental information, in addition to those given in ISO 14020 (ISO 2006a).

The overall goal of environmental labels and declarations is to encourage the demand for, and supply of, those products that cause less stress on the environment. This is provided through the communication of verifiable information that is misleading, thereby stimulating the potential for market driven environmental enhancement (ISO 2006a).

2.4.4 Core Rules for EPDs of Construction Products and Services

ISO 21930 is an international standard that deals with environmental impacts and aspects (ISO 2017b). The standard excludes considerations regarding the social and economic aspects of sustainability.

ISO 21930 provides the principles, specifications and requirements to develop an EPD for construction products, services, construction elements and integrated technical systems used in any type of construction works (ISO 2017b). The standard complements ISO 14025 by giving specific requirements for the EPD of construction products and services (ISO 2017b).

2.4.5 Core Rules for the Product Category of Construction Products

The European Standard, NS-EN 15804:2012, provides core Product Category Rules (PCR) for all construction products and services. Moreover, the content of the standard presents a structure to ensure that all EPDs of construction products, construction services and construction processes are derived, verified and presented in a harmonized way (NS 2012).

2.4.6 Method for GHG Calculation for Buildings

NS 3720:2018 provides a method for GHG calculation in buildings throughout the whole life cycle of 60 years, from cradle to grave. The standard comprises products, goods and services related to construction, operation and in use stages (NS 2018). NS 3720 is built upon NS-EN 15978 - sustainable buildings - assessment of environmental performance, and uses the table of building elements from NS 3451:2009 to structure construction and building components and elements into building categories.

The system boundary of the environmental assessment of the life cycle contains five stages (ISO 2017b):

- A1-A3: Production stage
- A4-A5: Construction stage
- B1-B7: Use stage
- C1-C4: End of life stage
- D: Optional supplementary information beyond the system boundary

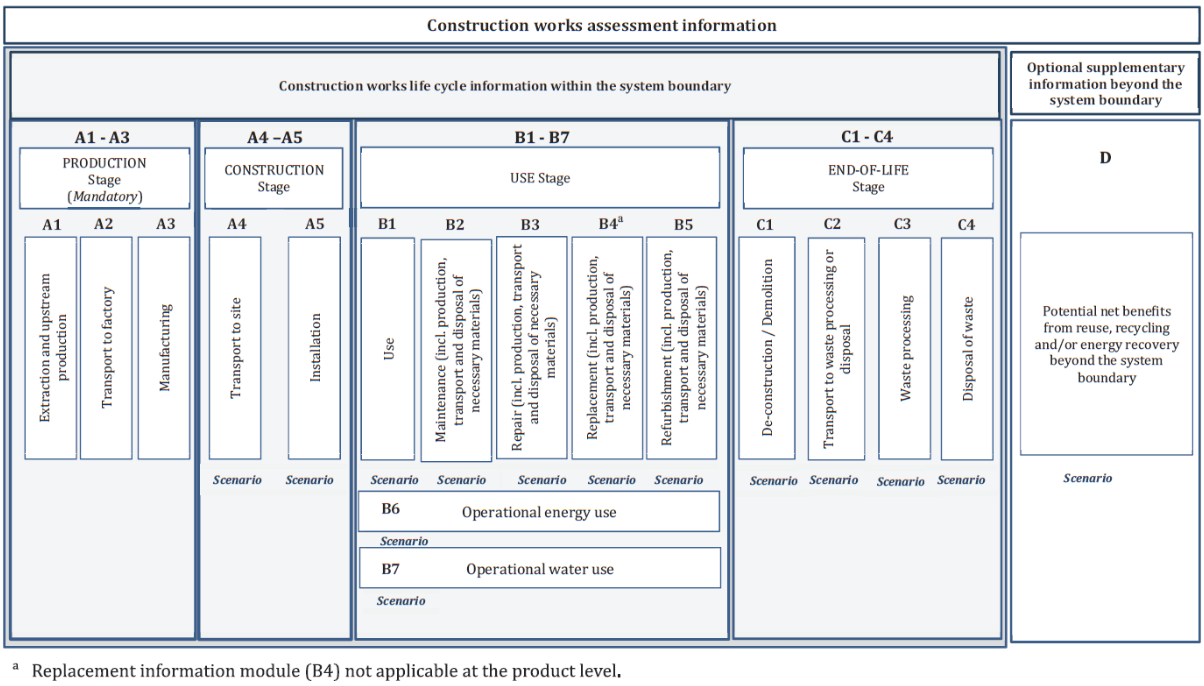

Figure 2.11: Construction works assessment information

Figure 2.11 shows types of EPD with respect to life cycle stages covered, and life cycle stages and modules for the building assessment (NS 2012). The building stages are production, construction, use and end-of-life.

2.4.7 PCRs and EPDs

One of The Norwegian EPD Foundation's (EPD Norway) functions is to ensure that the development of EPDs for all types of products shall be performed in accordance with the requirements of ISO 14025, ISO 21930, and related industry standards (EN 15804 for building materials), as well as carbon footprint standards ISO/TA 14067. The EPD program is primarily meant for business to business (B2B), but does not exclude business to consumers (B2C) (EPD-Norge 2014a).

EPD Norway shall secure that the development of PCRs associated within the EPD program is in accordance with the rules outlined in ISO 14025. During PCR development, efforts shall be made to harmonize the PCR with the goals of the program (EPD-Norge 2014a). The organizational structure is shown in Figure 2.12.

If the market is able to compare EPDs, then they must be prepared according to specific rules. In addition, if the market wishes to summarize the environmental performance of EPDs for a single product, than the EPDs must be compiled according to the same specific rules for the same product category, namely the PCR (EPD-Norge 2014a).

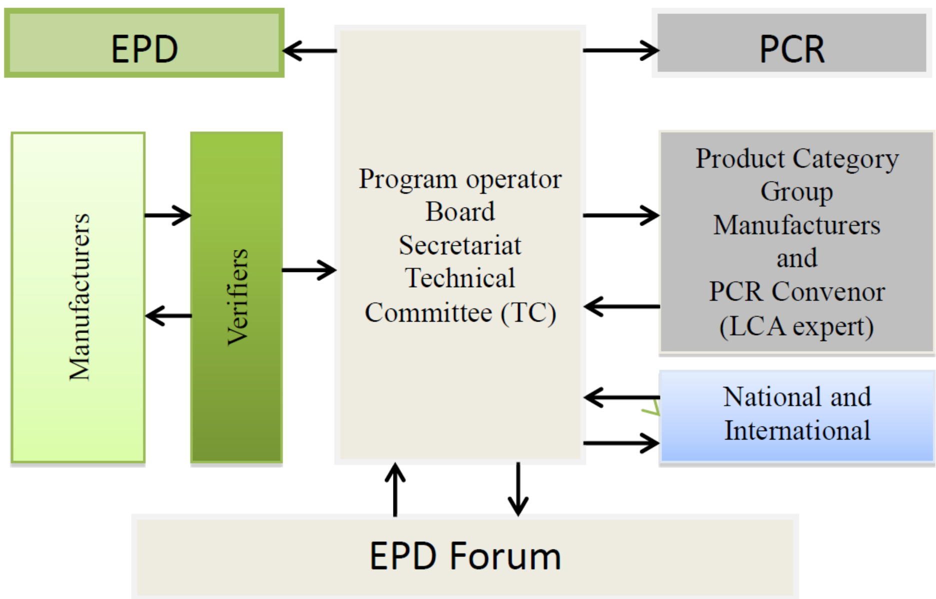

Figure 2.12: Flow chart showing the organizational structure of the EPD Norway programme

In Figure 2.12 the "*Light grey* colour shows activities related to administration and the EPD forum, *green* colour is related to the development of EPDs and verification, *dark grey* colours is PCR development, and *blue* colour represents PCR hearings" (EPD-Norge 2014a).

PCR is mandatory work before compiling the EPD of a product. The PCR intends to map the substances the LCA is going to cover. Consequently, the PCR and EPD organization make sure the producers outline the right content of the substances within the product. This work requires collaboration between several companies within the same industry and its stakeholders. The PCR can only be approved by "Stiftelse for Miljødeklarasjoner ved Verifikasjonskomiteen"

(EPD-Norge 2014b). A company can prepare an EPD by itself, but if the company does not have sufficient expertise, then an LCA or an EPD experts ought to be used (EPD-Norge 2014a).

NS 15804 defines the core of an PCR (NS 2012):

- "Defines the parameters to be declared and the way in which they are collated and reported.
- Describes which stage of a product's life cycle are considered in the EPD and which processes are to be included in the life cycle stages, see Figure 2.11.
- Defines rules for the developments of scenarios.
- Include rules for calculating LCA.
- Include rules for reporting.
- Defines the conditions under which construction products can be compared."

2.4.8 LCA Tools

Table 2.3, obtained from Anand and Amor (2017), shows an overview of the most used generic LCA tools in the industry and its indicators:

- C: Costs
- E: Environmental Impacts
- GHG: Greenhouse Gas

Table 2.3: Genereic LCA tools applicable to building LCA cases

Impact category	**Unit**
Gabi	C, E, GHG
SimaPro	C, E, GHG
Umberto NXT LCA software	C, E, GHG
Open LCA products	C, E
TEAM 5.2	E, C
EIO-LCA (Economic input-output LCA)	C, E, GHG
Boustead Model	E, GHG

The tools listed in Table 2.3 are the most building friendly tools that could benefit multiple impact assessment methodological options, such as provided in mainstream LCA tools (Bueno, Pereira, and Fabricio 2018). Most of the existing tools are too complex to be easily applied or too simplified to provide consistent results.

Furthermore, Table 2.4 placed in the end of this chapter, shows the BIM-LCA integrated tools applied in Bueno and Fabricio (2018) reviewed paper. As Table 2.4 shows, there are limitations such as lack of available materials, import from BIM files that does not perform full LCA studies, separate platforms, problem finding information etc.

This thesis will focus on one tool, namely OCL. The Norwegian Public Construction and Property Management organization, Statsbygg, has stated that more of their project has to perform an LCA with the use of OCL (Ingvil Arntzen 2018).

2.4.9 One Click LCA

OCL is ran by Bionova Ltd., which is the global leader for construction works life cycle assessment and embodied carbon optimization solutions (Bionova 2018a). Bionova is a developer of OCL, the building life cycle metrics software that allows for calculating life cycle assessment, life cycle costing, carbon footprint and other environmental impacts (Bionova 2018a).

The LCA tool has software that satisfy several standards like BREEAM (the UK and International), LEED v4 (USA and International), NS 3720 (Norway), DGNB DE (Germany) and Energie Carbone (France) (Bionova 2018a). OCL is also third-party verified for EN 15978, ISO 21931-1, ISO 21929-1 and for input data for ISO 14040/44 and EN 15804 standards (Bionova 2019a). OCL supports all the 24 impact categories in EN 15804 listed in Appendix B.1, obtained from Bionova (2019a), based on CML methodology and 6 TRACI impact categories. Furthermore, OCL supports interaction from IFC, Revit, IES-VE, ArchiCAD, Tekla Structures, simplebim and Naviate Simple BIM, Design builder, Excel, gbXML and Solibri Model Checker (Bionova 2018a).

2.5 LCA in Detail

An LCA depends on the collection of the environmental data listed in environmental databases as EPDs. To systematize the following subsections, this study will introduce a detailed explanation of the LCA methodological framework, as well as EPDs and its content, before heading on to LCA methodology specified. The LCA phases studied is shown in Figure 2.9. Moreover, the iterative approach toward an LCA is focuses on the inventory data collection and the modelling, which are shown in Figure 2.13, obtained from ILCD handbook "General guide for life cycle assessment - detailed guidance" (JRC 2010).

The International Reference Life Cycle Data System (ILCD), which give guidance for consistent and quality assured LCA data was utilized for deeper insight regards LCA methodology. The website states:

> "The ILCD handbook was developed by the Institute for Environment and Sustainability in the European Commission Joint Research Centre (JRC), in co-operation with the Environment DG. It is part of the Commission's promotion of sustainable consumption and production patterns. The ILCD Handbook is in line with international standards and has been established through a series of extensive public and stakeholder consultations". (JRC 2017)

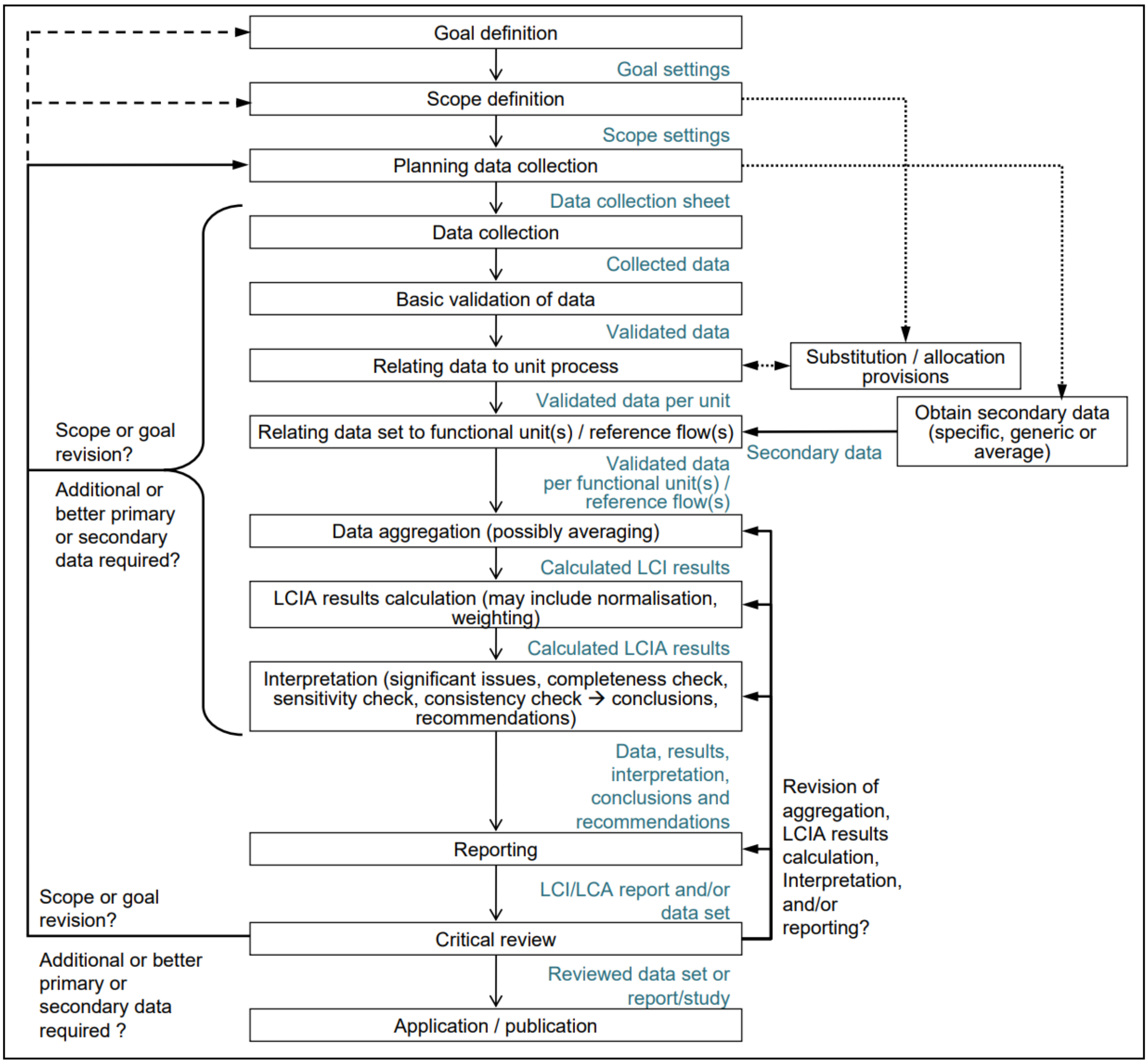

Figure 2.13: Iterative approach to LCA

2.5.1 EPD in Detail

EPD-Norge (2014a) states that:

> "The purpose of the information in an approved EPD is to provide a comprehensive picture of the environmental properties of the declared product or service. An approved EPD follows the format shown on EPD Norway's website and should be structured and divided into the following main sections:
>
> - General information
> - Manufacturer and verification
> - Description of the product or service with a declaration of content
> - LCA calculation rules

- Description of scenarios
- Presentation of the environmental performance
- Special Norwegian requirements"

The production part of an approved EPD consists of the LCA parts that encompasses the life cycle phases of extraction and refinement of raw materials, to the production of the goods including the energy extraction (EPD-Norge 2014a). Emissions are expressed in terms of characterization factors (Table 2.8) that indicate the effect of different emissions within the selection of environmental impact categories. EN 15804 is the European standard that provides different characterization factors for different impact categories, shown in Table 2.5 (EPD-Norge 2014a).

GHG emission from the use of electricity shall be documented in CO_2 equivalents or MJ (EPD-Norge 2014a). Based on average emission per kWh in a long term perspective, The Norwegian Research Center for ZEB has decided to use a conversion factor of 132 g CO_2/kWh to evaluate the emissions of electricity use (Graabak, Bakken, and Feilberg 2014). The electricity used in Norway does not originate from renewable energy sources only, as the energy market differ, and import/export of energy is present (Bohne 2019).

Table 2.5: Parameters describing the environmental impacts

Impact category	**Unit**
Climate change (GWP) and GHG emissions from the use of electricity	kg CO_2 equivalents
Depletion of stratospheric ozone (ODP)	kg CFC 11 equivalents
Acidification (AP)	kg SO_2 equivalents
Eutrophication (EP)	kg $(PO_2)^{3-}$ equivalents
Formation potential of tropospheric photochemical oxidants (POCP)	kg C_2H_4 equivalents
Depletion of abiotic resources	kg Sb^- equivalents
Depletion of abiotic fossil resources and GHG emissions from the use of electricity	MJ

When the essential information in an EPD differs from the requirements, or the conducted LCA report is performed in an improper way, further processing is required. Figure 2.14, obtained from EPD-Norge (2014a), illustrates this.

EPD-Norge (2014a) argues that if a product is based on recycled materials, the manufacturer may give information in the EPD about the quantity of recycled materials. In order to avoid misunderstanding regarding whether the materials can be considered as recycled or not, ISO 14021 proposes a guidance to follow for self declared environmental claims.

There is a large amount of complex data to structure, as well as to facilitate comparison across product alternatives, before EPD Norway is enabled to benchmark. Raw product data is seen

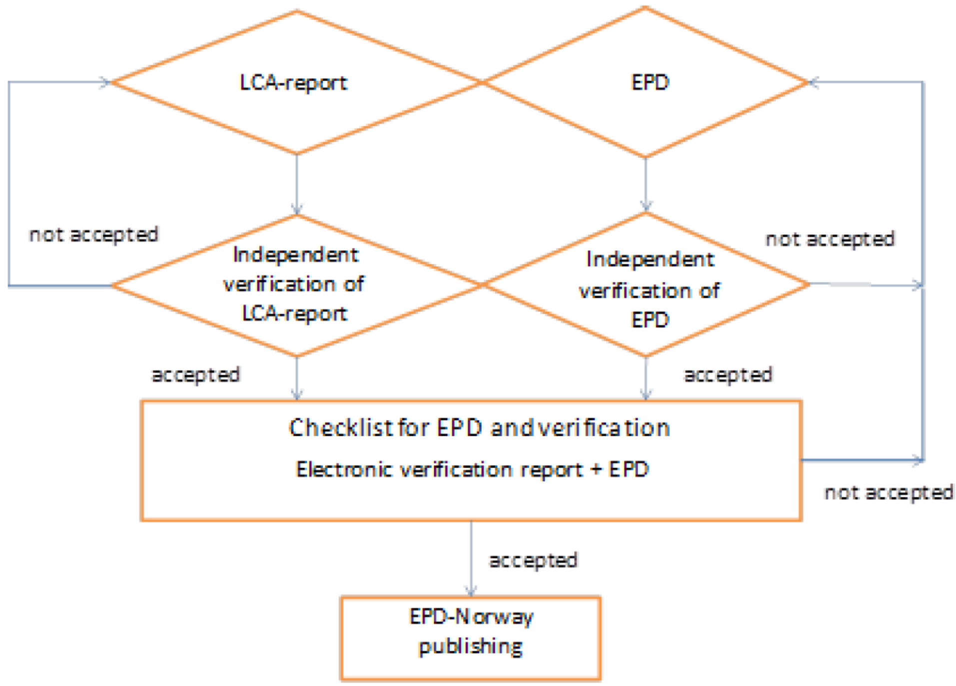

Figure 2.14: Flow chart showing the verification process

as difficult to understand and to compare. Therefore, a method for conducting and evaluating EPDs is essential. The procedure is shown in Figure 2.14.

2.5.2 Goal and Scope Definition

"Goal and Scope Definition is the LCA phase in which the aim of the study, and in relation to that, the breadth and depth of the study is established" (Bilbao 2018b; UNEP 2013).

The intended applications are product development and improvement, strategic planning, as well as public decision making and marketing. This phase states the reasons for carrying out the study. In Table 2.6, Bilbao (2018b) defines key terms used in this phase of an LCA.

Table 2.6: Goal and Scope Terms

Term	Definition
Functional Unit (FU)	The FU is a measure of the function of the studied system and it provides a reference to which the inputs and outputs can be related. This enables comparison of two essential different systems.
Temporal scope	As part of defining the scope, it is needed to determine and justify the temporal coverage (i.e. the time period covered) of the study in relation to its goal. This will be a reference point for other choices, e.g. will old data be acceptable?
Geographical scope	Similar to temporal scope, but about which geographical region the study covers? This will also affect choices about data sources, among other things.
Technology coverage	Defining what type of technology will be studied in relation to the goal of the study, e.g. for an LCA of coal fired electricity are you considering the state of the art coal power stations or an average of all power stations installed in the geographical region or the worst case?
Analytic tools	LCA is just one of many tools that can be applied to analyze, assess or study products or other systems for environmental performance or more broadly.
Change-oriented LCA	Focuses on comparing 2 options, i.e. what changes in environmental problems would occur if product A is replaced by product B?
Descriptive LCA	Focuses on determining what are the environmental impacts of a certain product, i.e. which of the environmental impacts in the world can be attributed to this particular product's life cycle?
Intended application	LCAs can be applied to different situations, e.g. product development and improvement (within a company), strategic planning (for corporations and government organizations), public decision making (governments), marketing (companies).

2.5.3 Inventory Analysis

"Inventory analysis is the LCA phase involving the compilation and quantification of inputs and outputs for a given product system throughout its life cycle" (Bilbao 2018a; Iuga 2009). The Life Cycle Inventory (LCI) is based on details of the unit processes, which is the smallest element considered in the LCI for which input and output are quantified (ISO 2006b). More terms used in this LCA phase are provided in Table 2.7, obtained from (Bilbao 2018b).

Table 2.7: Inventory Analysis Terms

Term	**Definition**
Flow diagram	A graphical representation of the interlinked unit processes comprising the product system. It is a tool to map the inputs and outputs to the system and provides a roadmap for data to be collected.
Unit process	The smallest element considered within a particular LCA study for which input and output data are quantified separately. Each unit process is one "box" in the flow diagram.
Flows	Flows are the intermediate products that pass between 2 unit processes or between a unit process and the environment, i.e. the arrows in the flow diagram.
Reference flow	Having defined the FU, the reference flow is the amount of product that is necessary to fulfil the function. It is used to calculate the input and outputs of the system. E.g. in an LCA comparing wind power and solar power, if the FU is defined as 1 kWh of electricity, then the reference flows are 1 kWh of wind power electricity and 1 kWh of solar electricity.
System boundary	The system boundary determines which unit processes are to be included in the product system being studied, and which will be excluded. Ideally, each product/material/service should be followed until it is translated into elementary flows (emissions, material resource extractions, land use. . .).
Data collection	The actual collection of the inventory data is the most time consuming part of an LCA study. Values are needed for all of the flows in and out of every unit process in the system.
Data quality	The accuracy of the results of the LCA depend on the quality of the inventory data. The 5 indicators of data quality are: - *Precision:* How accurate is the data? - *Completeness:*Do you have all of the data or is some missing? - *Representativeness:* Is the data you are using actually for the exact system you are studying in that exact location and using those exact resources? - *Consistency:* Is all of the data of the same standard? E.g. the same level of precision, all from primary sources, all with the same degree of uncertainty? - *Reproducibility:* Could the data be reliably obtained again and would you get the same answers?
Multifunctional process	A process that has more than one function, i.e. produce more than one useful product or service. This complicates the inventory calculations because it is not clear what fraction of impacts should be assigned to which product.
Allocation	Dealing with multifunctional processes by assigning fractions of the impacts on the different products. E.g: System expansion, substitution, surplus, partitioning...
Input-output analysis	Input-output analysis is an alternative method for doing an LCI, as opposed to the standard method called the 'process sum method'. It is the study of how each industry sector affects the other sectors in an economy of a particular nation or region. It is based on analyzing the monetary flows between sectors in the economy. Input-output analysis can be used to perform LCIs via a "top-down" approach rather than a "bottom-up" approach, and this avoids the system boundary problem.

The system boundary can differ depending on which stages of the life cycle that is considered. It is difficult for practitioners to include all processes and its background impacts. Therefore, it is essential to introduce the cut off criteria which determine the amount of total impact to complete an LCA, and what has been left out. The green arrows in Figure 2.15, obtained from JRC (2010), show examples of system boundaries.

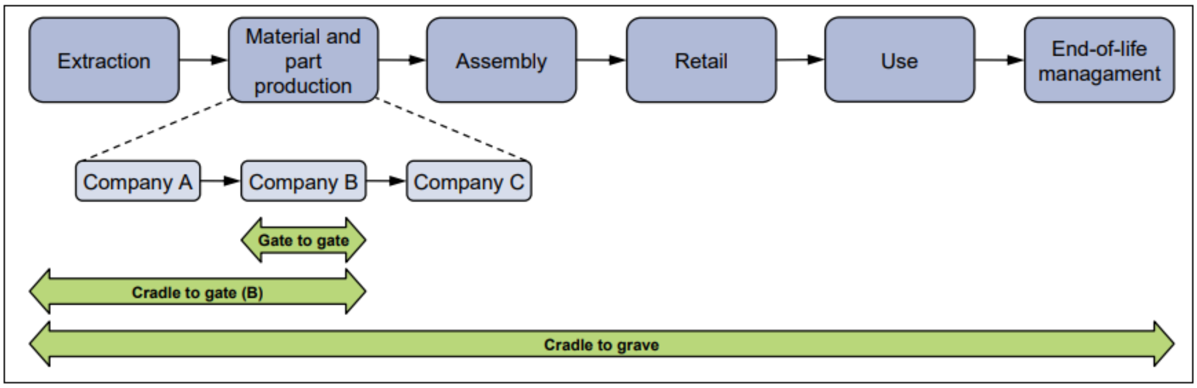

Figure 2.15: ILCD Handbook: System Boundaries

The process of conducting an inventory analysis is iterative. As more data is collected, the more is learned about the system. New data requirements or limitations may be identified, and this will require a change in the data collection procedures so that the the goal of the study will be met. Sometimes, issues may be identified that require revisions to the goal or scope of the study (ISO 2006b). The iterative processes are shown in Figure 2.16 provided by JRC (2010).

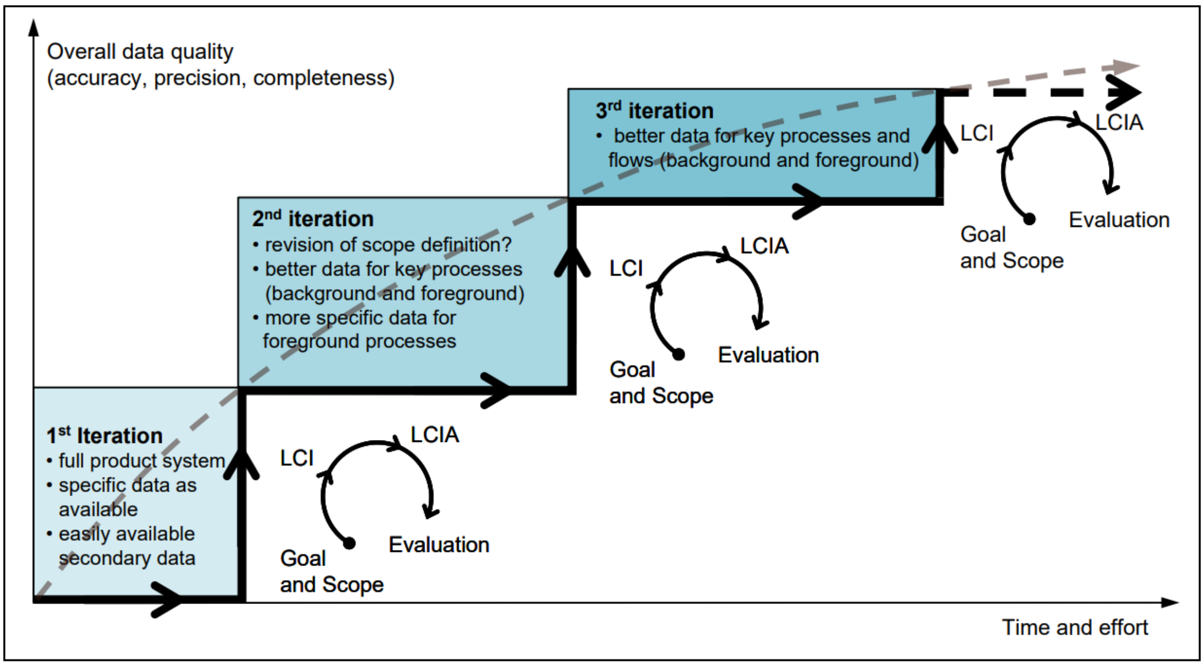

Figure 2.16: Iterative loops of goal and scope definition, inventory data, impact assessment

Data is obtainable from the actual party responsible for the unit process, for example private and public databases, published reports, articles and government statistics (Bilbao 2018a). Bilbao

(2018a) shows steps towards an LCI, as this LCA phase is comprehensive in content:

1. Preparing for data collection
2. Data collection
3. Calculation procedures: relate process data to the FU.
4. Allocation and recycling
5. Aggregation over all unit processes in the inventory table

2.5.4 Impact Assessment

"Life Cycle Inventory Assessment (LCIA) is aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system aid of the results of the inventory analysis" (Bilbao 2018a; Capaz and Seabra 2016). LCIA is the phase in an LCA where the inputs and outputs of elementary flows that have been collected and reported in the inventory, are translated into impact indicators results related to human health, natural environment and resource depletion (JRC 2010). LCIA is the LCA phase that is, according to JRC (2010), evaluating the potential environmental impacts that are caused by interventions that cross the border between technosphere and ecosphere and act on the natural environment and human. Important terms related to LCIA are defined in Table 2.8, obtained from Bilbao (2018b).

Table 2.8: Impact Assessment Terms

Term	**Definition**
Impact category	These are the categories representing different environmental issues of concern to which the LCI results can be assigned. - *Global Warming:* Impact of human emissions (GHG emissions) on the radiative forcing of the atmosphere, and the subsequent changing of the earth climate system. - *Abiotic Depletion:* Impact of human consumption of resources such as minerals and energy resources, and using up the reserves of these resources. - *Stratospheric Ozone Depletion:* Impact of human emissions on the thinning of the stratospheric ozone layer and subsequently increased UV radiation. - *Human Toxicity:* The impact on human health of toxic substances present in the environment. - *Ecological Toxicity:* The impact of toxic substances on aquatic, terrestrial and sediment ecosystems. - *Photo-oxidant smog formation:* The impact of the reaction of light with air pollutants to form reactive chemical compounds. - *Acidification*: The impact that acidifying pollutants may have on soil, groundwater, surface waters, ecosystems and materials (buildings). - *Eutrophication:* Impact of excessive levels of macronutrients in the environment.
Classification	Assigning the LCI results to the impact categories being studied. Each emission from the LCI can be assigned to more than one impact category.
Characterisation	The calculation of the category indicator results, using a formula or model, e.g. the IPCC model for calculating CO_2-equivalent units. This is like a 'translation' step, to account for all the inventory results assigned to each impact category and determine how much each individual emission contributes to the overall impact (some things are worse than others).
Mid-point categories	A system of defining impact categories that focuses on the impacts that occur relatively close to the interventions, e.g. the intervention is to emit CO_2 and the midpoint category is global warming. These categories rely on scientific information and well-proven facts. The LCA study has a problem-oriented approach (JRC 2010).
End-point categories	A system of defining impact categories that focuses on the impacts that occur at the end-points, e.g. the intervention is to emit CO_2, which then causes global warming, which impacts on humans, so one end-point category would be human health. The advantage is the information is appealing and understandable. The LCA study has a damage oriented approach (JRC 2010)
Normalisation	Calculating the magnitude of the LCIA results with respect to certain reference information, e.g. the total impacts in a region within a certain year. The purpose is to give the results more meaning so that the audience can interpret them and be able to see which impacts are more or less significant.
Grouping	Sometimes it is useful to group the LCIA results in some way by assigning them to one or more sets, e.g. global vs regional.
Weighting	Converting and possibly aggregating the results across different impact categories using numerical factors. This is based on value choices about which impact categories are more important.

LCIA is composed of mandatory and optional steps, also shown in Figure 2.17 obtained from ISO (2006c):

1. Selection and definition of impact categories, indicators and models
2. Classification: Group emissions into categories where they may contribute to environmental or health impacts
3. Characterization: Normalize to common reference substance, e.g CO_2-eq.
4. Weighting and Grouping are optional.

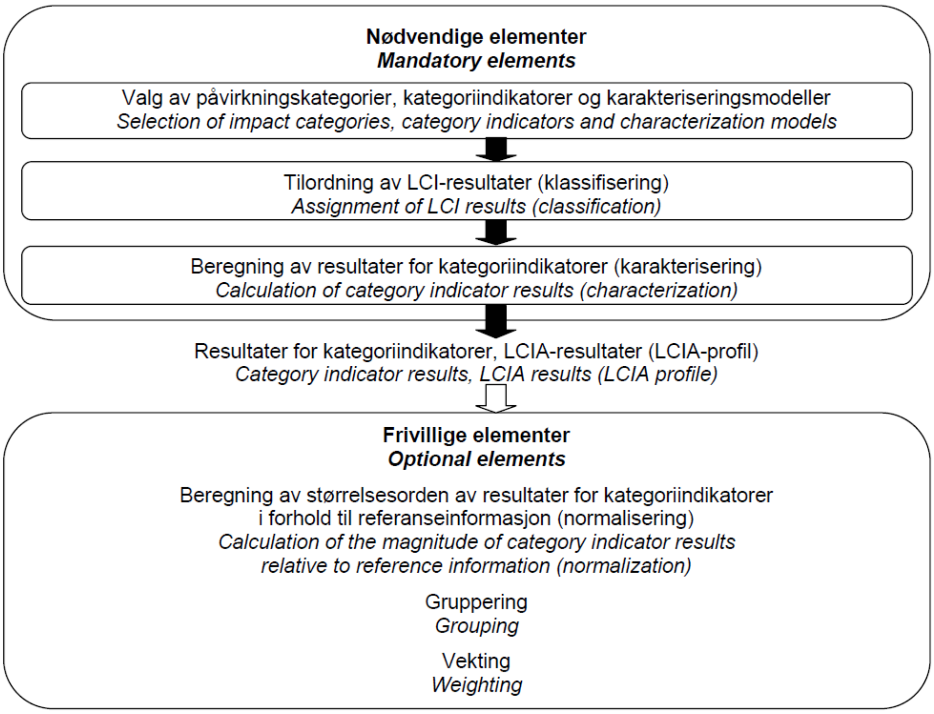

Figure 2.17: Mandatory and optional steps in the LCIA

2.5.5 Interpretation

"Interpretation is the final LCA phase in which the findings of either the inventory analysis or the impact assessment, or both, are combined consistently with the defined goal and scope in order to reach conclusion and recommendations" (ISO 2006b). The content of the interpretation phase is shown in Figure 2.18 obtained from ISO 14044. Important terms are collected in Table 2.9 by Bilbao (2018b).

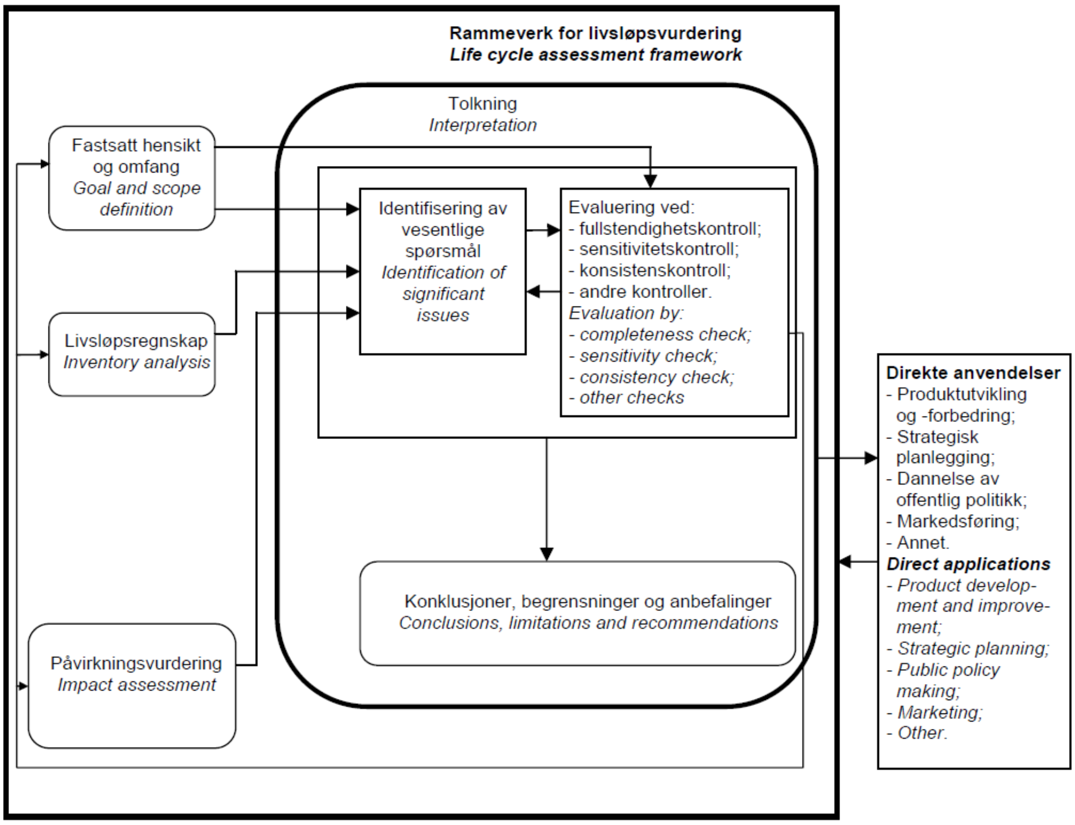

Figure 2.18: Content of the interpretation phase

Table 2.9: Interpretation Terms

Term	Definition
Significant issues	Analyzing the results to identify the key information, e.g. the dominant impact categories or the dominant source of emissions within the life cycle stages.
Completeness check	Ensure that all relevant data and information has been included, e.g. all assumptions documented, inventory is complete, etc.
Consistency check	Review the methodology and results to ensure that the goal of the study has been achieved – are the outcomes consistent with the intended goal?
Sensitivity analysis	Investigating inherently unstable elements by determining if a factor or piece of data is changed by 1% then how much do the results change?
Uncertainty analysis	Systematic study of the propagation of input uncertainties into output uncertainties. Can be done numerically or analytically.
Transparent reporting	All methodology, assumptions, calculations and results should be honestly and openly documented such that the study could be repeated to check the results.
Contribution analysis	Decompose results in contributing elements, e.g. processes, stages of the life cycle, different impact categories, etc. Highlight opportunities for improvement.
Break even analysis	Investigate trade-offs between environmental impacts to determine the better option. E.g. if only 2 drinks are needed then disposable plastic cups would be preferable to glass cups, but for 1000 drinks it would be better to re-use glass cups. Somewhere between 2 and 1000 would be a 'break-even' point. In renewable energy LCAs, the energy payback calculations are a type of break-even analysis.
Monte Carlo simulations	A numerical approach to uncertainty analysis. The simulations use a computer to run millions of repetitions of a scenario given certain input uncertainties to determine the likely spread of outputs.
Comparative analysis	A clear assessment comparing 2 alternatives to report which alternative performs better in certain aspects.
Discernibly analysis	A combination of comparative analysis and uncertainty analysis. E.g. showing the results of 2 Monte Carlo simulations to show the likelihood of one alternative outperforming the other.

According to ISO (2006c), the interpretation should be based on an evaluation of data quality, sensitivity analysis, consistency check and completeness check, as well as the limitations, are applied. Analysis can be extended to run different scenarios once the LCI model has been established.

2.5.6 Report and Critical Review

An LCA report consists of at least four parts: the main part, which is additionally condensed into a technical and an executive summary, an annex that documents e.g. assumptions, and lastly the data used (JRC 2010). The summaries should be able to stand alone without compromising the results of the LCA.

ISO (2006c) states that the critical review process shall ensure that:

- "The methods used to carry out the LCA are consistent with ISO 14044 and the methods are scientifically and technically valid.
- The data used are appropriate and reasonable in relation to the goal of the study.
- The interpretation reflects the limitations identified and the goal of the study.
- The study report is transparent and consistent."

The next section intend to collect the theory proposed in this master thesis, and present the state-of-the-art. In addition, best practise will be stated. The next section is based on the literature review and personal communication with supervisors at NTNU and NCC.

2.6 State-of-the-Art and Best Practice

There is no doubt that the trend of BIM and LCA publications has increased within the last 10 years. Topics of research areas like level of development, life cycle assessment and building information modeling are published with almost constant tendency (Santos et al. 2019a). Nevertheless, today there is limited integration between LCA and the BIM-model in the early design stages of a building project, that is capable of using BIM as the sole data for conducting LCAs (Volk, Stengel, and Schultmann 2014; Antón and Diaz 2014; Soust-Verdaguer, Llatas, and García-Martínez 2017; Yang et al. 2018; Jrade and Jalaei 2013; Rock et al. 2018; Nizam, Zhang, and Tian 2018; Bueno, Pereira, and Fabricio 2018; Soust-Verdaguer, Llatas, García-Martínez, and Gómez de Cózar 2018; Durão et al. 2019). No tools allow the manipulation of the environmental information in BIM objects (Durão et al. 2019). The very few software tools like Tally, IMPACT, ELODIE (see Table 2.4), that enable BIM interactions, do not link materials to LCI databases and require loads of plug-in information (Durão et al. 2019).

Literature presents three main approaches to BIM-LCA integration. The first is to conduct the LCA by using several programs (Santos et al. 2019b). The second is to connect a quantity take-off generated by a BIM model with an LCA database, to obtain the environmental impacts (Santos et al. 2019b). The third approach argues that the inclusion of LCA information in BIM could represent a step towards environmental integration, based on features in material comparison in BIM (Santos et al. 2019b; Antón and Diaz 2014). The first and second approach are best practice to evaluate the environmental impacts in building projects today.

These approaches stated by Santos et al. (2019b) will be discussed in Chapter 5. The case study and the execution of LCAs are based on the second approach. Consequently, this thesis suggestion is therefore founded on such methodology. These results are presented in Chapter 5.

Moreover, there are great agreements in the literature regarding the advantages of BIM-LCA integration. To acknowledge the need for improving the sustainability performance of buildings, and the fact that the integration of BIM-based LCA tool can reduce time, and improve the application on the environmental performance of buildings from the early design stages, e.g low

LOD levels, is a wake-up call that will benefit the building industry (Soust-Verdaguer, Llatas, and García-Martínez 2017). In addition, Antón and Díaz (2014) state that 30-40% of the time at the beginning of the project is effective, whereas 60-70% of the time is used more or less inefficiently.

The abundance of data requirements for interaction between BIM and LCA integrated into the same software, is in the literature presented as easy to implement and user-friendly (Soust-Verdaguer, Llatas, and García-Martínez 2017; Najjar et al. 2017). The most time-consuming aspect of the LCA methodology is the inventory analysis and its compilation of a detailed bill of quantities (Durão et al. 2019). Bueno, Pereira, and Fabricio (2018) states that the major issues in the application of LCA methodology at the building design process, are lack of availability of LCI data, and actual application of the method is only given in the final stages.

In the second half of the 1990s, ISO standard (Figure 2.10) became the most important recognized standards of LCA methodology (Najjar et al. 2017). The LCA methodology recognizes and analyses the different possibilities that help reducing energy and resource consumption, and the environmental impacts of building materials (Najjar et al. 2017). Since the mid-2000s, BIM has increasingly been used for architectural design, due to the offer of 3D building components, detailed elements and attribute information necessary for material take-off, cost reduction and process management (Lee et al. 2015). On the other hand, today there is a lack of standards and public incentives for the adaption of BIM within the sustainable construction industry. In addition, BIM libraries with enough sustainable data information, is a little extensive (Santos et al. 2019a).

Two different trends can be observed in the literature regarding how to perform LCA of buildings based on BIM. The first trend is doing detailed LCAs with refined processes and simulation tools, while the second trend involves simplified approaches towards an LCA in early design stages (Cavalliere et al. 2019). The following will discuss these trends and the state-of-the-art regarding the most recent stages of developing LCAs in early design stages.

Najjar et al. (2017) and Meex et al. (2018) agreed that the accuracy of the LCA varies with respect to life cycle phases. The literature divides a building LCA into three main phases to distinguish different activities and relevant contained energy as the items below.

1. Pre-building phase that characterize the embodied energy demand from A1-A3 (Figure 2.11)

2. Building phase which emphasizes the the construction stage and the use stage, A4-B7 in Figure 2.11, which contain induced energy, operation energy, maintenance, installation and replacement.

3. The third phase called post-building phase account demolition and recycling, C1-C4 in Figure 2.11. The third phase contain the energy consumed in the demolition and disposal of the building, end of life stage.

Figure 2.19 obtained from Meex et al. (2018) shows that adding components during later stages of the design process, causes an increase in environmental impact. This is shown by the fact that an LCA becomes worse due to different system boundaries.

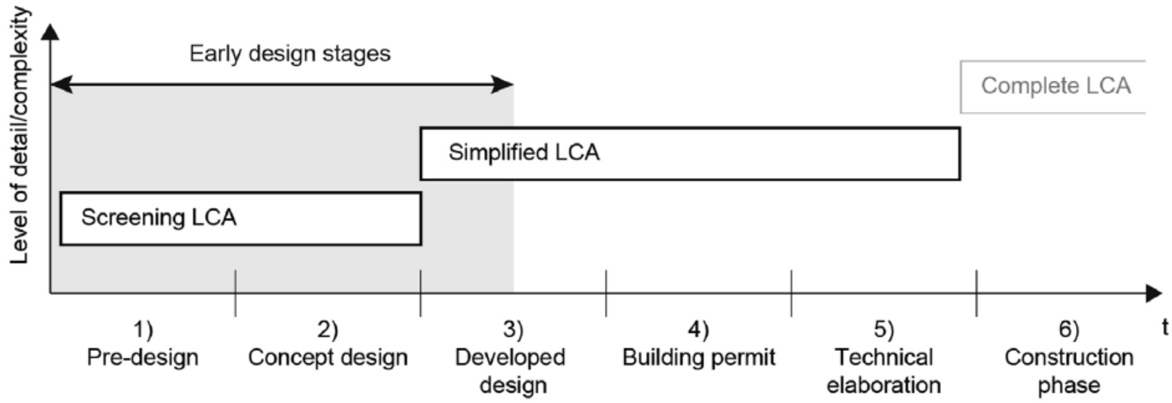

Figure 2.19: Relation between design stage and simplifications in LCA

LCA requires a verified declaration of the impacts in life cycle modules A1-A3, B6 and B7 (Meex et al. 2018). According to Cuéllar-Franca and Azapagic (2012), embodied energy, combined with the operational energy use, typically account for 70-90% of the environmental impact of buildings. Cuéllar-Franca and Azapagic (2012) study took place in the UK. However, for instance Lolli, Fufa, and Inman (2017) and Cabeza et al. (2014) show the huge impact the production stage have on the environment in Norway and northern Europe. Furthermore, input data from the embodied energy and operational module in an LCA, which can be found in EPDs, is declared with high accuracy (verified by a third party based on ISO 14025), and by then, the potential for environmental assessment in low LOD stage is possible.

As a solution for substitution of the missing or unknown data in early design, Meex et al. (2018) propose in their paper to limit the modelling effort for screening LCA, by employ default values. For instance, average values on the number of square meters can be used. LCA practitioners can either change the type of construction and its materialization, or choose the product from producers with the best environmental performance, within one type of material based on an EPD (Meex et al. 2018).

Table 2.10 shows some studies done with the use of several tools to best fulfill a BIM-based LCA. The studies employed in the table, testify the need for major effort to develop BIM tools that can handle environmental assessments, to highlight the environmental performance in the early design of building projects. The LCIA is based on average values, as Meex et al. (2018) propose, where no information is available to be compiled in early design stages (low LOD).

Table 2.10: Some BIM-based LCA studies

Reference	Tools	Limitations for LCIA
Ajayi et al. (2015)	Revit, Green Building Studio, Athena Impact Estimator, MS Excel	Average for transportation and construction impact
Jrade and Abdulla (2012)	Revit, IFC Analyzer, MS Excel Athena impact Estimator	Average values for all the impacts
Jrade and Jalaei (2013)	Revit, Athena Impact Estimator, MS Excel	Average for transportation and construction impact
Lee et al. (2015)	Revit, Korea LCI database	Average for transportation and construction impacts. (Some impacts are ignored)
Eleftheriadis, Duffour, and Mumovic (2018)	Revit, NSGA-II, Spons Architects and builders Price book 2017, C#, Autodesk Robot API, Finite Element Model	Price Book
Peng (2016)	Revit, Ecotect, MS Excel	Average values for emission calculations
Cavalliere et al. (2019)	Ecoinvent 2.2, Rhinoceros CAD	Average values for building components and also minimum and maximum values (uncertainty analysis). LCI database: Swiss Building database, KBOB (Okobilanzdatenim Baubereich), Bauteilkatalog
Rock et al. (2018)	Revit, Dynamo, MS Excel	Average values on construction options and also minimum and maximum values
Bueno, Pereira, and Fabricio (2018)	Revit, Dynamo, Excel	LCIA: ReCiPe 2008
Yang et al. (2018)	Revit, Glondon BIM5D tools, eBALANCE, MS Excel, Design builder, Ecoinvent	CLCD-China-public 0.8.1 2012 Version
Basbagill et al. (2013)	DProfiler, eQuest, Athena Eco-Calculator	SimaPro. The study had no range or any sensitivity analysis in the LCIA.

The great uncertainty related to the LCA evaluation can be described qualitatively by ISO standards, (ISO (2006b) and ISO (2006c)) and the ILCD Handbook (JRC (2010) and JRC (2017)), but LCA practitioners should be included in the building project at the same guidelines as designers. This is due to the reporting of the goal and scope definition of all elements that are part of the context uncertainty (Igos et al. 2018). For the LCIA, Igos et al. (2018) suggest that the practitioners justify the selection of indicators and models. By doing so, the consistency between the goal and scope definition becomes more valid and the uncertainty is decreased. When it comes to interpretation, the model definition and its limitation are already defined, and it is easier to handle the input data via completeness, sensitivity and consistency checks. A quantitative uncertainty assessment of an LCA in the early design stage can be done when the LCIA data is available. Igos et al. (2018) state that a proper LCA study should communicate all the different components of uncertainty treatment. Monte Carlo is a method that performs a discernibility analysis. Dupuis et al. (2017) suggest the use of the Monte Carlo simulation approach when the LOD is low and the lack of information is present in the generic process types. Providing the model and designers with key information as to which parts of the LCA that contribute most to the uncertainty of the score, and which thereby ones should be identified clearly in priority to reduce this uncertainty (Dupuis et al. 2017).

Another method used to decrease the uncertainty is the use of average values when the LOD is low. One can also take advantage of minimum and maximum values like Rock et al. (2018) and Cavalliere et al. (2019) utilize in their studies. This to clearly show the range of options available (see Table 2.10). This would also make the designers and decision makers perceive the materials that possess the worst and the best impact on the environment.

Commonly, an LCA is normally conducted after the building is completed, e.g to satisfy certifications like Figure 2.8 presents additional to DGNB, GBTool, AQUA (Jrade and Abdulla 2012; Bueno, Pereira, and Fabricio 2018; Mattoni et al. 2018). As such, the lack of project information is an obstacle for LCA performance during the design phase (Antón and Díaz 2014). In order to improve the overall environmental performance, the best option is to introduce LCA in the very beginning of a project. By doing so, one will have the ability to influence the project when the highest potential is presented (Dupuis et al. 2017). Alternatively to the use of averages, minimum and maximum values when the information is low, designers can use values based on experience (Andersen 2019).

The energy use of a building should be addressed and tested with different design alternatives during the planning and design phase when the level of influence is high. This is promoted in Figure 2.20 (Schade, Olofsson, and Schreyer 2011; Shadram et al. 2015). Implementing decision making processes at low LOD levels necessitates well-employed correlations between BIM tools and its standards, in terms of design, operation and maintenance, along with LCA software in order to appraise environmental impact at low LOD. Hence, as Antón and Diaz (2014) claims, there are two approaches to facilitate the integration between BIM and LCA. The first is "direct access to the BIM model information to calculate LCA performance", and secondly "environmental properties included in the BIM object". The first approach introduce LCA to join the concept of "BIM 360". This concept improve building project delivery by supporting informed decision-making throughout its life cycle and by connecting people, data and the workflow of the project on the same platform (Autodesk 2018). Moreover, the second approach relies on linking the BIM objects with EPDs, which allows the users to select elements and objects by considering the environmental properties (Antón and Diaz 2014). These approaches establish a high level of collaboration on several disciplines and may lead to fewer errors, due to environmental issues in a building project. Existing BIM guides and standards do not contain a suitable focus on sustainable dimensions and how such information should be structured in line with LOD (Santos et al. 2019a).

The use of BIM enable processes encourage more effort because of the early collaboration and open information sharing (Lu et al. 2014). In the schematic design showed in Figure 2.20, obtained from Lu et al. (2014), is it possible to improve both the execution of a construction project, as well as introducing the assessment of environmental aspect with the digital representation of the BIM evolving in early design.

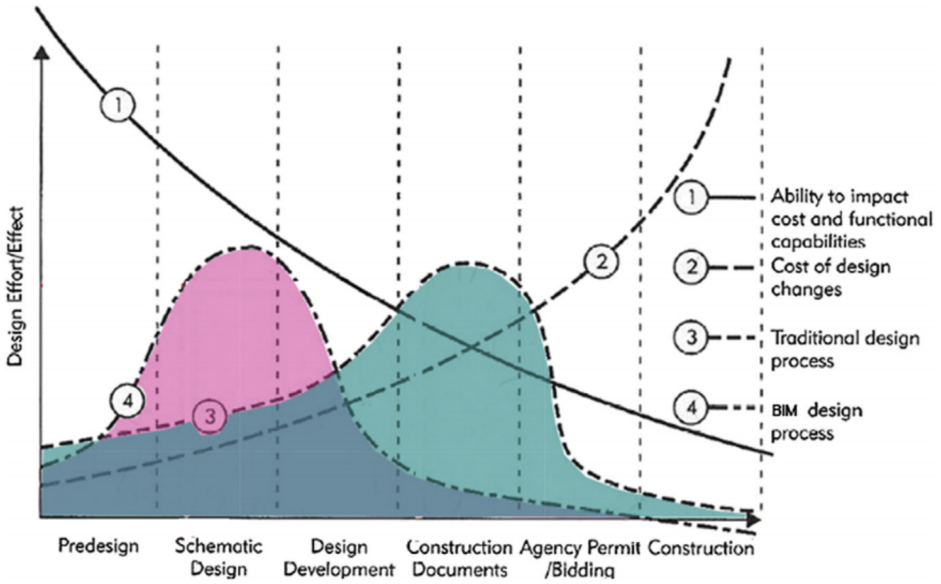

Figure 2.20: Distribution of design effort with respect to time and costs: MacLeamy Curve

Lee et al. (2015) argue that the evaluation of the embodied environmental impact of a building is to be done at LOD 300. At this LOD, there is enough information about the main building materials like concrete, steel, glass, concrete block, insulation material and gypsum board. These materials define 95% of the quantity of materials (Figure 2.7). On the other hand, Dupuis et al. (2017) argue that each object at a lower LOD level than 350, will be missing essential data elements (specific object's type, the assembly description etc.) that would improve an LCA calculation. Rock et al. (2018) study was based on a LOD 200 model to conduct environmental performance. There may be because of supporting the early environmental analysis and the second trend in the literature defined by Cavalliere et al. (2019), due to enhance the simplified LCA. There is no link between the first and the second trend, and the second trend proves to be more suitable for designers in the early design (low LOD) (Cavalliere et al. 2019). As such, at LOD 200, BIMforum (2015) argue that all elements are recognizable by the components they represent and the volume they occupy in the space. By knowing the occupied volume, it is believable that average values on the environmental impact can be used, and a simplified LCA is possible to accomplish.

Inconsistency between LOD levels in a BIM model and the LOD expected in common LCA analysis tools, would most likely result in unconscious and misleading results in the early design stages (Lee et al. 2015). The reasons for the inconsistencies are the level of information within the elements in a BIM authoring tool that is imported before being studied by qualified designers, and the lack of decision making processes in the early design stages (Lee et al. 2015). LOD specifications are not applicable to models, but rather to objects, defined by the IDM methodology, to the model (Durão et al. 2019). The IDM methodology defines the functionality-related exchange of process information in BIM (Volk, Stengel, and Schultmann 2014). This methodology should be further develop to coordinate according to LOD requirements. The identification of information (e.g environmental impact category) that could be incorporated in BIM objects to improve the environmental performances within a BIM-based environment, is not addressed (Santos et al. 2019a). ISO standards applicable to LCAs do not specify impact categories to be assessed, nor the method of the impact assessment (Durão et al. 2019).

Because there is no integration of LCA applications in a BIM environment yet, best practise today is obtaining a report from a BIM software and import this report of material quantities into an LCA platform (Andersen 2019). Inside this type of LCA application, there are possibilities to link the materials from the report to available EPDs. Moreover, in later LCA modules such as use stage and end-of-life, data has to be selected manually (Ingvil Arntzen 2018). This evidences the need to develop new tools based on open BIM schemas, and especially in IFC data models (Soust-Verdaguer, Llatas, and García-Martínez 2017). Export of BIM quantity take-offs to other platforms for sustainability analysis, proposes the extension of material properties to incorporate sustainability within the BIM tool. The manual input of environmental properties into the material, reference units and distance databases, make this method impractical as it would increase the modelling time and prone errors (Nizam, Zhang, and Tian 2018; Andersen 2019).

Nizam, Zhang, and Tian (2018) state two major challenges regarding the initial embodied energy (A1-A5 (Moncaster and Symons 2013)). The first challenge is the fragmented nature of the construction industry. The issue of specialized software that can be adopted by experts of the early design phase, is not interoperable with later phases. Thereby, this forcing re-input of data for the subsequent phases, which in turn breaks the virtual chain of the overall building process regarding environmental performances (Nizam, Zhang, and Tian 2018). The second challenge is the lack of a convenient tool to comprehensively input all relevant data, and link the construction process with the embodied energy estimation. This includes establishing a relationship with external data to obtain meaningful, quick and comparable solutions for embodied energy (Nizam, Zhang, and Tian 2018). Moreover, Jrade and Jalaei (2013) and Peng (2016) underpin the shortcomings of BIM environment to provide the data needed to conduct an LCA, such as limitations on the integration of BIM-LCA. Soust-Verdaguer, Llatas, García-Martínez, and Gómez de Cózar (2018) are obviously defending the two main challenges stated by Nizam, Zhang, and Tian (2018), where the missing linkage of different databases, automatize the design and impact calculation in the BIM-LCA integration need more development.

Current available embodied environmental impact evaluation tools is not fully developed. They lack the inter-data compatibility required during work sessions, despite the use of IFC open format. The missing evolution of EPDs availability, lower the reliability of the results of an embodied environmental impact evaluation. In addition, a missing evolution of EPDs, increases the processing time, given the need for format conversion to ensure interoperability and manual workload regarding data input (Lee et al. 2015). Various software vendors define the objects differently based on the context, integrated standards, LCI database(s) and plug-ins in their program. Since IFC, the data exchange standard, is developed by the non-profit buildingSMART, keeping up with the rapid growth of the BIM industry is a challenge (Jrade and Jalaei 2013).

Ramaji et al. (2017) study can be looked upon that the real potential of sustainability evaluation using BIM cannot be achieved without a proper information exchange framework, supporting technologies and interoperability. As the material production and operational stage share more than 90% of the energy demand of a building, there has been observed two gaps between predicted energy performance and measures building energy performance (Ramaji et al. 2017; Tuniki and Gultekin-Bicer 2017). The first gap is the uncertainty in occupants behaviours in further weather conditions, and secondly the error in geometric information during data exchange or model transformation. To concur the second gap, BIM implementation may help. IFC is designed to carry all information due to MDV, transport information (ISO 16739) and the methodology standards by buildingSMART (Figure 2.3). As a result of the high cost of implementation, no other MVD is widely implemented by software developers (except Design Transfer View in the IFC4 version) (Ramaji et al. 2017). According to Ramaji et al. (2017), the reality of the situation is that the practicality of using IFC for information exchange is currently inefficient or prone error. Errors found in Pinheiro et al. (2018) study were limited to missing pattern definition for schedules, heat pump units, agreement on system hierarchy and IfcDoc tool (IFC documentation generator). By making MVD to an employed system in the building industry, it can contribute to a better understanding of model views, as well as faster development in the exchange capabilities.

To complete the BIM model before the construction starts, a requirement of improvement regarding collaboration is needed. Ingvil Arntzen (2018) mentions a missing link between designers and architects regarding the workload during the construction phase. Andersen (2019) focuses on the abhorrence to influence the project in the early design stages by architects causing the ability to earn more money as the building project develops. The architects desire to influence the output on the design even after the BIM-model is considered complete. Today, the BIM model is not fully complete before the building is handed over (LOD 500) (Andersen 2019). This is due to some contracts are not signed, and orders are not decided. This affects the design and the screening and simplified LCA.

Basbagill et al. (2013) compiled a method for conduction of LCAs, which can be seen as an approach that can assist decision makers in the selection of environmentally friendly products. By extracting geometric information from BIM objects and export it to LCA tools, it would be more eco-friendly. Jrade and Jalaei (2013) study, which is based on Basbagill et al. (2013), uses the quantity take-off generated by BIM tools to feed an LCA. This method is further explained in Section 3.3 and executed in Section 5.2.

2.7 Theoretical Aspects Related to the Research Questions

This section summarizes the most important findings during the process of collecting theory to this master thesis related to the research questions. Table 2.11 is conducted to systematically withdraw the most important findings as a foundation to the research questions in the best possible manner.

Based on the global share of buildings' and construction final energy and emissions, there is no doubt that the building industry is a huge contributor to climate changes. The building industry is now a driver to GHG emissions and its impacts related to, for example, the ocean and the tundra. The impacts are present today, and it requires adaption to mitigate emissions, as well as an adaptive capacity for human and natural systems. Adaptation is the answer to the baseline of this thesis' initial problem, related to the need for a change in the building industry to mitigate the energy demand and emissions during building projects. Pathways to sustainable buildings and construction are listed in Subsection 2.1.2, and all of these pathways should be adopted in early design stages in BIM, and with the use of LCA methodology, to control the GWP and GHG emissions.

Table 2.11: Theoretical Aspect Related to the Research Questions

How is the environmental assessment treated in a building project today?	There are existing standards with respect to LCA, EPD and PCR, that determine the methodology for conducting LCAs. The LCA framework comprises four phases; goal and scope definition, inventory analysis, impact assessment and interpretation. These phases are iterative processes that calculate the impacts on the categories listed in Table 2.5 and B.1.
What is the interaction between BIM and LCA, and how is this interaction used to evaluate environmental performance in building projects?	Two types of software can interact with BIM. First, the data input applications providing services of import and data processing of transformation. Second, the data output applications providing reports or analyses supporting the technical and structural processes. The open standard for BIM that allows data exchange among software application, IFC, can assist the input/output applications through proprietary translators between BIM and LCA. Through object oriented information, MVD, BCF and the IDM methodology, BIM have standards that LCA software can adopt. BIM-LCA application are listed in Table 2.4. BIM can also assist LCA with geometric features in generic LCA tools listed in Table 2.3.
How can an early design LCA framework correspond to LOD with respect to OCL?	OCL supports interactions from IFC which enable an LCA framework based on LOD requirements. LOD can be seen as the overarching requirements for both the graphical level of object's, as well as the non graphical data in BIM objects. The different LOD levels determine the maturity of the BIM. IFC can be exchanged, transferred, withdrawn or reviewed to be assessed in OCL at different design stages in low LOD.

Table 2.2: Fundamental LOD Definitions

LOD	**Definition**
LOD 100: "Concept Design"	"The Model Element may be graphically represented in the model with a symbol or other generic representation, but does not satisfy the requirements for LOD 200. Information related to the Model Element (i.e. cost per square foot, tonnage of HVAC, etc.) can be derived from other Model Elements. BIMForum Interpretation: LOD 100 elements are not geometric representations. Examples are information attached to other model elements or symbols showing the existence of a component but not its shape, size, or precise location. Any information derived from LOD 100 elements must be considered approximate" (BIMforum 2018)
LOD 200: "Schematic Design"	"The Model Element is graphically represented within the model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non graphic information may also be attached to the Model Element. BIMForum interpretation: At this LOD elements are generic placeholders. They may be recognizable as the components they represent, or they may be volumes for space reservation. Any information derived from LOD 200 elements must be considered approximate." (BIMforum 2018)
LOD 300: "Detailed Design"	"The Model Element is graphically represented within the model as a specific system, object or assembly in terms of quantity, size, shape, location, and orientation. Non graphic information may also be attached to the Model Element. BIMForum interpretation: The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs. The project origin is defined and the element is located accurately with respect to the project origin" (BIMforum 2018)
LOD 350: "Construction Documentation	"The Model Element is graphically represented within the model as a specific system, object, or assembly in terms of quantity, size, shape, location, orientation, and interfaces with other building systems. Non graphic information may also be attached to the Model Element. BIMForum interpretation: Parts necessary for coordination of the element with nearby or attached elements are modeled. These parts will include such items as supports and connections. The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non modeled information such as notes or dimension call-outs." (BIMforum 2018)
LOD 400: "Fabrication and Assembly"	"The Model Element is graphically represented within the model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information. Non graphic information may also be attached to the Model Element. BIMForum interpretation: An LOD 400 element is modeled at sufficient detail and accuracy for fabrication of the represented component. The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non modeled information such as notes or dimension call-outs." (BIMforum 2018)
LOD 500: "As built"	"The Model Element is a field verified representation in terms of size, shape, location, quantity, and orientation. Non graphic information may also be attached to the Model Elements. BIMForum interpretation: Since LOD 500 relates to field verification and is not an indication of progression to a higher level of model element geometry or non graphic information, this specification does not define or illustrate it." (BIMforum 2018)

Table 2.4: BIM-LCA integration tools

BIM-LCA Tool Institution, Country	Features	Limitations
Elodie Centre Scientifique et Technique du Bâtiment (France)	• Simplified LCA compliant with European standards. • Design alternatives can be compared, • Energy performance in the design and construction solutions, • Environmental impacts assessment at the construction site, • Computation of transport of users and of major environmental contributions.	• Separate software, needs to import data from BIM File, • Software –most of the information is only available in French.
eTool LCA International Team Effort (Australia, UK, Brazil, Germany)	• Detailed reports with comparable information on environmental data, • Multiple Impact Reporting, including CO_2, Cost, Energy, Water, Land Use, Ozone Depletion, Human Toxicity. • Web-based software, with a pay-as-you-go certification, reviewed by third parties, • Compliant with ISO 14044 and European Standards.	• Separate software, needs to import data from BIM File; • Free version does not allow the user to print the assessment reports.
Green building assessment tool (GBAT) Istanbul Technical University, (Turkey)	• The framework builds a relationship between the BIM and the green building rating processes. • The framework builds a relationship between the BIM and the green building rating processes. • IMPACT Compliant assessments, including BREEAM credits.	• Separate software, needs to import data from BIM File, • Presents the available credits limited to only a subset of the available BREEAM materials, • The material database cannot be automatically updated from the BREEAM database and there is manual effort to convert it to the materials library.
Green Building Studio® Autodesk (USA)	• Carbon emissions report, • Energy analysis of complete buildings, • Daylighting, Water use and related costs and natural ventilation analysis, • Cloud-based software, • It can be used as a support tool for impact assessment of the building operation phase, • Support for LEED and Energy Star certifications.	• Very broad thermal and energy balance software, not only dedicated to LCA studies, • Does not perform full LCA studies, • Separate software, needs to import data from BIM File.
Impact Compliant Suite IESVE (United Kingdom)	• LCA compliant with British standards, • Integrated LCA, Life Cycle Costing (LCC) and Capital Costing (CC), • IMPACT Compliant assessments, including BREEAM credits, • BRE ecopoint output.	• Separate software, needs to import data from BIM File.
LCA Design™ (Ecospecifier) National Research Center on Sustainable Built Environment (Australia)	• A single ecopoint score, • Choice of environmental inventory, impacts and point-score measures; • Comparative ecoprofiling at all levels of design, • Detailed graphical and tabular outputs • Cost variations, • Compliant with ISO Standards	• Difficulty in finding detailed information about the software and the data and methods applied on it, • No trial version available for testing so far.
Lesosai Several institutions, notably the Solar Energy and Building Physics Laboratory of Ecolepolytechnique fédérale de Lausanne (Switzerland)	• Basic version of building LCA, directed mainly to Switzerland, France, Luxembourg, Italy, Germany and Romania, • Calculation of environmental impacts from energy consumption from building operation, • LCIA methodology according to the Swiss standards, • Database updated by the materials producers, • Unlimited time use for free Demo version.	• Separate software, needs to import data from BIM File, • Very broad thermal and energy balance software, not only dedicated to LCA studies, • LCA studies are regionally specific; • Demo version does not allow to print the assessment reports.
One Click LCA Bionova (USA, Finland)	• Simplified LCA, • Compliant with BREEAM, LEED, HQE, DGNB and other certification schemes, • Integrated building site impacts and life cycle cost (LCC), • EPD database, • Verified by third parties.	• Difficult do find information.
Tally™ Kieran Timberlake Innovations in partnership with Autodesk and PE International (USA)	• LCA for the whole building or a comparative analysis of building design options, • Identification of the largest environmental impacts and their comparison between the different materials and design options, • As a Revit plug-in, it allows the user to perform LCA within BIM environment, with no special modelling practices, • Available information on applied data and methods, and complete tutorials, • Flexible non commercial licenses, • Intuitive and user friendly interface.	• It is specific for Autodesk Revit software, • The inventory data as the LCIA methods cannot be changed or updated by the user.

Chapter 3: Method

The Chapter is included in the master thesis to document how data is acquired, and to ensure that it is verifiable as far as possible. The final part of this chapter evaluates the methods used based on validity and reliability, to provide reproduction of the results.

3.1 Scientific Methods

Qualitative and quantitative research methods are cultivated in this study. Table 3.1, based on Golafshani (2003) reflective findings, summarizes the most important differences between quantitative research and qualitative research. The following sections explain the research methods in detail and how these are executed in the study.

A quantitative method is useful when doing measurements, and to compare the data in purpose to calculate the environmental impacts (Golafshani 2003). Quantitative research allows the researcher to familiarize him/herself with the problem to be studied, and generate hypotheses to be tested. Winter (2000) defines quantitative research as follow:

> "A quantitative researcher attempts to fragment and delimit phenomena into measurable or common categories that can be applied to all of the subjects or wider and similar situations".

On the other hand, a qualitative method is essential to cover what kind of science that has been carried out, and what the building industry is doing regarding environmental assessments. Qualitative research is commonly known as the research that produces findings and results not arrived at by means of mathematical and statistical measures, or other means of quantification (Golafshani 2003). Patton (1990) defines qualitative research as follow:

> "Qualitative research uses a naturalistic approach that seeks to understand phenomena in context-specific settings, such as real world setting where the researcher does not attempt to manipulate the phenomenon of interest".

If the intention is to map the occurrence of one action, a quantitative research method is to prefer. By contrast, for investigation of communication in different tools and strategies, a qualitative research method may be better. A striking feature is a combination of quantitative and qualitative methods called triangulation. A triangulation research method is a convergence, corroboration, correspondence or results from different methods (Bryman 2006). In triangulation, the emphasis is on seeking corroboration between quantitative and qualitative data.

Table 3.1: Research methods

Quantitative research	**Qualitative research**
Searching insight	Searching overview
Numbers and measures	Oral and written information
Limited information, but several objects	Variety of information, but few objects
Seeking verification based on one or more hypothesis	No need for hypothesis to investigate a phenomenon
Purpose of explaining	Generating understanding
Seek determination, prediction and generalization	Seek illumination, understanding and extrapolation to similar situations

3.2 Selection and Description of Methods

In this section, an overview of the methods used when working with the thesis, will be presented. This thesis selected methods that best answer the research questions. The purpose of this study is to get an overview of how the LCA methodology is executed in today's building projects, as well as to obtain an understanding of how the environmental assessments are executed during the early design stages. To conduct the best results and finally propose a suggestion to the building industry, both quantitative and qualitative research methods were utilized. The combination of both methods, triangulation, dominated the way towards reliable and valid results in the execution of LCAs. In Table 3.2, the methods used are presented and justified to best answer the research questions. Personal communication such as e-mails and dialogues is utilized through for all research questions for supplementary information regarding the building industry.

Table 3.2: Research strategy

Research question	**Method**	**Justification**
1) How is the environmental assessment treated in a building project today?	**Qualitative research**: Literature review.	Assemble the most relevant articles, papers, standards, manuals and books to gain the knowledge of the state-of-the-art and best practice. The evolution process of literature, identified knowledge gaps and predicted trends.
2) What is the interaction between BIM and LCA, and how is this interaction used to evaluate environmental performance in building projects?	**Qualitative research**: Literature review, document review. **Quantitative research**: Case study: Conducting LCAs in different LOD levels.	Verify and test the hypothesis of an improvement in LCA results in later LOD levels using OCL. Moreover, get an overview of several case studies in the field of BIM-based LCA, and the issues within the interaction and integration of BIM-LCAs based on literature reviews.
3) How can an early design LCA framework correspond to LOD with respect to OCL?	**Triangulation research**: Using both qualitative and quantitative research methods to conduct LCAs in different LODs, and finally create a framework that emphasis OCL. Standards and findings in the literature are also used.	Literature review gave insight into how a framework should be displayed. Document review was necessary to obtain .smc files from the case, as well as general information about the building project. Designing the LCA in OCL fed this thesis with results, verification on the hypothesis and numbers from the assessments.

3.2.1 Quantitative Research

Quantitative research is data that covers measurements and mathematical, statistical and numerically analyses. This method is seeking to generalize a problem by collect and organize, often, unstructured data (Bryman 2006). To perform a LCA for the production stage (A1-A3), a range of inventory data is needed. In this case, the quantification of materials is found in IFC files (.smc files) and linked to different EPDs of the LCA tool OCL.

The advantage of using quantitative research is, among other things, that the data gives you measurable units, and the numbers gives you the option of doing calculations (Dalland 2017).

As mentioned in Table 3.3, the FU in the LCA in the case, Valle Wood, is kg $CO_2 - eq$ emission while the reference unit is m^3.

Quantitative research requires strict specifications and discussion in case of variables, errors, deviations and the accuracy. Therefore, further explanation of the execution of the LCA and the calculation is described in Section 3.3 and 3.4, as this is where quantitative research is utilized. The LCA methodology used, and assumptions made, can be found in Table 3.3.

3.2.2 Qualitative Research

A qualitative research method is built up on theories and interpretation of experience. This is a method regarding ways of collecting, analyzing and revising material (Skolbekken et al. 2010). The method covers a lot, and to split it into pieces, Skolbekken et al. (2010) and Fangen (2015) mention different types of methods to obtain qualitative information, and this thesis selected two of them to utilize:

- Literature review
- Document review

Literature Review

The literature research aims at studying the integration between BIM, LOD and LCA on the basis of interoperability. However, the objectives of the literature review are to establish the context of the main issue to this master thesis, understand the structure of the problem, show what needs to be done in light of the existing knowledge, and to relate theories and ideas to the problem. Literature review is the information gathered from literature available online and from libraries. Because there exist "paying-walls" on some literature online that did not allow students from NTNU to read it, and the huge amount of information on the web, required a comprehensive survey of the sources. The ease of finding information on the Internet, required reviews of the sources to figure out if they were trustworthy or not. An overview of the literature review procedure related to searching terms, number of hits, the different searching engines, and how the different sources were filtered is shown in Figure 3.1, located at the end of this chapter.

To describe the literature used as sources for this master thesis findings, it was necessary to do a survey of the sources. The *credibility*, *objectivity*, *accuracy* and the *suitability* are criteria that determine the quality of the sources (NTNU 2018). This method is called "TONE" which is one of several methods for assessing literature. The criteria are described below, and an example is shown in Appendix C.

Credibility reflects on who the writer is and how many citations the writer has on the publication. Is he/she an expert? What about the experience and earlier work, and where did the writer publish the study?

Objectivity is the assessment of the general presentation of the article. Is there a link between earlier science done in the same field? Does the writer intend to inform the readers, or persuade?

Accuracy is about the methodology of the theory described. What kind of references does the writer use? Accuracy is all about the reflection on the different science. The data has to be up-to-date and should be confirmed by qualified people among the scientific field.

Suitability is the impact on how the article fits this thesis needs. Is this thesis study in the same spotlight as the article that is found?

The information gained from doing research for this master thesis, comes from book series, articles and papers from journals and conferences, standards and manuals. The process of collecting relevant literature ranges from October 2018 till May 2019 and is limited to English and Norwegian languages. Reviewed articles were counted as they generally summarize the literature which is already published. Literature not older than 8 years were preferable as the trend of BIM and LCA publications has increased significantly the last 15 years. This symbolize great interest in the field of BIM-LCA and a lot of science has been developed since the early 2000's. This can be seen in the growing h-index of authors working on BIM-LCA science within the recent years. The "h-index" is a bibliometric measurement on a scholar's leverage of publications (Bohne 2019).

Relevant literature was saved and systematized according to Figure 3.2, and important information in the literature was marked. The collection of literature was used to easily remember the content of each article and paper by using the "comment"-flag diligent. The metrics to quantitatively analyze the scientific literature were utilized using bibliometric analyze and later on scientometric. The bibliometric analysis focuses on the quantitative analysis of the published articles, which focuses on for example the bibliography and number of publications per year (Santos et al. 2019a). The scientometric analysis was used to quantify the researchers' achievements to unveil the process of scientific development such as numbers of citation.

Date	Title	Year	Author	Reference type	Keywords	Abstract	Journal	DOI	Publisher	Land	Type of contract	URL	Comment

Figure 3.2: Collection of literature

Document Review

Jacobsen (2005) state that a document study is a collection, adaption and interpretation of secondary data. When the primary data is not available, it is preferable to work on some written documents such as a compiled LCA done by a company or investigation on IFC files designed by designers or experts. Private sources of information that is not meant to be published in terms of e-mails, evaluations, as well as research for this master thesis done in collaboration with for instance NCC, is going to be a great part of this study. Through this, it is possible to gain knowledge about different ways of doing research.

In the early design stage and low LOD respectively, there is greater uncertainty prior to the decision making process and input materials. As a result, there is big interest in evaluating the environmental assessment in different stages of LOD, and investigate the differences. All IFC files were made available through NCC's own PortWise Access Manager 4.12. In the same portal, all relevant documents were available such as subcontractors' drawings and calculations. In addition, description of materials were listed. This thesis took advantage of three different IFC files and distinguished the LOD levels based on BIMforum (2015) and BIMforum (2018) requirements. Appendix D shows the graphical illustrations of the different LOD levels in the BIM models. There are justified to which LOD levels the models (.smc-files) belongs to below.

1. **.smc-file published February 2017 - LOD 200**. The model is represented with approximate quantities, size and shape. There are limited objects that are similar to the planned type of materials in the project description (Figure 4.1). It looks like elements are generic placeholders. See Figure D.1.

2. **.smc-file published July 2018 - LOD 300**. The model contains more specific and developed objects. Non-graphic information does also occur in this LOD level, but the size, shape and orientation of elements are located with respect to the project origin. See Figure D.2.

3. **.smc-file published December 2018 - LOD 350**. The quantity, size, shape, location and orientation of the element as designed, can be measured directly from the BIM model. Despite that there are existing non-graphical information to the model, the model can now be used to decision making and as project guide into different locations. See Figure D.3.

3.2.3 Triangulation

Triangulation demands integrate a variety of data and methods, and it can be seen as a continuum that ranges from simple to complex designs. This thesis will use a combination of qualitative and quantitative methods, especially when scaling environmental impacts on different design stages. Scaling refers to the quantification of qualitative measures (Jick 1979).

A case study is a survey and investigation of an ongoing phenomenon in the actual context (Yin 2014). Valle Wood is the name of the project investigated during the work with this master thesis, and is thereby the thesis' case study. The case is utilized to conduct and evaluate LCAs at different stages of level of development. In this section, methods used will be presented, and a step-by-step explanation will be given, of how this thesis used the BIM software, Solibri Model Checker, in combination with OCL, to obtain environmental impact result with respect to GWP and kg $CO_2 - eq$ emission.

Three analyses are done using BIM and OCL together, and the fourth analysis is conducted using input data to OCL, based on empirical values obtained from supervisors in NCC. Triangulation is utilized while combining the document review, Solibri Model Checker (BIM quality assurance) and OCL in the case study. It is relevant to apply a combination of methods when there is not adequately to describe one side of the phenomenon or occurrence to understand the whole picture (Yin 2014).

The quantitative results of this master thesis, are based on the case study provided by NCC. According to Ingvil Arntzen (2018), the OCL application is going to dominate the conduction of LCAs in the future, there was thereby no doubt that this thesis was going to investigate the new LCA tool. Tally, which is a plug-in LCA tool in Revit (BIM authorized software), could have been an option, but Tally ignores the level of detail present in the model, and requires attribution of LCA data for every materials (Nizam, Zhang, and Tian 2018). Moreover, Tally is a simplified LCA tool for buildings (Bueno and Fabricio 2018).

The system boundary is limited to A1-A3, production stage (see Figure 2.11 and Table 3.3). Moncaster and Symons (2013) show an overview of the percentage of the different stages in construction work life cycle stages, with respect to emission and energy consumption. The distribution shows that embodied carbon accounts for 50%, and embodied energy accounts for 54%, of the total contribution of A1-C4 stages. Moreover, Ramaji et al. (2017) claim that material acquisition and production of materials (A1-A3) and operation (B1, B6 and B7) accounts for 90% of footprint of the life cycle energy demand of a building. These statements formed the system boundary for this case study. The production stage (A1-A3) is also listed in EPDs. Since this LCA is static, time variables are not concerned, and the manual work within OCL will be held to a minimum. EPDs can therefore be linked directly to the materials based on five grouping criteria (see LCI analysis and data collection in Table 3.3). Calculation of environmental impacts are done according to characterization factors as per CML-IA 2012 methodology.

Triangulation is used to create a framework that correspond to LCA and BIM. This suggestion to the AEC professionals is based on findings in the literature, as well as knowledge of the LCA application used, OCL. The method that gave this thesis insight in how a framework should look like, is proposed below.

Proposed Framework in the Literature

Cavalliere et al. (2019) show that it is possible to continuously assess the embodied environmental impacts in all phases of the building design process. Because the functional elements and construction categories are modelled at different LODs, Cavalliere et al. (2019) utilize different LCI databases according to the building element that match the LOD (see Table 2.10). Definition of construction categories were based on Swiss building element classification, while the definition of design stage were defined as the following:

- Project Planning (PP)
- Project (P)
- Building Permit Application (BPA)
- Tendering (T)
- Construction (C)

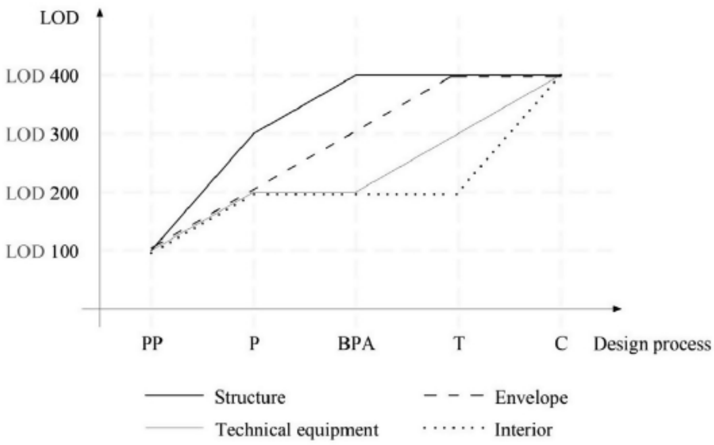

Figure 3.3: Design process proposed by Cavalliere et al. (2019)

In spite of the different databases utilized at different LOD levels, average values of the building component catalogue were used, as well as the minimum and maximum value was provided into the LCA when the LOD was lower than 400 (Cavalliere et al. 2019). Furthermore, as Figure 3.3 in Cavalliere et al. (2019) study explains, *structure* is reaching LOD 400 first at BPA stage because of the big impact on the building scope (columns, base slab, ceiling, roof and walls). The *envelope*, which is the exterior finishing parts, reach LOD 400 after *structure* at tendering stage because of assembly reasons and enough information to calculate costs and environmental impacts. Consequently, the *technical equipment's* and *interior structures* reaches LOD 400 at the construction phase. Henceforth, the BIM model should be completed with all the right environmental input to assess complete environmental impacts at the construction phase and LOD 400. As such, the framework consists of three main steps according to Cavalliere et al. (2019):

1. Definition of an evolution of LOD.
2. Consistent combination of LCA databases.
3. Link between LOD levels and LCA databases.

3.3 BIM

Solibri model checker is capable of analyzing BIM-models and architectural and engineering designs for integrity, quality and safety (Graphisoft 2019). Solibri can import models from all major BIM software by using IFC interface. Files obtained from Solibri Model Checker is named a .smc file. The IFC is an open and standardized way of storing digital BIM descriptions (Solibri Inc 2019).

Findings from the document review resulted in compounded .smc files exported by subcontractors NCC collaborate with. Figure 3.4, 3.5 and 3.6 enlighten how this thesis took advantage of the information takeoff in Solibri and how a material quantity report were obtained.

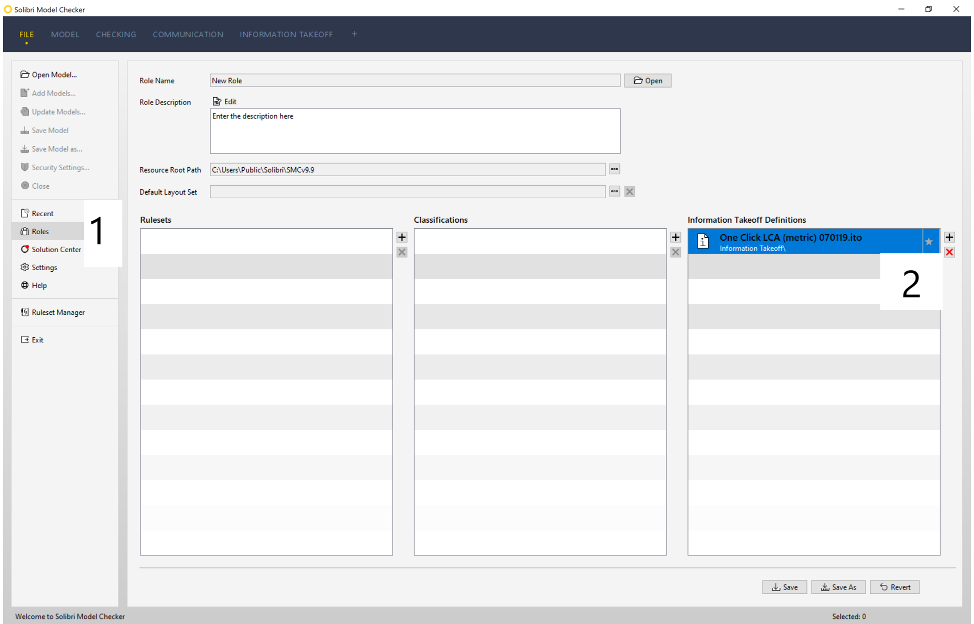

Figure 3.4: Solibri Model Checker step 1-3

1. The first step is to insert the template available on OCL's own website. By clicking onto "Roles" in the file tab in Solibri, one can retrieve the template named in Table 3.3. This template is crucial to use to get the right amount, units and the right material distribution in later stages in OCL.
2. Upload the saved .ITO file (template).
3. Go to the "information takeoff" tab. Now, there is no model displayed.

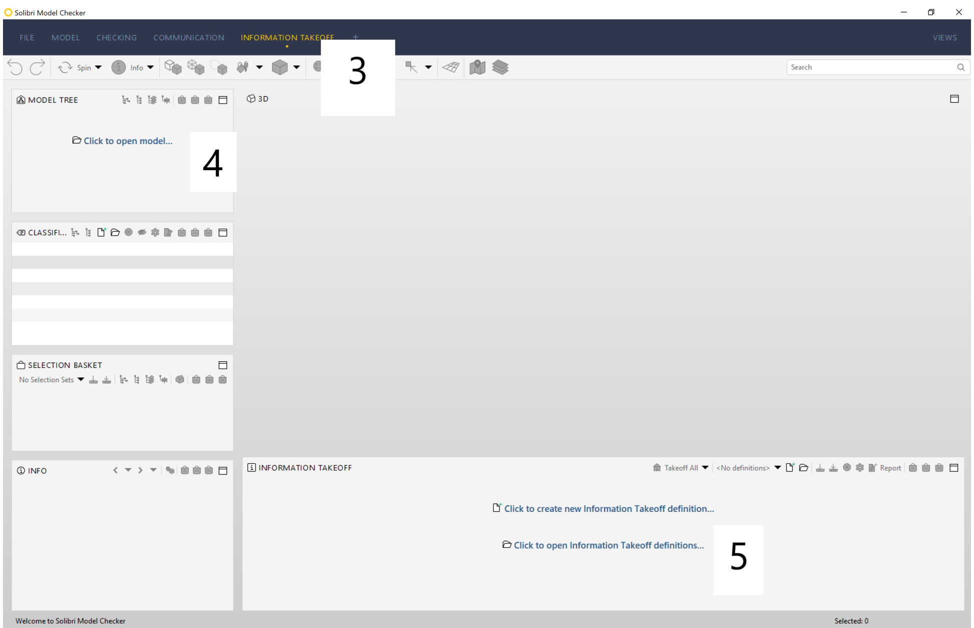

Figure 3.5: Solibri Model Checker step 4-5

4. Upload the .smc file obtained from the document review.
5. The takeoff definition is following the .ITO requirements.

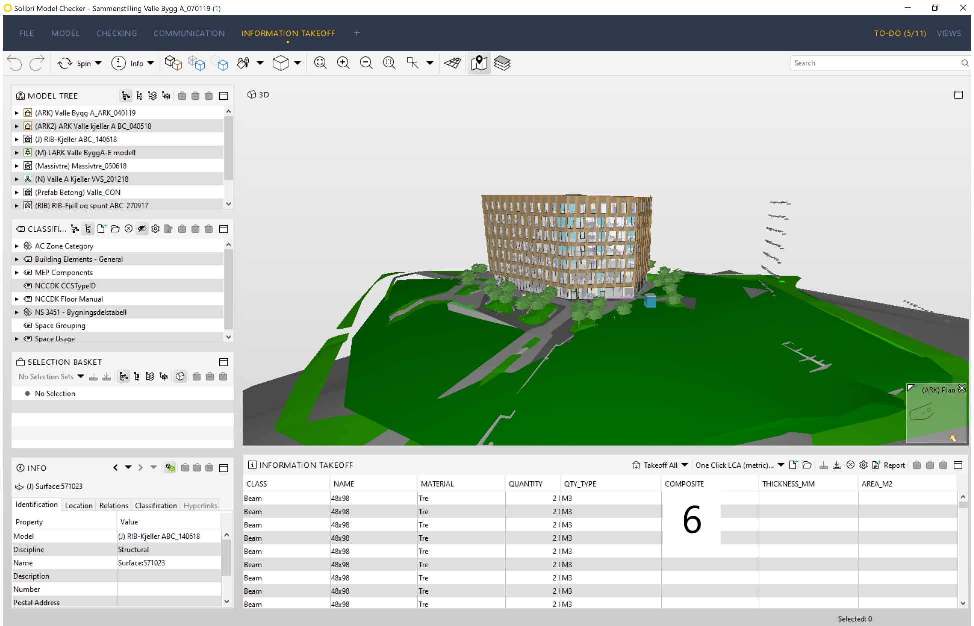

Figure 3.6: Solibri Model Checker step 6

6. The remaining is to take off all elements in the BIM. This is a time consuming process. The report is an MS Excel file.

The quantitative reports obtained from the BIM, is the LCI that is going to be used in the first three LCAs.

3.4 LCA

OCL is an online LCA application that require reports, such as a BIM model inventory file from either MS Excel or gbXML. It is possible to import files from IDA ICE, IES-VE, Tekla, ArchiCAD and DesignBuildiner, but this require further software integration setup (Bionova 2018b). Moreover, OCL has more features than the LCA study. The tool makes it possible to conduct life cycle costing (LCC), material and site tracking, climate resiliency, and services for environmental certification systems (BREEAM, HQE, DGNB, LEED, VERDE, BNB) (Bionova 2019a). The elaboration of the LCAs that use MS Excel reports from Solibri are explained in Figure 3.7 and 3.8. The LCA obtained from NCC, called final LCA (Figure 5.4), used empirical input data because the IFC convey objects to the information take-off reports that causes errors (Andersen 2019). According to Andersen (2019), the structural systems are better to analyze on empirical values, as they will save time compared to checking all objects from the IFC. This is shown in Figure 3.9 and explained shortly in item 7 and 8 below. Table 3.3 describes software features related to theoretical aspects in the LCA. This table is located at the end of this chapter.

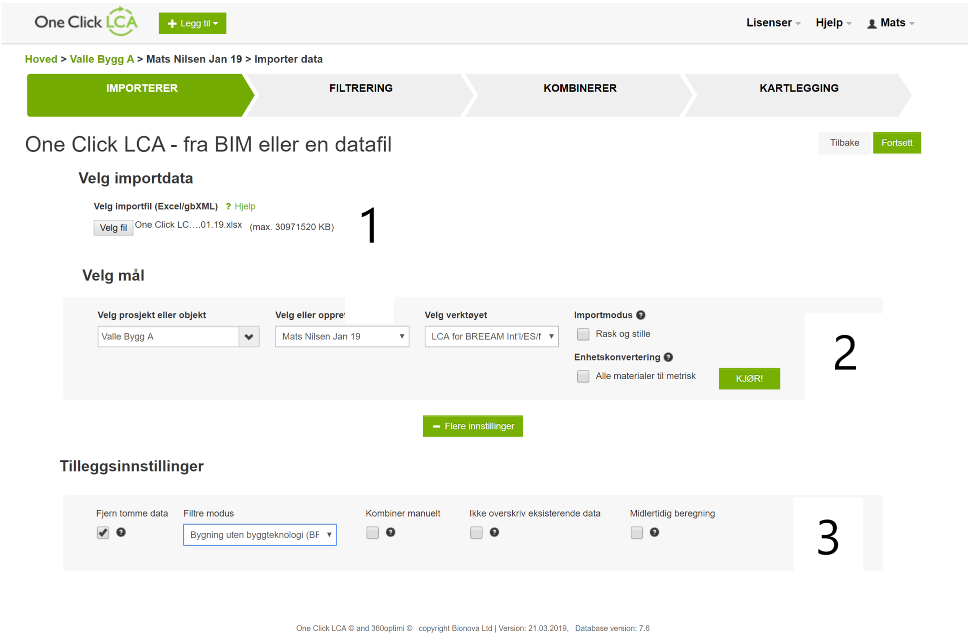

Figure 3.7: One Click LCA step 1-3

1. The first step is to upload the MS Excel file conducted from "information takeoff" in Solibri. The inventory data is structured as per NS-EN 3451 (chosen in Solibri), and systematized the results as per EN 15978. The LCA tool extracted information from the BIM-model and allocated it to available EPD (or other LCI databases), to calculate the LCA of Valle Wood. The disadvantage with this method is that each change in the BIM model implies a new independent LCA calculation, which is not a dynamic and smooth process (Durão et al. 2019).

2. Step 2 regards sorting the report so that it is aided for the correct project, namely Valle Wood.

3. This study exclude empty data in the MS Excel report, and do not consider building technology causing missing information and incomplete EPDs.

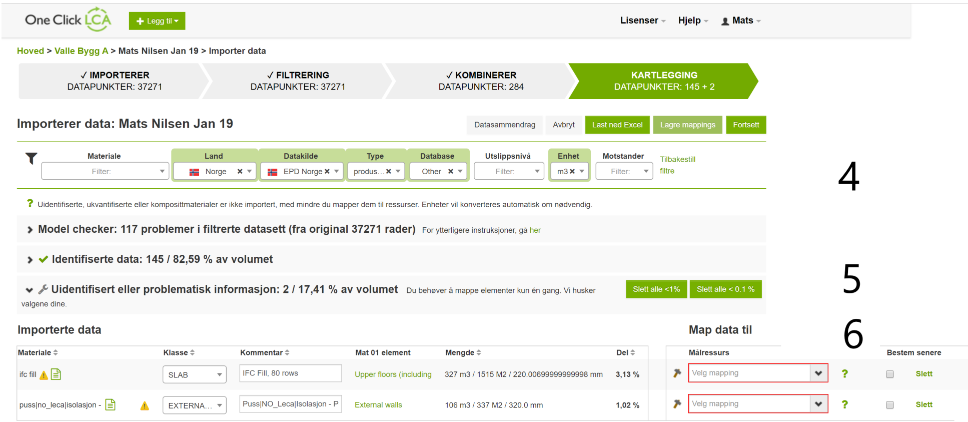

Figure 3.8: One Click LCA step 4-6

4. Step 4 is the filtering process. The material section is sorting the type of material in main groups like concrete, steel and wood.

   This study is located in Oslo (Norway) and EPD-Norway is therefore going to be the LCI database. It is possible to obtain LCI data from "Gabi" and "Ecoinvent", but this study only took advantage of, and evaluated the capability of EPDs.

   OCL gives options between generic LCI data or specific data from producers in the building industry. This step has a great impact on how representative the results can be. This means that not only the assessment taken into consideration of the material quantities, but also the type of material. This is due to the fact that products differ in environmental and economic impacts (Santos et al. 2019b). All LCA data is not stored in the BIM, which serve as a centralized data repository (Santos et al. 2019b). Consequently, this study is based on environmental data obtained from producers, and not generic data.

   The reference unit is m^3. OCL has no conversion factor which caused errors regarding the total volume accounted. The quality in the BIM-model has to be very precise to the geometry, otherwise the result would be incorrect.

5. The cut off criteria is data less than 1% of the volume. This percentage comprises mostly ifc-fill and undefined materials that is not recognizable. It was observed in the .smc file that these materials and fills consist of air and had random geometry and locations.

6. Where OCL did not recognized the materials, it was necessary to investigate this material in the Solibri-model. When knowing the material, it was easy to find an appropriate EPD to link the material to. The results are shown and discussed in Chapter 5.

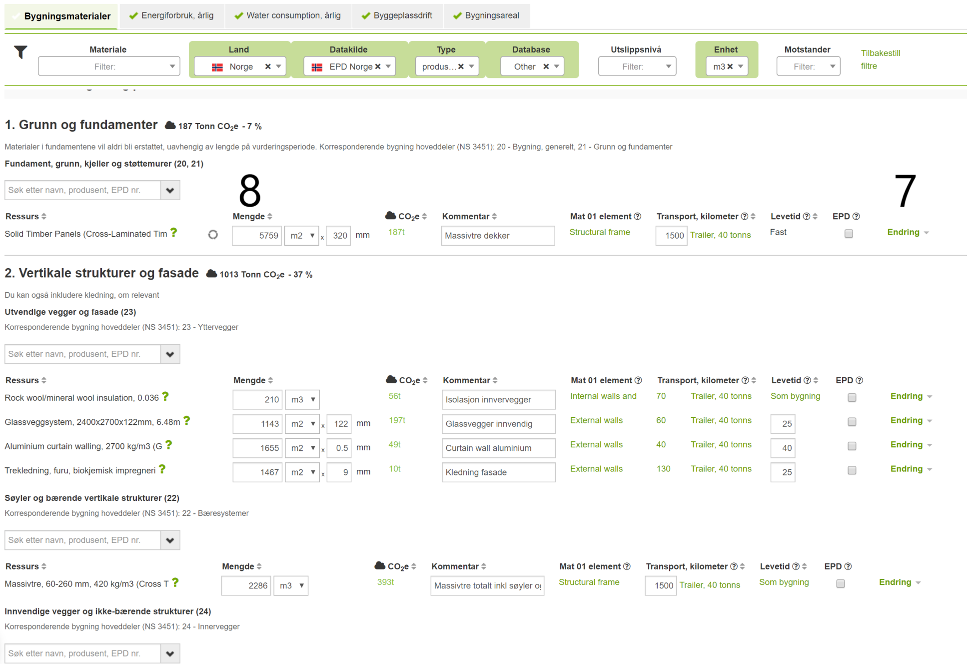

Figure 3.9: One Click LCA step 7-8, Final LCA

7. To manually influence the LCA result, one can either edit the material or delete it. Appendix E shows an example to the mismatch in BIM-LCA versus a traditional LCA. The traditional LCA is done when the quantity of materials from the BIM are replaced with values not taken from the information takeoff in the Solibri excel file.

8. Instead, NCC added known products by searching on EPDs or type of material. Appendix E shows an example of the different products and EPDs used. What this example demonstrates, is the automated connection of BIM objects and EPDs (left side), versus manually selected EPDs to the right type of products and correct amount of materials done by NCC (right side).

This master thesis' LCAs had no third party to verify the work. LCAs in OCL were accomplished by the author in corporation with NCC.

The low level of information in the geometry within the BIM objects present in the LCAs, brought this thesis invalid results (Figure 5.1, 5.2 and 5.3). The occurrences of mismatched materials in OCL compared to the reality, express low data quality. After the completeness check and consistency check, it was obvious that the BIM did not contain the environmental information inside the objects, nor the right type of materials.

Figure 5.4 and 5.5 show the complete LCA results in LOD 350 when the materials are changed to the right type and correct amount, based on both EPDs and empirical data (final LCA) (Ingvil Arntzen 2018).

3.5 Evaluation of the Methods Used

To assess the quality of the research, validity and reliability are relevant indicators. If the result from an exercise or study can be reproduced under a similar methodology, then the research instrument is considered to be reliable. And, if the data obtained is relevant for the study, then the validity is good (Golafshani 2003). However, both methods need to demonstrate that their studies are credible. In quantitative research, the credibility depends on instrument construction, while regarding the credibility in qualitative research, "the researcher is the instrument" (Golafshani 2003). Thus, when quantitative researchers speak of research validity and reliability, they are referring to an existing credible research, while the credibility of a qualitative research depends on the ability, suitability, objectivity and effort of the researcher. Triangulation is used to compensate for weaknesses in qualitative- and quantitative research methods (Olsson 2011). By combining different methods, it was easier to unveil errors, imperfections and biases. This helped to increase the credibility of the thesis' results.

According to Figure 3.10 obtained from Sander (2017), four scenarios are possible combinations of validity and reliability. In the case, the circular target in the middle of the "dartboard" represents the research questions.

"Reliable, not valid" are research methods that to not hit the heart of the study's aim, but repeated attempts get nearly the same, but wrong, results. "Low validity, low reliability" are not valid as the research method do not hit the heart of the research aim and the attempts are unfocused. "Not reliable, not valid" are illustrating a research method that hit the aim of the study fairly closely, but that is not reliable as repeated attempts have scattered results. "Both reliable and valid" are research methods that hit the heart of the research aim and every attempt ended up as similar results (Bolarinwa et al. 2015).

Figure 3.10: Reliability Versus Validity

3.5.1 Qualitative Research Assessment

In qualitative research, reliability and validity are assessed because these terms are conceptualized as trustworthiness, rigor and quality in qualitative paradigm (Golafshani 2003).

Reliability

A good qualitative study can help us understand a situation that would otherwise be enigmatic and confusing (Eisner 1991). During the literature review, knowledge was gained regarding environmental assessments and how designers measure the GWP and the environmental footprint of buildings. The same arguments and statements were found in articles where they referenced to the same sets of standards, which made the goal and scope reliable. The LCA methodology is widely spread and acknowledge in the literature. The case studies investigated in the literature had several approaches, and distinguished the possibilities in BIM and LCA separately. In addition, the case studies somehow combined the features of both to conclude with an efficient method to utilize an interaction between LCA and BIM in early design stages. As mentioned, literature review was the tool of this master thesis to obtain knowledge about the state of the art and best practise in the building industry nowadays. Due to the same findings in the literature world wide, and the use of the same theory, the literature review is found trustworthy and reliable on the basis of the high quality of acknowledge and recognized theory and methodology.

Transferable studies are credible as they examine both the process and the product of the research for consistency. The process in the literature review is shown in Figure 3.1 and the products (literature used) are listed in the way Figure 3.2 explains. This method of systematizing the products, highlights the transferability of the literature review.

The document review is neutral in the manner of directness into secret and private documents. Through these documents the master thesis gained essential materials for investigation and assessments. This is due to the fact that these documents helped answering the thesis' research questions, and assessing the environmental issues in the building industry, to a large extent. The confirmability of these neutral documents by one of the biggest prosecutors in the building industry in Norway, outline the reliability of the private documents. These documents are made by experts with broad experience (Andersen 2019).

Validity

"There can be no validity without reliability, a demonstration of the former (validity) is sufficient to establish the latter (reliability)" (Lincoln 1985).

Exploring subjectivity and reflexivity in the literature, forms a basis to tell if the qualitative research is covered with high quality, validity and rigor. Reviewed papers were preferred as they contain a comprehensive discussion of the literature published, and they decreases the issues regarding bias from the authors. The more reflective the literature is, the more suitable it is for this thesis purpose. Proposed authors from the supervisor to the author of this thesis, were given to increase the quality of the literature in the beginning of the literature review process (forward snowballing) (Bohne 2019). The impact factor were diligently used when evaluating the quality and the credibility of the journal the article or paper were derived from. Journal impact factor is "a measure of the frequency with which the average article in a journal has been cited in a particular year. It is used to measure the importance or rank of a journal by calculating the times it's articles are cited" (UIC 2016).

By "snowballing" throughout the reference lists from high quality papers, it was straightforward to substantiate the different claims in the literature regarding the research questions.

3.5.2 Quantitative Research Assessment

"Terminology that encompasses both reliability and validity, such as trustworthiness and transferability are terms that matches quantitative research methods in the way they weighting precision in the research higher than the relevance" (Golafshani 2003).

Reliability

When evaluating the reliability of the quantitative research methods used, it is important to have in mind that the case study can be divided into two main parts. The first part comprises three LCAs, see Figure 5.1, 5.2 and 5.3, that use quantity take-offs generated by BIM, with an LCA database to obtain environmental impacts. No modifications are done regards product exchange. The second part is the *final LCA* conducted with empirical values (see Figure 5.4). This part is based on familiar products that NCC have knowledge about. This method of doing LCA is time consuming. The final LCA utilizes BIM to withdraw measurements, but do not rely on the quantity take-off.

The first part is very reliable and trustworthy. This is due to the fact that the results can easily be repeated when having the same .smc file and doing the same cut-off criteria as this thesis does. The template is universal for all .smc file that intends to use OCL to assess the environmental impact of a building. Using the same specifications as Figure 3.4 to Figure 3.9 describe, as well as Table 3.3, there is no doubt that the same result will occur. Since the .smc file remain the same after designers have saved it and exported the file into the PortWise Access Manager 4.12, there is not an ongoing environmental assessment. When further developing the .smc file, the output will change, and the LOD will increase respectively, as the model become more detailed.

On the other hand, the reliability in the second part is low. The unit conversion factor is absent in OCL. Andersen (2019) states that their method of doing cost estimates, and Norwegian standards, require different units than cubic meters which is this study's reference unit. Furthermore, Andersen argues that the misunderstanding between NCC' cost calculations and model designers, differ in the amount of materials regarding national building requirements. Consequently, the BIM model causes error regarding the quantity of materials. The building materials that accounted for the maturity of the volume, were therefore calculated with empirical values. How to reproduce the same output in this case, based on the foregoing discussion, is therefore uncertain. In addition, the reliability is limited regarding access into the documents (in Portwise Access Manager) and personal communication with people who are working on the project.

The data quality is reliable as this study is based on EPD-Norway as the LCI database. The comprehensive EPD program in Figure 2.12 and the national and international standards that shall ensure the high quality of any EPD and PCR, are considered trustworthy.

Validity

Validity in quantitative research determines whether the research truly measures what it was intended to measure, or how truthful the research results are (Joppe 2000). In the case study of Valle Wood, the system boundary and the functional unit are well defined, which led to valid results. OCL separated life cycle construction work categories that simplified the orientation of the results into A1-A3 and kg CO_2-eq emission as Figure 5.6 illustrates. There was a continuous reduction in the GWP from LOD 200 to LOD 350, which supported the quantitative hypothesis of a more reliable LCA. The more detailed the BIM model became, the more accurate data acquisition appeared in the LCI (see Chapter 5). As this master thesis only consider one case, it is difficult to compare the GWP to other BREEAM buildings. This makes the validity of the research results less truthful. Moreover, directly data acquisition from the BIM-model was checked and considered not reliable, and therefore the LCI was reassessed in the final LCA. This use of triangulation unveiled unreliable data compared to the actual materials that was going to be used.

Yin (2014) argue that there are three tactics to increase validity when doing case studies. The first tactic is the use of multiple sources of evidence during data collection. The LCI in the first part of the case study was retrieved from the BIM model, which was found with low level of information, and later LCI obtained from empirical measurements. Commonly, the numbers used in calculation (LCIA stage), are all obtained from EPDs, which can be found trustworthy as this is the intended method for this particular LCA database. The only difference is the source of material acquisition. The second tactic by Yin (2014) is to establish a chain of evidence. The evidence to the error in material acquisition is observed when it was used concrete instead of timber in a building project that was going to be built in timber as the dominating building material. In addition to invalid building materials, there was observed unreliable quantity of materials (see Appendix E). The third tactic is to have the draft case study report reviewed by key informants (Yin 2014). Related to this master thesis, these informants are people in NCC that said the right amount in building materials are given in the final LCA (Ingvil Arntzen 2018). After discussing the LCA results from the first part in the interpretation phase, the results were stated not trustworthy. This helped the writer of the thesis to reconsider the output, and investigate how an LCA could be done in OCL properly. The final LCA is the product from the first part's unreliable results, which is presented in Chapter 5.

The next chapter will be informative about this master thesis' case, Valle Wood.

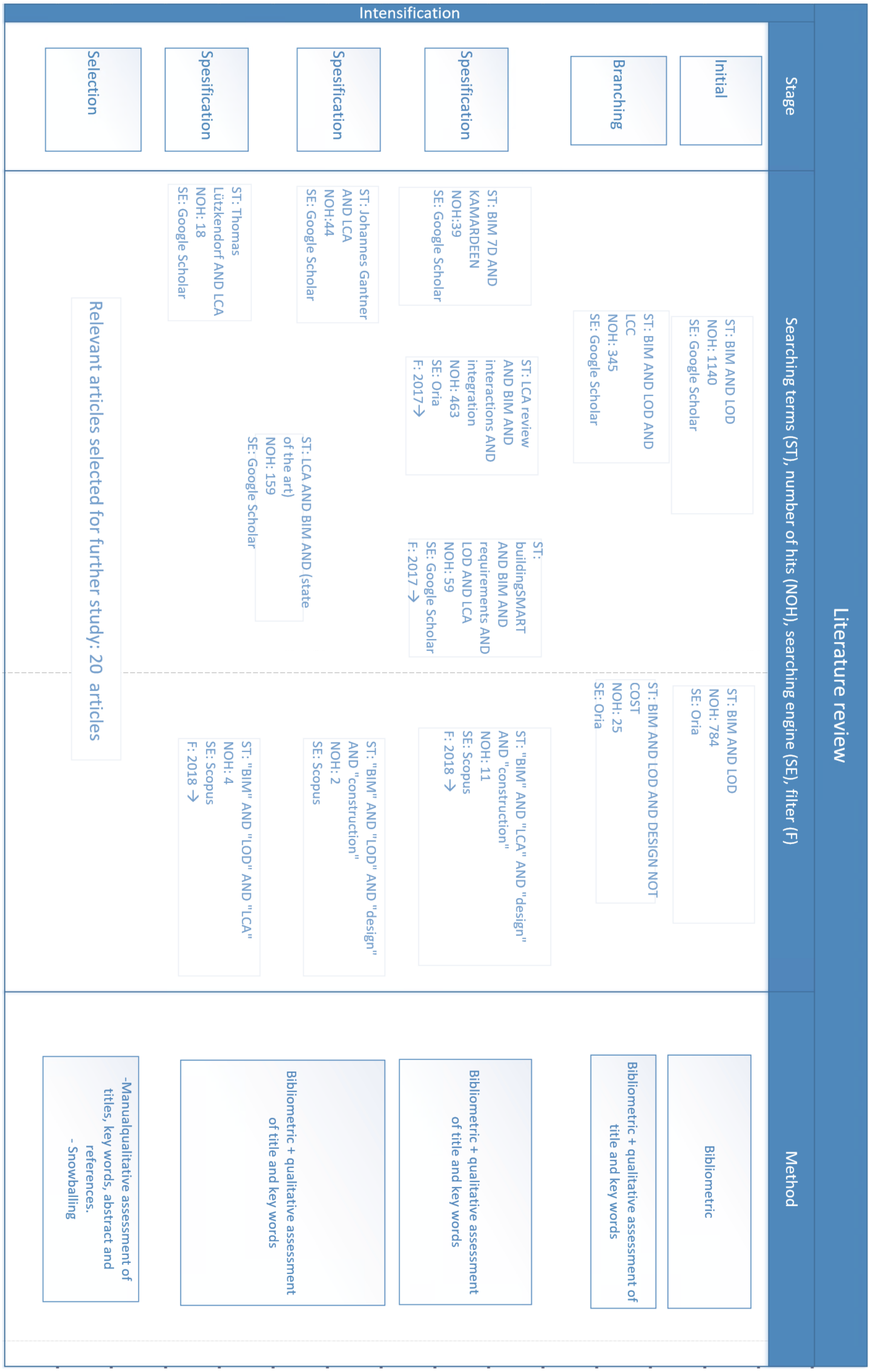

Figure 3.1: Search procedure

Table 3.3: LCA methodology in One Click LCA

	LCA methodology and assumptions made in One Click LCA
Goal and scope definition	Evaluate the GWP caused by Valle Wood using OCL.
Functional Unit (FU)	FU of this LCA is Kg $CO_2 - eq$ emission per material. The reference unit is m^3. Other units like kg, kW, kWh, l m and m^2 could have been applied, but OCL do not possess a unit conversion factor.
Temporal- and geographical scope	OCL execute a static LCA model. It is possible to setup the service of the materials that would be preferable to include. This will have an impact on B4-B5 (Replacements) during the building life cycle and impacts associated with B6-B7 are introduced on an annual basis. At the moment OCL do not allow changes to the energy mix as this is not allowed in the standards OCL follow. Operating variables do not affect the inventory of the system. Nevertheless - this is out of the scope of the study, and mitigate the potential downsides in terms of only gather LCI data to unit processes (O'Connor, Garnier, and Batchelor 2013). The time period covered in this LCA is updates in the BIM model as per December 2018 (Bionova 2019c). Geographical scope is Oslo, Norway.
Technology coverage	The tool utilized is LCA for BREEAM NOR. The template used to export and structure information from Solibri is "One Click LCA (metric).ITO".
Change-oriented LCA	This is a change-oriented LCA that comparing three BIM models (three LOD levels), up against a modified and reliable LCA at a correct LOD 350.
Intended application	This is a LCA that can be applied to different situations; BIM-model improvement, strategic planning and public decision making.
System boundary	Consider embodied emission, cradle to gate, A1-A3 as this contribute the most to GWP.
LCI analysis and data collection	MS Excel file that imported materials from the BIM (.smc file) and grouped them based on 5 criteria: CLASS: values have to be one of the listed ones in exactly the same format (sorted in .ITO template used in information takeoff in Solibri). IFC-MATERIAL: Use the distinguishable material name to map the material to the label in the tool. Mapping is based on CLASS and IFC-MATERIAL combination. For material label, the database is EPD-Norway. When importing it for the first time, one can teach it to the tool and it will be automatically recognized in the future. QUANTITY: Number, comma as decimal separator. QTY-TYPE: Units. TRANSPORT-KM: Transport distance in km from manufacturer site to the building site (optional, can also be added later in the query).
Data quality	Cut-off criteria to this LCA is materials $< 1\%$ of the volume. Also, OCL's category 6, Building Technology, is out of the scope. The cut-off lead to the fallacy of disaggregation by splitting up processes which lower the data quality and putting flows explicitly to zero (Guinée 2002). The cut-offs are related to undefined objects from the BIM model. Data information included are obtained from EPDs witch follows the same sets of standards (see Appendix F and G).
Impact assessment (LCIA)	The impact category is global warming, characterized as per CML-IA 2012 methodology, required by EN 15978 and EN 15804 (Bionova 2019b).
Interpretation	OCL is an transparent analysis as the tool is online and can be easily modified. As this features, this assessment is also a comparative analysis in the way the assessments comparing four alternatives to which performance at different LOD.

Chapter 4: Case: Valle Wood

"Valle Wood is going to be Norway's largest commercial building in cross laminated timber. The material choice will give a natural Nordic feel that establishes an identity for the building itself and the surrounding area. The buildings will be certified in accordance with BREEAM, the world's most demanding environmental certification system, which takes a holistic view of the building's entire ecocycle. Work started in 2017, and Valle Wood will be ready early 2019. Inside Valle Wood, the plan is to create a different office concept, with space for co-working and start-ups, plus meeting rooms, conference facilities and various catering and service provision" (NCC 2017)

Figure 4.1: Valle Wood

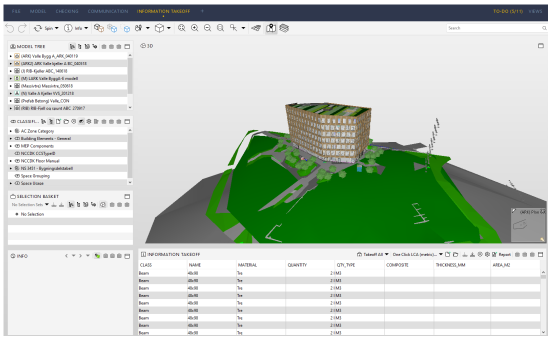

Figure 4.2: Valle Wood in Solibri Model Checker

Valle Wood is located in Oslo near Helsfyr. This area of Oslo has one of the city's largest public transport hubs, as well as modern cycle paths. Valle Wood covers the first phase of the project. This phase is 6700 m^2, and the total site is going to be 60000 m^2 including all five phases. NCC Building is executing the project in the form of a Integrated Project Delivery (IPD) contract with NCC Property Development, which is the client to the office buildings (NCC 2017). The contract between the project owner, NCC Property Development, and NCC Building is estimated to be 190 MNOK for the first phase.

Chapter 5: Results and Discussion

This chapter is divided into three main parts that answer the research questions of this master thesis. Along with the results, it will be discussed how the results correspond to each other. In addition, Section 5.4 summarizes the most important findings related to the research questions.

1. Results from the literature review are presented in Section 5.1. This part covers how environmental assessments are treated in a building project. Research question 1 and 2, based on findings in Chapter 2, will be discussed.
2. Results retrieved from OCL of Valle Wood in different LOD levels, limited to embodied emissions demand from A1-A3 are given in Section 5.2. This part is supplementing research question 2 and will be viewed as a precursor to research question 3.
3. Purposed LOD framework and milestones within the early design stages, based on literature reviews, earlier proposals and OCL's layout. This proposal is presented in Section 5.3. Research question 3 is enveloped in this part.

5.1 Environmental Assessments in Building Projects

The environmental assessments in a building project are using LCA methodology to calculate environmental impacts. An LCA is normally conducted when the building is built, namely complete LCA, to satisfy green building rating systems. Moreover, the conduction of LCA requires information of the inventory. The most time-consuming aspect of the LCA methodology is the LCI phase and the compilation of a detailed bill of quantities. To minimize the time in this phase, it would be necessary to adopt environmental data input into the building elements within the BIM. If all the inventory and the environmental impact is connected to the geometry, then the LCA would be integrated into the design process. The additional effort and time-investment for learning and applying an IDM tool, can accordingly be kept to a minimum. A solution to this, which is well employed in the industry today, is adapting OCL in the early stages. The disadvantage to this is that once the architect or engineers make changes in the BIM model, there is a need for a re-assessment in the LCA-tool. The re-assessment includes the modifications in the BIM model for retrieval of new results. This would again be time-consuming and the environmental issues struggle to get attention when decisions have to be done quickly.

The LCA methodology is widely accepted and an ongoing development in different LCA software is present today. The LCA methodology recognizes possibilities that help to reduce energy and resource consumption of building materials. Environmental assessment is today present using

LCA software at final stages of the building project, but there are trends and studies that intend to include LCA in earlier stages (before LOD 350). In early design stages, it is important to be devoted to the system boundary stated in the goal and scope definition phase. This is due to not increase the environmental impacts. Therefore, the same system boundary should be stated at the very beginning of a building project. The iterative loops during goal and scope definition, inventory data and impact assessment (Figure 2.13 and 2.16) are held to a minimum by clearly stating the system boundary at early stages.

Screening and simplified LCAs are developing, as well as the uncertainty can be reduced by being consistent to the goal and scope definitions. LCI databases like EPD-Norway can be used to evaluate the impact assessment, but whereas there is no information related to materials or products, average or most likely values, can be adapted into the LCA. In addition, Monte Carlo simulations can be employed in low LOD levels where the lack of LCIA information is present. This will decrease the uncertainty in the LCA at early design stages. Using maximum and minimum values, obtained from LCI databases, will display the range of options available regarding environmental impacts.

Statements in the literature argues that 60-70% of the time at the beginning of the project is used inefficiently. Hence, the large amount of work used inefficiently reflects the importance of a systematized LOD framework in a building project. In terms of evaluating the complexity of decisions facing designers performing LCAs, the feedback provided in the LCA can be traced to which LOD level that was the most time-consuming stage. Comparing Figure 2.19 and Figure 2.20, there is clearly space for improvement in conducting screening LCAs at the very early stage. As mentioned, the meaning of environmental assessment participation in early design is to test several design solutions, and to choose the most appropriate design that satisfies environmentally requirements, as well as the structural and architectural design.

There are three main approaches to BIM-LCA integration in early design stages:

1. Conduction of LCAs using several programs: BIM is not able to act as the sole software to conduct LCAs. It is required plug-ins and input as environmental data.

2. Quantity take-off generated by BIM with an LCA database to obtain environmental impacts: Using features in BIM and LCA for data acquisition in the LCA software retrieved from the BIM model is possible. OCL possess this feature.

3. Inclusion of LCA information in BIM: adapt environmental data input into the building elements within the BIM.

The interaction of BIM-LCA is utilized in several ways. Table 2.10 shows studies that have used several programs and LCIA databases to conduct LCAs at different stages. Moreover, the studies in the same table have developed their own workflow with the use of different tools. Some studies also take advantage of LOD implementation. In spite of several attempts, there is clearly a missing linkage of different databases, automatized design and impact calculation. BIM-LCA integration needs more development. One can also find different BIM-embedded life cycle and optimization approaches in the studies in Table 2.10. One of the most common findings in the studies is the absence of appropriate information to make critical decisions, due to the lack of collaboration, information exchange, LOD in the BIM model, LCI databases with respect to environmental impact and different tools used.

To improve the screening LCA at the early design stage, there is clearly a need for more information regarding all building components that are limited at this stage, or distinguish which building material(s) that should dominate in the pre-design. This requires more effort related to modelling and collection of data required in the LCIA. A screening LCA can be used for an initial LCA, before there is added more information into the materials in later advanced stages, such as simplified LCA. The complete LCA study corresponds to the framework proposed in ISO 14040 and ISO 14044. This is due to known materials and defined boundary in final stages of a building project. At the final stages, decisions are taken and the LCA is considered well defined. This explains the mismatch between the second and third approach. The advantage of the third approach, is since the BIM can be used as a data repository of transfer formats, it is allowing adjustments in the properties of BIM objects for future users. Hence, quick updates can be present during the entire early design phase, namely stages before construction starts. Moreover, the first and second approach do not support such integration. In opposite to the first and second approach, the third approach require re-export of materials' quantities and re-link the BIM materials with the materials inside the LCA database. The first and second approach are best practice to evaluate the environmental impacts in building projects today.

5.2 LCA of Valle Wood

The quantity takeoff information for building materials provided by Solibri Model Checker is obtained in units of volume. The mismatch between the properties in the smc files, quantity takeoff information, and OCL screening method, provides errors regarding the actual amount of materials and due to dissimilar products and EPDs. The MS Excel upload purely contains the information from the .smc file, but it is structured in a way so that the MS Excel can be read by OCL. When this occurs, a unit conversion factor is needed to evaluate the embodied environmental impacts. OCL does not possess this feature, which leads to heavier workload on the LCA performance in early design. An example can be incomplete design by architects that ignore specific requirements, regarding fire or lighting in the BIM.

Two methods are used to compile LCA in OCL. The first method is executed in Subsection 5.2.1, and the second method is performed in Subsection 5.2.2.

5.2.1 LCAs Using Quantity Take-Off Generated by BIM With EPD-Norway as the LCA Database to Obtain Environmental Impact in OCL

Figure 5.1, 5.2 and 5.3 show LCA results from OCL when the quantity take-off in Solibri Model Checker was used to generate the LCI report that was attached to EPDs in OCL.

The main contributors to GWP in all these designs are *horizontal structures* and *other structures*. Metals and concrete are the materials with the highest impact on the environment. Despite the fact that steel and concrete are the materials responsible for the high GHG emission, a reduction of 75% between LOD 200 (Figure 5.1) and LOD 350 (Figure 5.3) is present. The different BIM models (Figure D.1, D.2 and D.3) express maturity in the design. The absence of data information through the transitional process into OCL, initiated unreliable results.

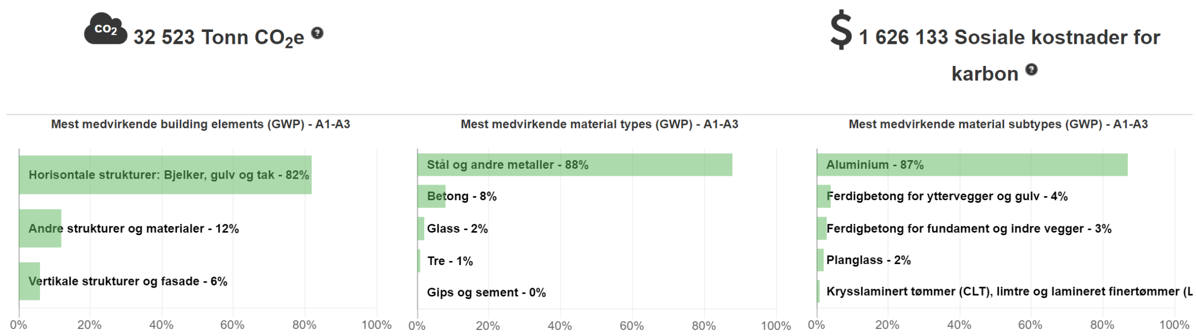

Figure 5.1: Total GWP A1-A3. February 2017. LOD 200

Figure 5.1 indicates a low level of information in the BIM object, as the GHG emission is calculated to be more than 32000 tons of $CO_2 - eq$. Valle Wood, which is presented in Chapter 4, is going to be built in cross laminated timber, which is not the case illustrated in February 2017 (LOD 200). Only 1% of the materials are timber. In low LOD levels, there is not a requirement to specify the type of materials, and because of the low level of information inside the BIM object, the design has not distinguished the environmental and material properties. Default settings were probably sat to materials during the early design process in BIM.

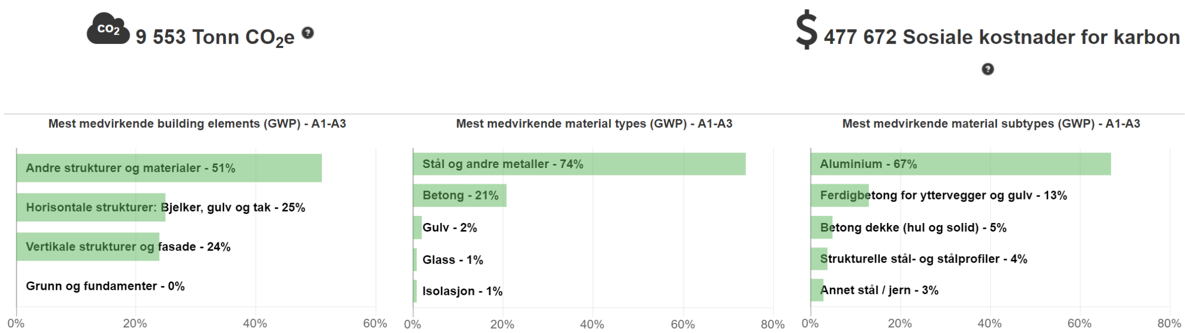

Figure 5.2: Total GWP A1-A3. July 2018. LOD 300

At LOD 300, the materials are not yet in accordance with the project description. Steel and concrete are still dominating the design, and no timber is contributing to the design, which contradicts to the information in the BIM model (Figure D.2), and the project description.

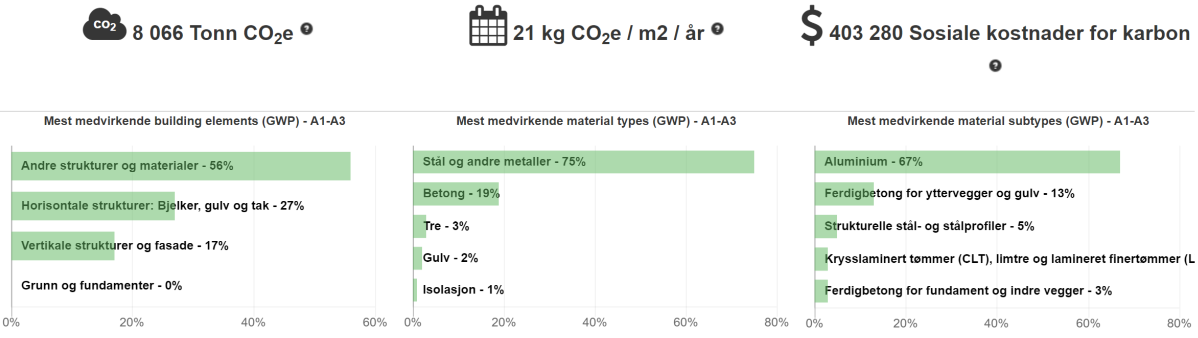

Figure 5.3: Total GWP A1-A3. December 2018. LOD 350

At LOD 350, literature state that the BIM model should contain all relevant information to be environmentally assessed, but as one can see from Figure 5.3, essential data elements are missing. This leads to errors that do not correspond to the reality of materials that should have been in the LCA. Despite the great improvement in GHG emission, the LCA is not reliable as the material distribution differs from the project description. In addition, the number of materials in OCL are incorrect compared to the BIM model in Solibri Model Checker.

5.2.2 Final LCA Conducted With Empirical Values

Instead of improving the quantity take-off generated by Solibri and the transitional format (.ITO template), empirical values were added in OCL to calculate a correct value for the GHG emissions, with the right quantity for the right type of materials. This is shown in Figure 5.4, 5.5 and 5.6. Here, 42% of the material contribution is timber, which is reliable at LOD 350, as well as it is in accordance to the project description. Figure 5.5 and 5.6 can be found at the end of this chapter.

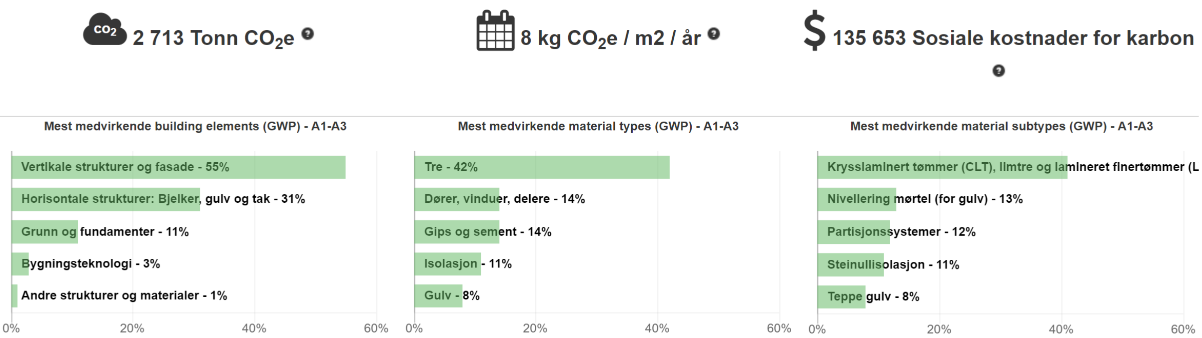

Figure 5.4: Total GWP A1-A3. Final LCA. LOD 350

The great reduction in GHG emission was calculated with the right type of materials, linked to the right EPD, which resulted in 2700 Tons of $CO_2 - eq$. This is an improvement of 66%

within the same LOD level (LOD 350). The measurements and units were obtained from the BIM model without utilizing the quantity take-off generated by Solibri Model Checker at LOD 350 (Figure D.3 in Appendix D).

5.3 Suggested Use of LOD in a BIM Environment With Respect to LCA Application

To support an efficient and user-friendly LCA application in early design which can last for the entire lifespan of a building project, strategies for simplification in BIM-based LCAs have been proposed by several parties (see Table 2.10). The common knowledge gap in the proposals is the need for an envelope that deprives BIM to carry out an LCA single-handily.

However, LCA is a data-intensive methodology and require a high level of information, especially for the assessment of building materials' embodied impacts. Therefore, a framework for the information needed throughout the early design phase with respect to LOD stages, is crucial to implement in the BIM-LCA development. To enhance the interpretation phase of the LCA methodology in low LOD, it may be useful to focus on the simplified LCA results to provide enough support for the decision-making processes by the AEC professionals. This simplification can be done by considering a decreasing aggregation of the sustainable information available. This can be done by weight single scores for lower LOD, and dis-aggregate this for higher LOD.

5.3.1 Using LOD as the Direction-Setting Process in OCL

To minimize the carbon footprint, the writer of this thesis believe that early design delivery phases can help the efficiency and the automated work regarding LCAs. By using LOD as the direction-setting process in LCA, the more environmental attention is given to the design, and the GHG emission is considered as a determining factor through decisions. This approach and proposal desires to connect AEC professionals and designers to deal with the issues through BIM-based LCA in the early design stages (low LOD), where the influence to alter the functionality of the building is high and the costs are low.

The proposal of this thesis is to establish an environment that considers LOD requirements and the LCA application, OCL, to compose a framework in the early design stage in a production stage perspective. The following discusses the method proposed.

The capability of IFC's layered data structure, which has different objects with different level of details for the representation of information, should be specific with regards to MVD and BCF standards before heading to a higher LOD level. The IFC consist of two distinct advantages of a standardized LOD related to the embodiment of an LCA:

1. IFC files can be imported into LCA analysis tools from any BIM authoring tools, without performing further data manipulation for mapping imported data to the used LCI database.

2. More realistic and concise results can be achieved by choosing a proper LCI database and a LCA calculation method, with respect to LOD of the elements contained in a BIM model.

A BIM model is a comprehensive collection of objects that are rich in information. An LCA is a set of unit processes that are linked with each other using flows. A unit process is the smallest element considered in the LCI for which input and output are quantified. It is by this required to link object in the BIM to LCI database using flows. Therefore, it can be hard for designers to handle several unit processes at a time. Henceforth, this proposal allow to break down this information into manageable and logical groups according to NS 3451 building table of building elements and OCL main distribution of building elements (Table 5.2 and Figure 5.7). This approach is based on the level of LOD and different sources to LCI.

1. Definition of an evolution of LOD: The definition of element categories is the Norwegian Standard NS 3451 shown in Table 5.1. The definition of early design phase that appear as project delivery phases in this case are shown in Table 5.3. OCL's own element category sat in the context of LOD requirements is shown in Figure 5.8.

2. Consistent combination of LCA databases: EPDs are the determined LCI database. At lower LOD, where materials is not decided, generic databases to find average, mean, min/max, and/or most likely values has to be used (see Table 5.4 and Figure 5.9).

3. Link between LOD levels and LCA databases: At LOD 400, the exact quantities of each materials are known and product specific values as EPDs can be used.

Table 5.1: NS 3451 - Table of building elements

NS 3451 - Table of Building Elements	
1 digit building element	**2 digits building element**
2 - Building	20 - Building in general 21 - Ground and foundation 22 - Structural system 23 - External walls 24 - Interior walls 25 - Slab 26 - Roof 27 - Building inventory 28 - Stairs and balcony 29 - Other building related parts
3 - Plumbing installations	30-39: out of scope of this study
4 - Electrical Power	40-49: out of scope of this study
5 - Telecom and automation	50-59: out of scope of this study
6 - Other installations	60-69: out of scope of this study
7 - Outdoor area	70-79: out of scope of this study

Table 5.2: Construction categories divided with respect to LOD and its milestones

Construction categories divided with respect to LOD		
OCL main distributions	**NS 3451**	**LOD**
1) Ground and foundation	20	100
	21	150
2) Vertical structures and facade	22	175
	23	175
	24	175
3) Horizontal structures	25	175
	26	200
4) Other structures and materials	27	300
	27	300
	29	350
6) Building technology	3	350
	4	350
	5	350
	6	400
5) Outdoor area and elements on site	7	400

The table of building elements, Table. 5.1, is the base of the following LOD framework suggestion along with the distribution OCL has defined (found in Table 5.3). By merging those tables, Table 5.2 arises. The evolution in LOD milestones with respect to OCL's elements can be seen in Figure 5.7.

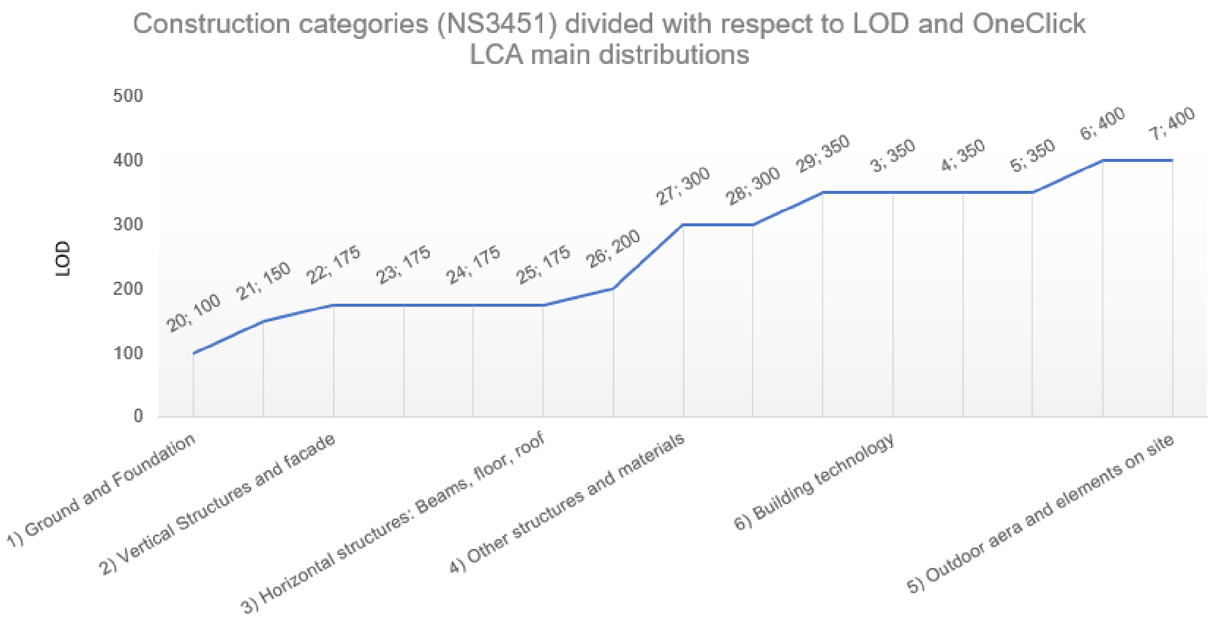

Figure 5.7: Construction categories with respect to OCL distribution

Now, milestones to which LOD levels construction categories have to be developed in the BIM are expressed. The remaining is to systematize to which early design phase (or project delivery phase) that represents the different LOD levels. Table 5.3 and Figure 5.8 shows this evolution.

Table 5.3: LOD with respect to design phases and OCL's own category distribution

LOD criteria with respect to design phases		OCL distributions
150	Pre-design	1) Ground and foundation
175	Concept design	2) Vertical structures and facade
200	Developed design	3) Horizontal structures: beams, floor, roof
350	Building permit	4) Other structures and materials
400	Technical elaboration	6) Building technology
400	Construction	5) Outdoor area and elements on site

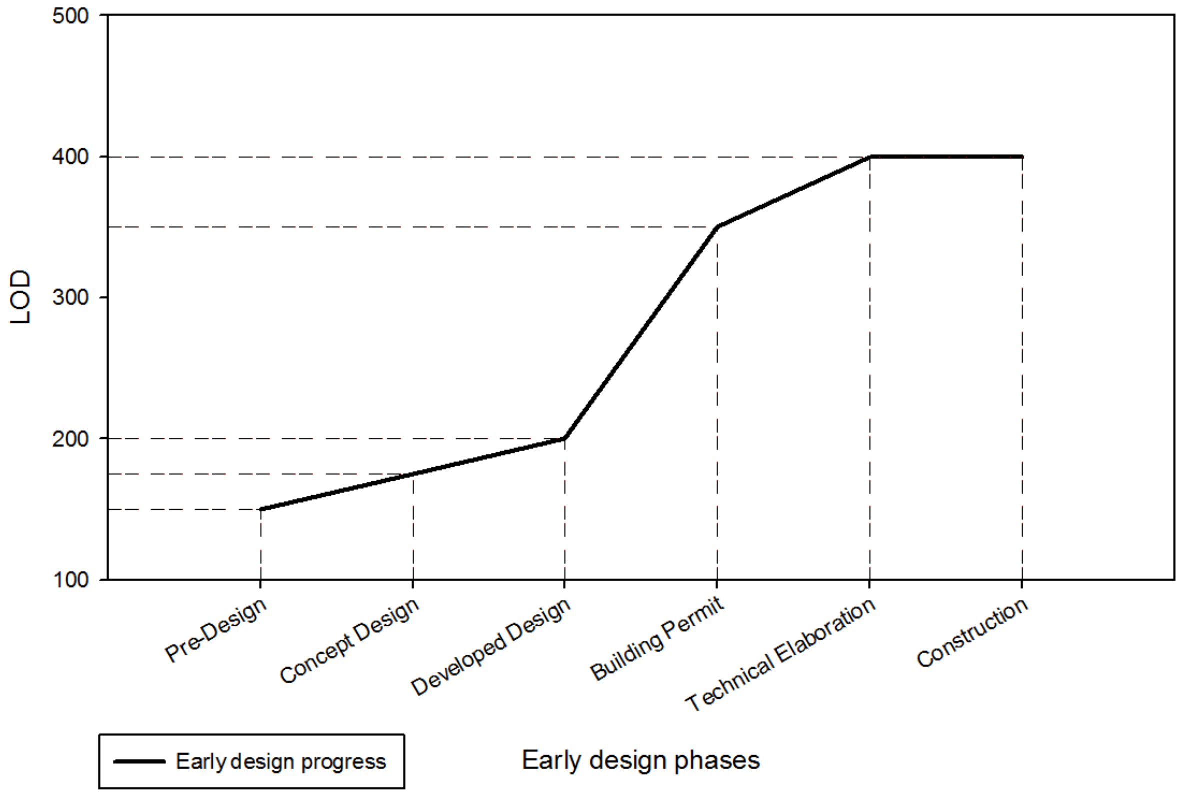

Figure 5.8: Design phase evolution according to LOD

A comprehensive LCA is to be done at LOD 350, building permit stage. By this stage, the major elements are stated, and 80% of the 3, 4, 5, 6 and 7 categories (see Table 5.1 and Figure 5.9) are agreed upon. The building can be stated complete in the BIM, apart from the uncertainty in the empirical, min/max or most likely values in the 80% of LOD 400 posts according to Table 5.4. Generic LCA databases can be used to obtain LCIA data when the BIM is incomplete. Another source to most likely values is considering conservative EPDs. An example of conservative EPD can be concrete instead of cross laminated timber. When assessing both cross laminated timber and concrete, designer can notice the range of impacts and assist them throughout the decision making process.

At technical elaboration, the BIM represents LOD 400, and the environmental impacts are assessed on equal terms as the structural design issues. EPDs are the dominated LCIA database at LOD 400. Environmental impacts on different products are various, and therefore should EPDs represent the specific brand of the selected material. This will lower the uncertainty in the complete LCA. By using endpoint indicators instead of midpoint indicators in the low LOD LCAs, it would simplify the results and turn the interpretation phase into a more understandable phase for AEC professionals.

Table 5.4: Level of completeness and LCIA databases

LOD	NS 345 (1 digit)	% of LOD 400	LCIA database for building elements
LOD 200	2	80	Average values, mean values, min/max values, most likely value
	3, 4, 5, 6	50	
	7	10	
LOD 350	2	100	EPD-Norway
	3, 4, 5, 6	80	Average values, mean values, min/max values, most likely value
	7	80	
LOD 400	2	100	EPD-Norway
	3, 4, 5, 6	100	
	7	100	

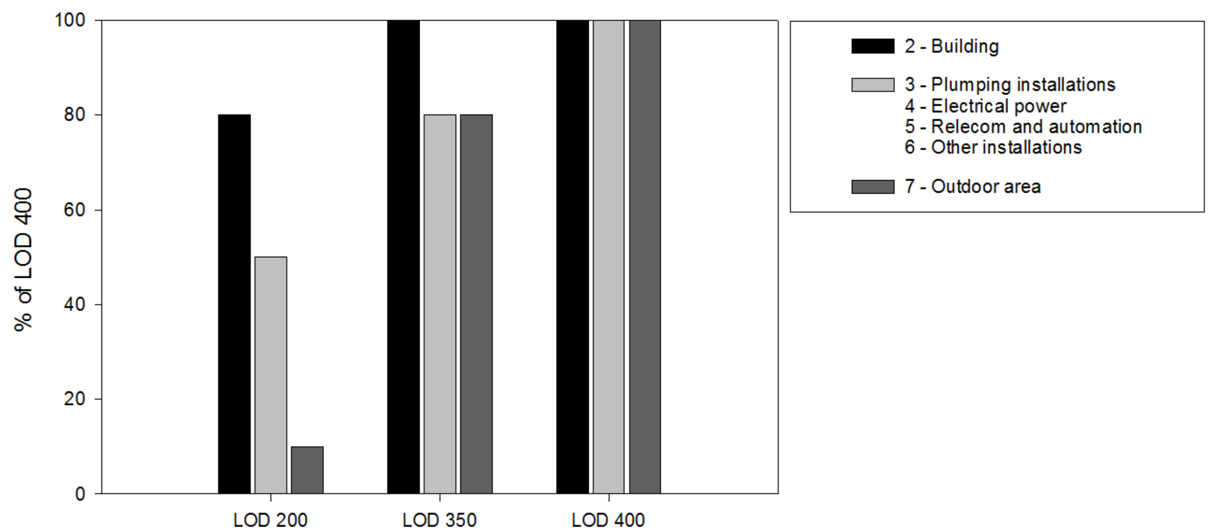

Figure 5.9: Degree of completeness in different stages of LOD

Components regarding building manner should be given important effort in LOD 200, while plumping, electrical, telecom and automation and other installations are usually depending on the architectural design as Figure 5.9 shows. The building components are 80% completed at LOD 200. This is due to unpredictable issues regarding clash detection and if building elements within 3, 4, 5 or 6 categories are determinate. At LOD 350, building components is fixed as these components are the major contributors to GWP (Figure 5.1, 5.2, 5.3, 5.4 and 5.5). In addition, the building components determines the structural design of buildings. By clearly state these materials in LOD 350, than the majority of building materials can be assessed with high accuracy.

5.4 The Results and Discussion Chapter's Answers To the Research questions

Table 5.5 is fully answering the research questions in short sentences. This Chapter was utilizing Chapter 2 as the base for further investigation into this master thesis' main issues.

Table 5.5: The Results and Discussion Chapter's Answers To the Research Questions

<table>
<tr><td>How is the environmental assessment treated in a building project today?</td><td>A LCA is normally conducted when the building is built, complete LCA, to satisfy green building rating systems. The LCA methodology is widely accepted and an ongoing development in different LCA software is present today. The LCA methodology recognizes possibilities that help to reduce energy and resource consumption and the environmental impacts of building materials. Environmental assessment is today present using LCA software at final stages of the building project, but there are trends and studies that intend to include LCA in earlier stages (before LOD 350). Screening and simplified LCAs are developing as well as the uncertainty can be reduced by being consistent to the goal and scope definitions. LCI databases like EPD-Norway can be used to evaluate the impact assessment, but whereas there is no information related to materials or products, average or most likely values, can be adapted into the LCA.</td></tr>
<tr><td>What is the interaction between BIM and LCA, and how is this interaction used to evaluate environmental performance in building projects?</td><td>There are three main approaches to BIM-LCA integration, and all approaches are seeking on reduce costs, lower the GHG emissions and increase the efficiency during early design stages of buildings:
1. Conduct LCAs using several programs: BIM is not able to act as the sole software to conduct LCAs. It is required plug-ins and input as environmental data.
2. Quantity take-off generated by BIM with an LCA database to obtain environmental impacts: Using features in BIM and LCA for data acquisition in the LCA software retrieved from the BIM model is possible. OCL possess this feature.
3. Inclusion of LCA information in BIM: adapt environmental data input into the building elements within the BIM.
The interaction of BIM-LCA is utilized in several ways. Table 2.10 shows studies that have used several programs and LCIA databases to conduct LCAs at different stages. Some studies also take advantage of LOD implementation. In spite of several attempts, there is clearly a missing linkage of different databases, automatized design and impact calculation. BIM-LCA integration needs more development.</td></tr>
<tr><td>How can an early design LCA framework correspond to LOD with respect to OCL?</td><td>When compiling LCA at LOD 200, 300 and 350 utilizing the second main approach, the initial quantitative hypothesis was verified. The LCAs were not reliable compared to the project description. Therefore, an accurate LCA at LOD 350 were conducted using empirical and average values obtained from supervisors in NCC. 66% improvement in GWP within LOD 350 occurred. When acknowledge the error in BIM-LCA using OCL, a LOD framework were established as a recommendation to AEC professionals: Combining LOD requirement related to early design stages (project delivery phases) divided as per table of building elements (Table 5.1, 5.2 and Figure 5.7). Whereas the building elements are not in accordance to LOD 400 requirements - average, mean, min/max or most likely values has be used to display the range of GWP outcomes (Table 5.4, Figure 5.8 and 5.9).</td></tr>
</table>

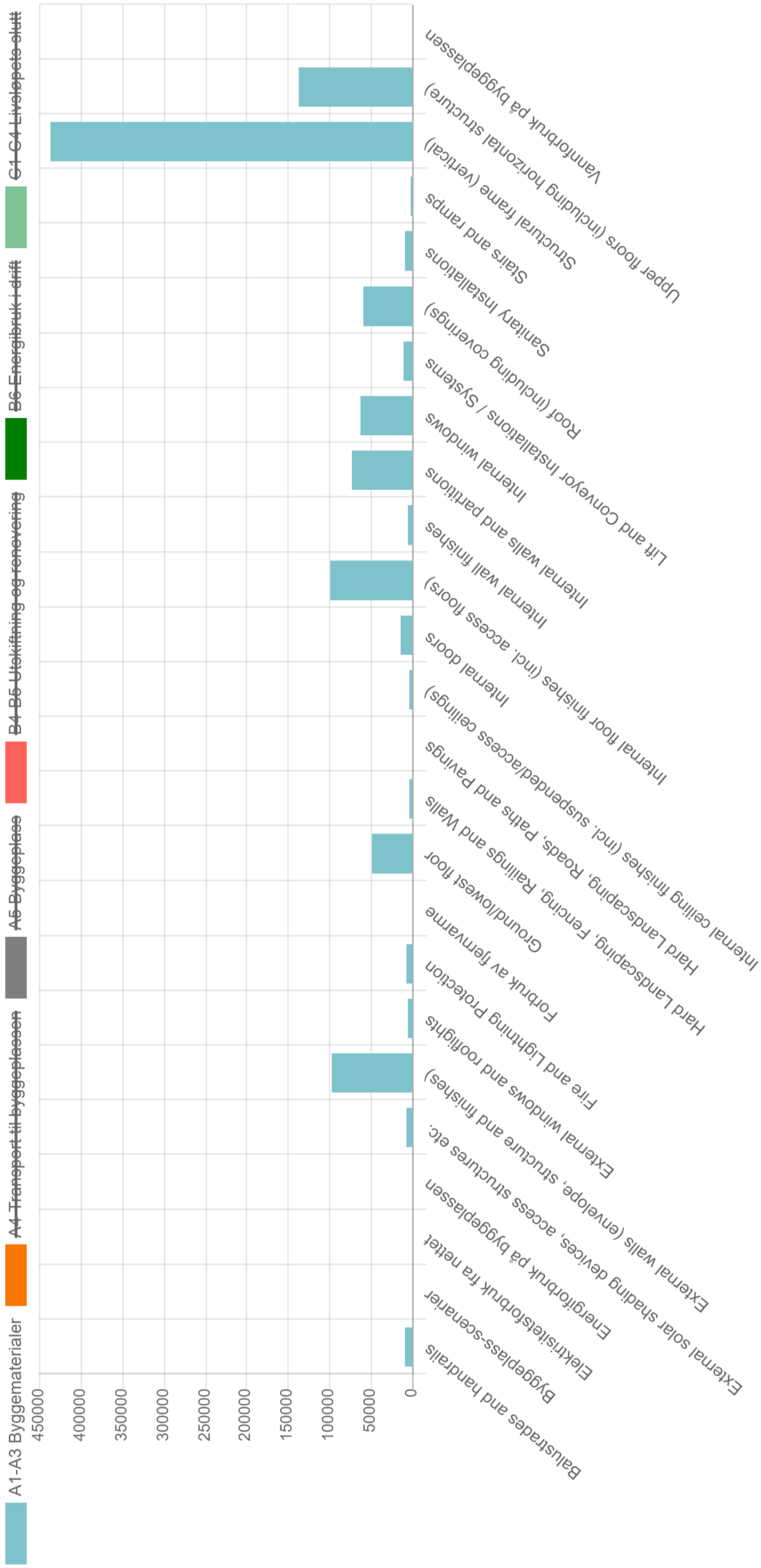

Figure 5.5: Major material categories accountable for GWP

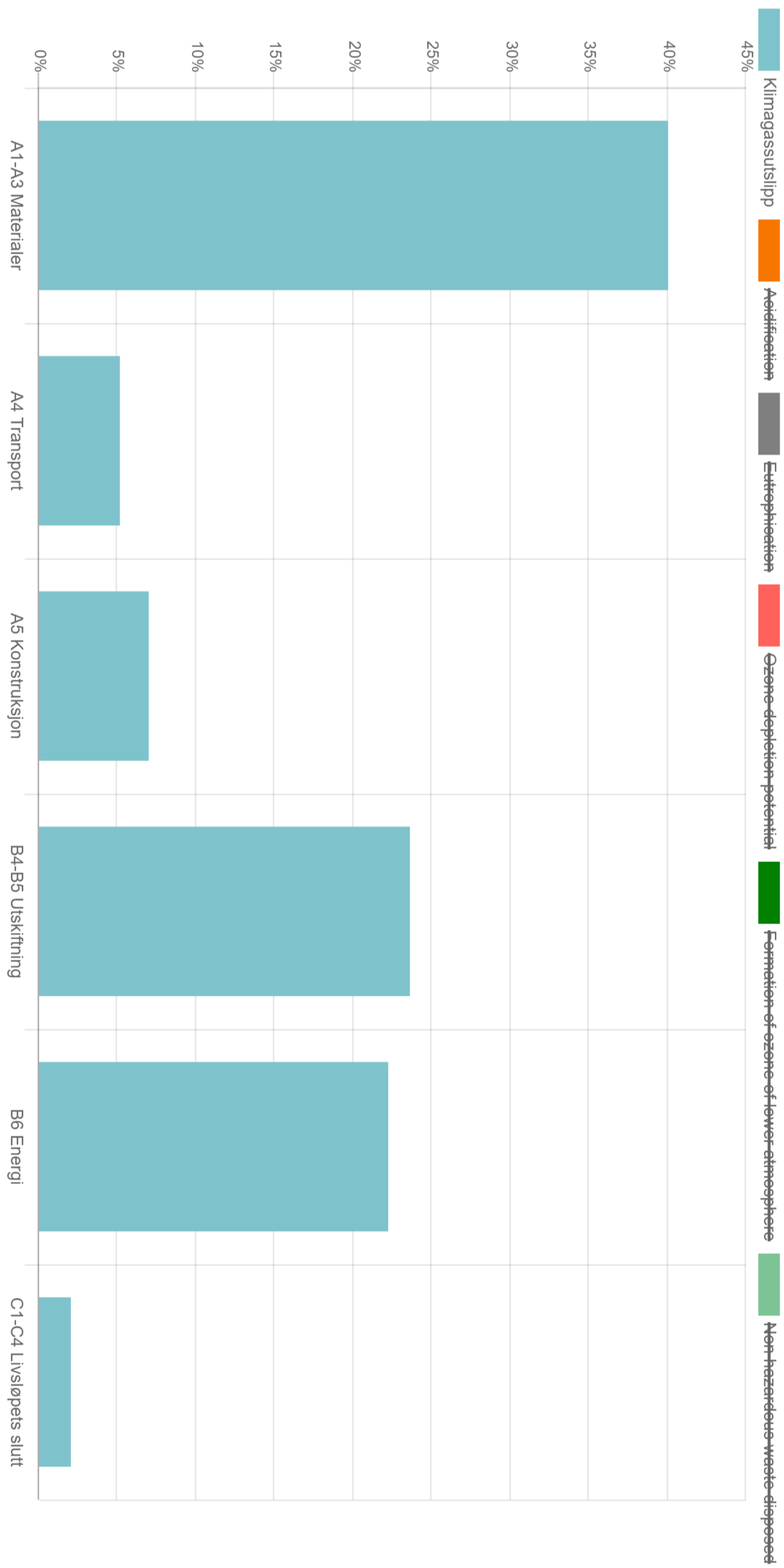

Figure 5.6: GHG emissions proportions

Chapter 6: Conclusion

Main aims of a BIM-based LCA is to establish a convenient decision-making method with an environmental perspective, and an ongoing environmental assessment during the early design stages. This emphasizes the ability to substitute objects when the cost is low, and the ability to impact when the functional capabilities are high. This method should not be used only by LCA experts, but also by designers on a day-to-day basis. Investing more time in the design stages and utilize LOD and its requirements consistently, would enhance the level of information and detail in BIM objects. This amplifies the information within the IFC files and leads to fewer errors in BIM-LCA tools.

Today, environmental assessment is present through the widely accepted LCA methodology. An LCA is normally conducted when the building is already built, often motivated to be certified with green building rating systems. Moreover, there are initiatives that develop the LCA methodology in low LOD, called screening and simplified LCAs. Average and most likely values can be adapted in LCA databases where a low level of information is present. Inconsistency between the different phases of an LCA, leads to high uncertainty regarding the LCIA databases. This newborn proposal of assessing environmental impacts proves that the interaction between BIM and LCA is not satisfied.

There are three main approaches to BIM-LCA integration used to evaluate environmental performance in building projects:

- Conducting LCAs using several programs and software, because BIM is not able to act as the sole method of doing LCAs. BIM objects require plug-ins and environmental data.
- Quantity take-off generated by BIM with an LCA database to obtain environmental impacts.
- Inclusion of LCA information in BIM object. Adaptation of environmental data within BIM elements is needed.

The case study used in this master thesis utilized four different scenarios to conduct LCAs, namely LOD 200, LOD 300, LOD 350 and an additional LOD 350. The additional LOD 350, called final LCA, was deployed when project designers had implemented changes within OCL. These changes constituted 66% improvement in GHG emissions from Valle Wood. The findings in the literature argue that an LCA should be done at LOD 200, LOD 300 or LOD 350, but this thesis' case study suggests ongoing assessments in every LOD level. At LOD 350, the building permit stage, the BIM require major material information and a comprehensive LCA ought to be compiled. Findings from the case identified lack in development of the BIM model, and the effort in conduction of LCA is remarkable greater in the LCA software compared to the BIM model.

Therefore, I suggest the designers and design tools to be acquainted with the requirements to each LOD levels, and consequently use average and mean (±) values, as well as best practice where the LOD level is low. The proposed LCA framework is corresponding to LOD levels, as the design delivery phases are determined by milestones of completeness in the BIM model. Designing the building project in BIM in accordance with this framework will improve the GWP, as interaction with BIM and LCA tools enables substitution of materials that contribute to the highest release of CO_2. Such automation in LCAs, and the ability for ongoing assessments will assist the decision-making processes to emphasize the environmental issues during design.

Chapter 7: Suggestions For Further Work

Further work on the development of standards is required, which should identify environmental properties in BIM objects. This requires collaboration between BIM expert, LCA experts and AEC professionals. It is important to assemble the EPDs and the environmental sustainable information of products available, and be aware of the procedure regarding how information is available through different formats (BCF). Methodological standards for sustainability in buildings should be given more effort. Requirements and methodologies to develop ZEB and satisfaction among green building rating systems, are necessary to highlight the changes required to build in accordance to reach 1.5 °C target.

Moreover, the development of EPDs and PCRs should be given more effort in order to link all the inventory in the BIM model to respective EPDs. This would decrease the uncertainty in the screening and simplified LCAs in low LOD. Uncertainty in quantity take-offs from BIM models should be identified in each LOD. This information can assist to improve the LOD framework along with BIM-based LCAs. There should be more accurate assessments at early design stages, and the combination of BIM-LCA tools should interact to provide an automated environmental performance assessment of buildings.

The economy in not considered in this study. This master thesis proved that less uncertainty in the environmental impacts improved the life cycle assessments results regarding the production stage LCA. I am sure that the more incentives given to the development in EPDs and PCRs, the faster improvement towards an environmentally friendly building industry.

Lastly, methodologies regarding BIM and LCA has to adapt for future interactions. The weighting factor between environmental impact categories should be further discussed. This thesis considered the GWP, and ignored the other impact categories as well as broader system boundaries. This has to be included to display the whole building LCA.

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APPENDIX

Appendices A: SBE19 Conference Paper

Evaluation of BIM-based LCA in the early design phase (low LOD) of buildings

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Abstract.
Building Information Modelling (BIM) is a convenient tool that is capable of collecting information throughout the whole life cycle of a building in one platform. The evolution in the digital BIM model in early design stages is not standardized, but Level of Development (LOD) is a concept that systematically structures the design processes divided into five levels. LOD is assessed in this paper as an opportunity to enhance the calculation of the environmental impacts in different early design stages more efficiently, using the methodology Life Cycle Assessment (LCA). Enlightening the building elements that contribute to highest release of CO_2, permits early building material selection. This facilitates a pathway towards sustainable and environmentally friendly buildings. This study evaluates BIM-based LCA in early design stages (low LOD) through literature reviews and a case study. This papers' case study executes LCAs at different LOD levels using the LCA software One Click LCA (OCL). Assessments in LOD 200, LOD 300, LOD 350 and an additional LOD 350 were utilized. The additional LOD 350 was deployed when LCA experts had implemented changes within OCL. Moreover, a concretized suggestion where today's unpredictable development of BIM becomes part of a LOD framework is proposed.

1 Introduction

There are several basic, well-established scientific links that constitute the background for this report. The UN Intergovernmental Panel on Climate Change (IPCC) states that the human fingerprint on greenhouse gases (GHGs) have risen to record levels not seen in three million years [1]. There are limitations to adaption and adaptive capacity for human and natural systems, but most adaptation needs will be lower for global warming of 1.5 °C compared to 2 °C according to the Paris Agreement [2].

The proposal of this report is to investigate which features that are required in an interaction between BIM and LCA in the early design stage (low LOD), to evaluate the environmental performance of a building. In addition, this paper research question is how an early design LCA framework corresponds to LOD.

The sustainability of buildings is depending on several aspects. This report is evaluating one of them, namely the environmental impact of buildings regarding CO_2 emission. This study focuses on the LOD in the design stage using BIM, and how a BIM-based LCA can help improve the environmental impacts, limited to buildings. The study is illustrated by one case study, Valle Wood in Oslo (Norway), and one LCA tool, OCL. Cradle to gate processes for materials and services used in construction is considered as the system boundary for the study [3]. The embodied energy is the energy required to produce the building materials, and it is related to the production stage (A1-A3) of the life cycle stages. Furthermore, the in-use energy is energy consumption related to the use stage, and will not be considered in this report. Moreover, the incidence of embodied energy in building energy analyses account for the major part (50 %) of the whole primary energy demand, compared to the operational energy stages in the use stage [4–6]. The built environment have the highest potential to limit the global warming [7], and therefor an LCA framework regards to LOD is proposed.

2 Method

2.1 Conduction of LCAs

Qualitative and quantitative methods are the basis of this report's results. The qualitative methods investigate the findings regarding the interactions between BIM and LCA, as well as how BIM-based LCAs can be advantageously rendered through comprehensive literature reviews. BIM models were deliberated this study through document reviews, received from NCC. The quantitative LCA calculations on the BIM models are based on using quantity take-off generated by BIM, as well as one LCA using input data retrieved from designers in Valle Wood, to obtain environmental impact in OCL.

All smc files were made available through NCC's own PortWise Access Manager 4.12. In the same portal, all relevant documents were available such as subcontractors' drawings and calculations. In addition, description of materials were listed. This study took advantage of three different smc files and distinguished the LOD levels based on [8, 9] requirements. The different BIM models (Figure 2, 3 and 4) express maturity in the design.

(i) **.smc-file published February 2017 - LOD 200**. The model is represented with approximate quantities, size and shape. There are limited objects that are similar to the planned type of materials in the project description (Figure 1). It looks like elements are generic placeholders. See Figure 2.

(ii) **.smc-file published July 2018 - LOD 300**. The model contains more specific and developed objects. Non-graphic information does also occur in this LOD level, but the size, shape and orientation of elements are located with respect to the project origin. See Figure 3.

(iii) **.smc-file published December 2018 - LOD 350**. The quantity, size, shape, location and orientation of the element as designed, can be measured directly from the BIM model. Despite that there are existing non-graphical information to the model, the model can now be used to decision making and as project guide into different locations. See Figure 4.

Table 1 describes theoretical aspects in an LCA along with OCL features, as well as assumptions made. OCL is an online LCA application that require reports, such as a BIM model inventory file from either MS Excel or gbXML. The elaboration of the LCAs that use MS Excel reports from Solibri Model Checker were based on quantity take-offs from BIM and attached automatically to EPDs in OCL. These LCAs represents three calculations, namely LOD 200, LOD 300 and LOD 350. The LCA obtained from NCC, called *final LCA*, used empirical input data because the Industry Foundation Class (IFC) convey objects to the information take-off reports that causes errors. The structural systems are better to analyze on empirical values in OCL, as they will save time compared to checking all objects from the IFC [10].

2.2 Proposed LCA framework

The proposed framework consist of three main steps [11].

(i) The definition of an evolution of LOD: The definition of element categories is the Norwegian Standard NS 3451 shown in Table 3. The definition of early design phases which appear as project delivery phases is shown in Figure 6 with respect to LOD evolution.

(ii) Consistent combination of LCA databases: EPDs are the determined LCA database. Where no EPDs are available, average values should be employed as Table 5 shows.

(iii) The link between LOD levels and LCA databases: At LOD 400, the exact quantities of each materials should be known as product specific data can be utilized.

3 Case

> "Valle Wood is going to be Norway's largest commercial building in cross laminated timber. The building will be certified in accordance with BREEAM, the world's most demanding environmental certification system, which takes a holistic view of the building's entire ecocycle" [16].

Valle Wood covers the first phase of the project. This phase is 6700 m^2, and the total site is going to be 60000 m^2 including all five phases [16].

Figure 1: Valle Wood

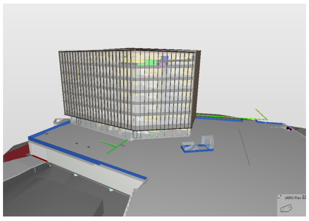

Figure 2: LOD200

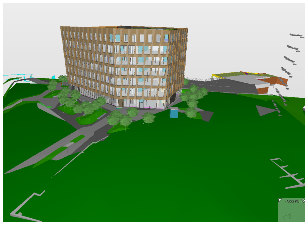

Figure 3: LOD 300

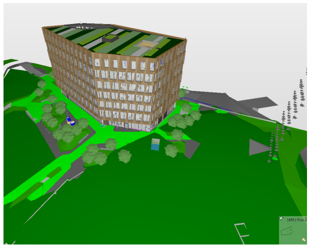

Figure 4: LOD 350

4 Results and Discussion

There are three main approaches ranging from the use of several software, the inclusion of LCA information in BIM, and quantity take-offs generated by BIM, to conduct BIM-based LCAs. All approaches are seeking on reduce costs, lower the GHG emissions and increase the efficiency during early design stages of buildings [17]. Moreover, the interaction of BIM-LCA is utilized in several ways. Studies in [11, 18–27] have used several programs and LCIA databases to conduct LCAs at different stages. Some of the studies also take advantage of LOD implementation. In spite of several attempts, there is clearly a missing linkage of different databases, automatized design and impact calculation. However, the integration of LCA within the BIM is not available.

4.1 LCA of Valle Wood

The quantity takeoff information for building materials provided by Solibri Model Checker is obtained in units of volume. The mismatch between the properties in the smc files, quantity takeoff information, and OCL screening method, provides errors regarding the actual amount of materials and due to dissimilar products and EPDs. The MS Excel upload purely contains the information from the .smc file, but it is structured in a way so that the MS Excel can be read by OCL. When this occurs, a unit conversion factor is needed to evaluate the embodied environmental impacts. OCL does not possess this feature, which leads to heavier workload on the LCA performance in early design. An example can be incomplete design by architects that ignore specific requirements, regarding fire or lighting in the BIM.

Table 1: LCA methodology in One Click LCA

LCA methodology and assumptions made in One Click LCA	
Goal and scope definition	Evaluate the Global Warming Potential (GWP) caused by Valle Wood using OCL.
Functional Unit (FU)	FU of this LCA is Kg $CO_2 - eq$ emission per material. The reference unit is m^3. Other units like kg, kW, kWh, 1 m and m^2 could have been applied, but OCL do not possess a unit conversion factor.
Temporal- and geographical scope	OCL execute a static LCA model. It is possible to setup the service of the materials that would be preferable to include. This will have an impact on B4-B5 (Replacements) during the building life cycle and impacts associated with B6-B7 are introduced on an annual basis. At the moment OCL do not allow changes to the energy mix as this is not allowed in the standards OCL follow. Operating variables do not affect the inventory of the system. Nevertheless - this is out of the scope of the study, and mitigate the potential downsides in terms of only gather Life Cycle Inventory (LCI) data to unit processes, which is the smallest element considered in the LCI for which input and output are quantified [12]. The time period covered in this LCA is updates in the BIM model as per December 2018 [13]. Geographical scope is Oslo, Norway.
Technology coverage	The tool utilized is LCA for BREEAM NOR. The template used to export and structure information from Solibri is "One Click LCA (metric).ITO".
Change-oriented LCA	This is a change-oriented LCA that comparing three BIM models (three LOD levels), up against a modified and reliable LCA at a correct LOD 350.
Intended application	This is a LCA that can be applied to different situations; BIM-model improvement, strategic planning and public decision making.
System boundary	Consider embodied emission, cradle to gate, A1-A3 as this contribute the most to GWP.
LCI analysis and data collection	MS Excel file that imported materials from the BIM (.smc file) and grouped them based on 5 criteria: CLASS: values have to be one of the listed ones in exactly the same format (sorted in .ITO template used in information takeoff in Solibri). IFC-MATERIAL: Use the distinguishable material name to map the material to the label in the tool. Mapping is based on CLASS and IFC-MATERIAL combination. For material label, the database is EPD-Norway. When importing it for the first time, one can teach it to the tool and it will be automatically recognized in the future. QUANTITY: Number, comma as decimal separator. QTY-TYPE: Units. TRANSPORT-KM: Transport distance in km from manufacturer site to the building site (optional, can also be added later in the query).
Data quality	Cut-off criteria to this LCA is materials $< 1\%$ of the volume. Also, OCL's category 6, Building Technology, is out of the scope. The cut-off lead to the fallacy of disaggregation by splitting up processes which lower the data quality and putting flows explicitly to zero [14]. The cut-offs are related to undefined objects from the BIM model. Data information included are obtained from EPDs witch follows the same sets of standards.
Life Cycle Impact assessment (LCIA)	The impact category is global warming, characterized as per CML-IA 2012 methodology, required by EN 15978 and EN 15804 [15].
Interpretation	OCL is an transparent analysis as the tool is online and can be easily modified. As this features, this assessment is also a comparative analysis in the way the assessments comparing four alternatives to which performance at different LOD.

4.2 LCAs Using Quantity Take-Off Generated by BIM With EPD-Norway as the LCA Database to Obtain Environmental Impact in OCL

LOD 200, LOD 300 and LOD 350 in Table 2 shows LCA results from OCL when the quantity take-off in Solibri Model Checker was used to generate the LCI report that was attached to EPDs in OCL.

The main contributors to GWP in all these designs are *horizontal structures* and *other structures*. Metals and concrete are the materials with the highest impact on the environment. Despite the fact that steel and concrete are the materials responsible for the high GHG emission, a reduction of 75% between LOD 200 and LOD 350 is present. The absence of data information through the transitional process into OCL, initiated unreliable results.

The LCA on LOD 200 indicates a low level of information in the BIM object, as the GHG emission is calculated to be more than 32000 tons of $CO_2 - eq$. Valle Wood, presented in Section 3, is going to be built in cross-laminated timber, which is not the case illustrated in February 2017 (LOD 200). Only 1% of the materials are timber. In low LOD levels, there is not a requirement to specify the type of materials, and because of the low level of information inside the BIM object, the design has not distinguished the environmental and material properties. Default settings were probably sat to materials during the early design process in BIM.

At LOD 300, the materials are not yet in accordance with the project description. Steel and concrete are still dominating the design, and no timber is contributing to the design, which contradicts to the information in the BIM model (Figure 3).

At LOD 350, [28] state that the BIM model should contain all relevant information to be environmentally assessed, but as one can see from Table 2, essential data elements are missing. This leads to errors that do not correspond to the reality of materials that should have been in the LCA. Despite the great improvement in GHG emission, the LCA is not reliable as the material distribution differs from the project description. In addition, the number of materials in OCL are incorrect compared to the BIM model in Solibri Model Checker.

4.3 Final LCA Conducted With Empirical Values

Instead of improving the quantity take-off generated by Solibri Model Checker and the transitional format (.ITO template), empirical values were added in OCL to calculate a correct value for the GHG emissions, with the right quantity for the right type of materials. This is shown in Table 2. Here, 42% of the material contribution is timber, which is in accordance with the project description.

The great reduction in GHG emission was calculated with the right type of materials, linked to the right EPD, which resulted in 2700 Tons of $CO_2 - eq$. The measurements and units were obtained from the BIM model without utilizing the quantity take-off generated by Solibri Model Checker at LOD 350 (Figure 4).

4.4 Suggested Use of LOD in a BIM Environment With Respect to LCA Application

To support an efficient and user-friendly LCA application in early design, strategies for simplification in BIM-based LCAs have been proposed by several parties. The common knowledge gap in the proposals is the need for an envelope that deprives BIM to carry out an LCA single-handily.

To minimize the carbon footprint, the writers of this report believes that early design delivery phases can help the efficiency and the automated work regarding LCAs. By using LOD as the direction-setting process in LCA, the more environmental attention is given to the design and,

Table 2: Results from OCL related to different LODs

LOD	Builing Element	%	Material Type	%	Material Subtypes	%	Tons of CO_2-eq
LOD 200	Horizontal Structures (HS)	82	Steel and Metals (SM)	88	Aluminum	87	32523
	Other Structures (OS)	12	Concrete	8	Prefab. concrete walls	4	
	Vertical Structures (VS)	6	Glass	2	Concrete foundation	3	
			Timber	1	Cross Laminated Timber (CLT)	1	
			Gypsum	0	Glass	2	
LOD 300	OS	51	SM	74	Aluminum	67	9553
	HS	25	Concrete	21	Prefab. concrete	13	
	VS	24	Floor (undefined)	2	Concrete	5	
	Ground and Foundation (GF)	0	Glass	1	Steel	4	
			Insulation	1	Steel and Iron	3	
LOD 350	OS	56	SM	75	Aluminum	67	8066
	HS	27	Concrete	19	Prefab. Concrete	13	
	VS	17	Timber	3	CLT	12	
	GF	0	Floor (undefined)	2	Steel	5	
			Insulation	1	Concrete	3	
LOD 350 (Final LCA)	VS	54	Timber	42	CLT	56	2713
	HS	31	Windows and doors	14	Mortar	13	
	GF	11	Gypsum	14	Interior walls	12	
	Building technology	3	Insulation	11	Rockwool	11	
	OS	1	Floor (undefined)	8	Carpets	8	

the GHG emission will be considered as a determining factor through decisions. This approach and proposal desires to connect Architecture, Engineering and Construction (AEC) professionals and designers to deal with the issues through BIM-based LCA in the early design stages (low LOD). The influence to alter the functionality of the building is high and the costs are low in early design stages [29, 30].

The capability of IFC's layered data structure, which has different objects with different level of details for the representation of information, should be specific regards to Model View Definitions (MVD) standard before heading to a higher LOD level. There is two distinct advantages of a standardized LOD related to the embodiment of an LCA. These are that the IFC can be imported into LCA analysis tools from any BIM authoring tools, without performing further data manipulation for mapping imported data to the used LCI database [21]. In addition, more realistic and concise results can be achieved by choosing a proper LCI database and a LCA calculation method, with respect to LOD of the elements contained in a BIM model [21].

A BIM model is a comprehensive collection of objects that are rich in information, and an LCA is a set of unit processes that are linked with each other using flows [31, 32]. It is by this required to link object in the BIM to LCI database using flows. Therefore, it can be hard for designers to handle several unit processes at a time. Henceforth, this proposal allow to break down this information into manageable and logical groups according to NS 3451 building table of building elements and OCL main distribution of building elements shown in Table 4. In addition, milestones to which LOD levels construction categories have to be developed in the BIM are expressed in the same table.

Table 3: NS 3451 - Table of building elements

NS 3451 - Table of Building Elements	
1 digit building element	**2 digits building element**
2 - Building	20 - Building in general 21 - Ground and foundation 22 - Structural system 23 - External walls 24 - Interior walls 25 - Slab 26 - Roof 27 - Building inventory 28 - Stairs and balcony 29 - Other building related parts
3 - Plumbing installations	30-39: out of scope of this study
4 - Electrical Power	40-49: out of scope of this study
5 - Telecom and automation	50-59: out of scope of this study
6 - Other installations	60-69: out of scope of this study
7 - Outdoor area	70-79: out of scope of this study

Table 4: Construction categories divided with respect to LOD and its milestones

Construction categories divided with respect to LOD		
OCL main distributions	**NS 3451**	**LOD**
1) Ground and foundation	20 21	100 150
2) Vertical structures and facade	22 23 24	175 175 175
3) Horizontal structures	25 26	175 200
4) Other structures and materials	27 27 29	300 300 350
6) Building technology	3 4 5 6	350 350 350 400
5) Outdoor area and elements on site	7	400

To systematize to which early design phase (or project delivery phase) that represents the different LOD levels is suggested in Figure 6.

A comprehensive LCA is to be done at LOD 350, building permit stage [11, 18, 21, 24, 25, 28, 33–35]. By this stage, the major elements are stated, and 80% of the 3, 4, 5, 6 and 7 categories (see Table 3) are agreed upon. The building can be stated complete in the BIM, apart from the uncertainty in the empirical, min/max or most likely values in the 80% of LOD 400 posts. Generic LCA databases can be used to obtain LCIA data when the BIM is incomplete and not considered as LOD 400. Another source to most likely values is considering conservative EPDs. An example of conservative EPD can be concrete instead of CLT.

At technical elaboration, the BIM represents LOD 400 (Figure 6), and the environmental impacts should be assessed on equal terms as the structural design issues. EPDs are the dominated LCIA database at LOD 400. Environmental impacts on different products are various, and therefore should EPDs represent the specific brand of the selected material. This will lower the uncertainty in the complete LCA. By using endpoint indicators instead of midpoint indicators in the low LOD LCAs, it would simplify the results and turn the interpretation phase into a more understandable phase for AEC professionals.

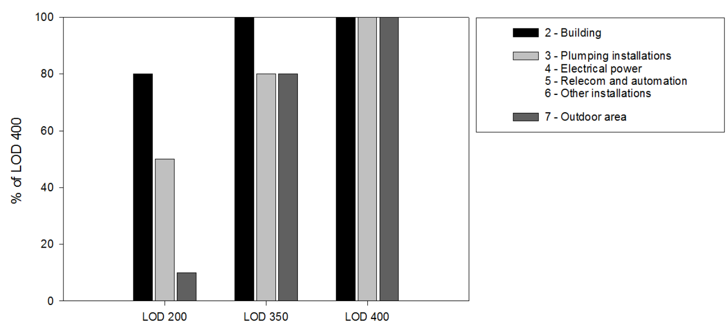

Figure 5: Degree of completeness in different stages of LOD

Table 5: Level of completeness and LCIA databases

LOD	NS 345 (1 digit)	% of LOD 400	LCIA database for building elements
LOD 200	2	80	Average values, mean values, min/max values, most likely value
	3, 4, 5, 6	50	
	7	10	
LOD 350	2	100	EPD-Norway
	3, 4, 5, 6	80	Average values, mean values, min/max values, most likely value
	7	80	
LOD 400	2	100	EPD-Norway
	3, 4, 5, 6	100	
	7	100	

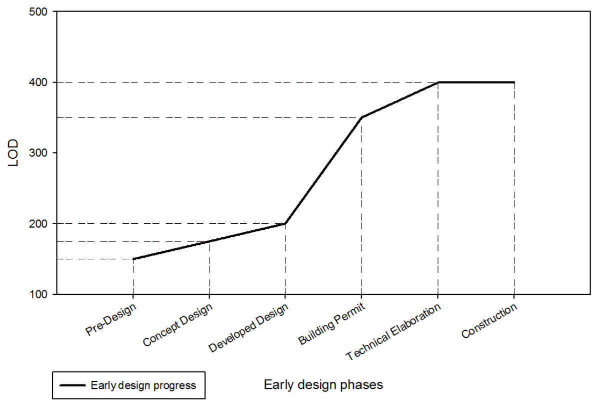

Figure 6: Design phase evolution according to LOD

Components regarding building manner should be given important effort in LOD 200, while plumping, electrical, telecom and automation and other installations are usually depending on the architectural design as Figure 5 and Table 5 shows. The building components are 80% completed at LOD 200. This is due to unpredictable issues regarding clash detection and if building elements within 3, 4, 5 or 6 categories are determinate. At LOD 350, building components is fixed as these components are the major contributors to GWP and determine the structural design of buildings. In addition, the building components determines the structural design of buildings. By clearly state these materials in LOD 350, than the majority of building materials can be assessed with high accuracy.

5 Conclusion

Main aims of a BIM-based LCA is to establish a convenient decision-making method with an environmental perspective, and an ongoing environmental assessment during the early design stages. Investing more time in the design stages and utilize LOD and its requirements consistently, would enhance the level of information and detail in BIM objects. This amplifies the information within the IFC files and leads to fewer errors in BIM-LCA tools.

Therefore, we suggest the designers and design tools to be acquainted with the requirements to each LOD levels, and consequently use average, mean ($\pm$) values and best practice where the LOD level is low. The proposed LCA framework is corresponding to LOD levels, as the design delivery phases are determined by milestones of completeness in the BIM model. Designing the building project in BIM in accordance with this framework will improve the GWP, as interaction with BIM and LCA tools enables substitution of materials that contribute to the highest release of CO_2. Such automation in LCAs, and the ability for ongoing assessments will assist the decision-making processes to emphasize the environmental issues during design.

Acknowledgments

We want to thank NCC Building Nordics for handing over IFC files and access into the project "Valle Wood". Thanks for the great information and method regarding environmental assessments in the LCA application One Click LCA.

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Appendices B: Impact Categories

Table B.1: Complete list of impact categories in One Click LCA

- Global warming potential (Kg CO2 e) - Ozone depletion potential (Kg CFC-11 e) - Acidification potential (Kg SO2 e) - Eutrophication potential (Kg (PO4)3- e) - Photochemical ozone depletion potential (Kg C4H4 e) - Abiotic depletion potential (kg Sb e) - Abiotic depletion potential (MJ net calorific value)
Other EN standard impact categories included in One Click LCA: - Use of renewable primary energy excluding renewable primary energy resources used as raw materials (MJ net calorific value) - Use of renewable primary energy resources used as raw materials (MJ net calorific value) - Total use of renewable primary energy resources (primary energy and primary energy resources used as materials) (MJ net calorific value) - Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials (MJ net calorific value) - Use of non-renewable primary energy resources used as raw materials (MJ net calorific value) - Total use of non-renewable primary energy resources (primary energy and primary energy resources used as materials) (MJ net calorific value) - Use of secondary material (kg) - Use of renewable secondary fuels (MJ net calorific value) - Use of non-renewable secondary fuels (MJ net calorific value) - Net use of fresh water (m3) - Hazardous waste disposed (kg) - Non hazardous waste disposed (kg) - Radioactive waste disposed (kg) - Components for re-use (kg) - Materials for recycling (kg) - Materials for energy recovery (kg) - Exported energy (MJ per energy carrier)
The 6 TRACI 2.1 impact categories (LCA for LEED in USA and Canada): - Ozone depletion - Global Warming - Acidification - Smog formation - Eutrophication - Human health cancer

Appendices C: Example of Literature Review

Findings from: "Critical review of bim-based LCA method to buildings"
Authors: Bernardette Soust-Verdaguer, Carmen Llatas, Antonio Garcia-Martinez
Published: 2017, Elsevier
Journal: Energy and Buildings

Credibility: This is a reviewed paper that contains several case studies and notices the knowledge gaps to assist in the integration of BIM-LCA, especially in the early design stage. The comprehensive reviewed paper provides evidence of the growing interest in the integration of BIM with environmental impact calculation methods. However, literature about the subject is still scarce (Soust-Verdaguer, Llatas, and García-Martínez 2017). The review found cases from all over the world, which has utilized different methods and tools for calculating environmental impacts and developing BIM-models. This paper gave the writer an overview of the state of the art, and summarized the challenges regarding BIM-LCA and discussed the use of LOD. With over 80 references and a deep survey into the subjects, gave this paper great credibility and opportunity for further snowballing. Over 60 citations on Google Scholar is also credible as the paper included topics of BIM, LOD and LCA. The journal, Energy and Buildings, had the highest possible impact factor of 2 in 2017 when this paper was published.

Objectivity: The lack of reviews that analyzes the integration of BIM, LOD and LCA is identified as a gap in the literature. This paper aims to review recent case studies that integrate all of these topics which make this paper informative. Moreover, the review collects the newest studies into this paper and compare the methodology, software and techniques used. This is an objective approach which explains the advantages and disadvantages of the given case studies.

Accuracy: The methodology of the cases are described and shown in tables. The authors reflect on different science published. This is a field that is not implemented in the design stage yet, but several studies have tried to develop new tools to enhance the efficiency in the design regarding BIM-LCA. There were challenges found in the paper to improve the implementation of BIM-LCA. The scientific writers of the collected case studies were familiar with the gap and attempt to come up with a solution. The paper was as accurate as it could have been hence new science. It was a great source to state the progress of BIM-LCA today.

Suitability: The author focuses on how BIM can simplify and reduce data acquisition, improve the interoperability in BIM, introduce LCA and quantification of materials and building elements in a BIM-model by using LOD. The authors claim "the application of LCA during the early stages of design should be done in a LOD that allows a quick modelling, and an easy and accurate environmental impacts calculation" (Soust-Verdaguer, Llatas, and García-Martínez 2017). This is a confirmation that my study need improvement, and I have found a knowledge gap that suite my master thesis.

Appendices D: Evolution in BIM: LOD levels

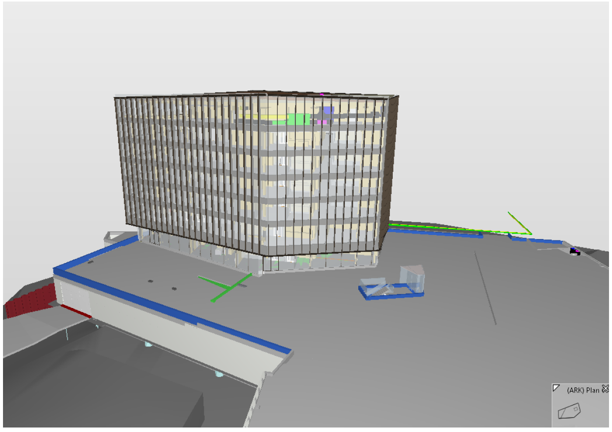

Figure D.1: LOD 200

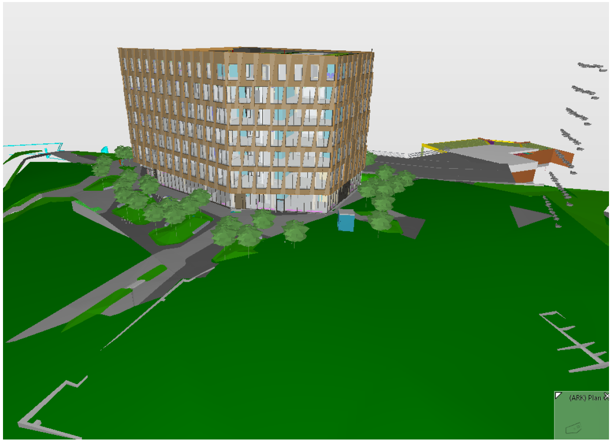

Figure D.2: LOD 300

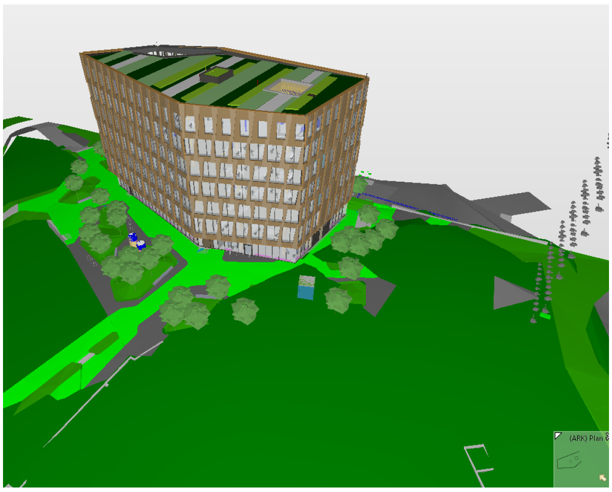

Figure D.3: LOD 350

Appendices E: BIM-LCA VS Traditional LCA

OneClick LCA A1-A3 building materials and its embodied energy impact on GWP						Edited LCA using One Click LCA A1-A3 building materials and its embodied energy impact on GWP (NCC)				
One Click LCA Distribution	**(NS 3451 - Table of building elements)**	**Resource**	**Values retrieved from One Click LCA**	**Unit**	**Method**	**Resource**	**Values edited by NCC**	**Unit**	**Method used in editing**	**Assumptions and justification by NCC (if present)**
1) Ground and foundation	Foundation, ground and retaining walls (20, 21)	Low-carbon ready-mix concrete, Lavkarbonklasse A - B30 M60 (Skedsmo Betong)	8,81	m3	Obtained .ITO tamplate from One Click LCA, performed information takeoff in Solibri, imported the report into One Click LCA and did the LCA without edit any data	Solid Timber Panels (Cross-Laminated Timber, CLT), 320 mm (KLH Massivholz)	1842,88	m3	The amount is known on beforehand	
		Steel, rebar products (concrete reinforcement), 7850kg/m3, scrap - 100%, Ribbed reinforcement bars (Norsk Stal)	0,659	m3	Obtained .ITO tamplate from One Click LCA, performed information takeoff in Solibri, imported the report into One Click LCA and did the LCA without edit any data					

OneClick LCA A1-A3 building materials and its embodied energy impact on GWP						Edited LCA using One Click LCA A1-A3 building materials and its embodied energy impact on GWP (NCC)				
One Click LCA Distribution	**(NS 3451 - Table of building elements)**	**Resource**	**Values retrieved from One Click LCA**	**Unit**	**Method**	**Resource**	**Values edited by NCC**	**Unit**	**Method used in editing**	**Assumptions and justification by NCC (if present)**
		Structural hollow sections, S420MH, S355J2 double grade steel (SSAB)	0,011	m3	Obtained .ITO tamplate from One Click LCA, performed information takeoff in Solibri, imported the report into One Click LCA and did the LCA without edit any data					
		Insulation, EPS 100, 0.035 W/mK, 18-22 kg/m3 (100 kPa), without flame retardant (EUMEPS)	0	m3	Obtained .ITO tamplate from One Click LCA, performed information takeoff in Solibri, imported the report into One Click LCA and did the LCA without edit any data					
		Glue laminated timber, 470 kg/m3, 12% moisture content (Moelven Modus)	326,8	m3	Obtained .ITO tamplate from One Click LCA, performed information takeoff in Solibri, imported the report into One Click LCA and did the LCA without edit any data					
4) Other structures and materials	Other structures and materials (27, 28, 29)	Aluminium curtain walling, 2700 kg/m3 (GAA)	68,73	m3	Obtained .ITO tamplate from One Click LCA, performed information takeoff in Solibri, imported the report into One Click LCA and did the LCA without edit any data	Galvanized steel staircase, indoor use (Lonbakken)	3000	kg		
		-	-	-	Obtained .ITO tamplate from One Click LCA, performed information takeoff in Solibri, imported the report into One Click LCA and did the LCA without edit any data	One storey timber staircase, 2587x225x905 mm, 41.9 deg (Stair Craft)	7	units		
		Precast concrete cover slab, Thickness 50-80 mm, 2.4x7.4 m (Ryfoss)	57,9	m3	Obtained .ITO tamplate from One Click LCA, performed information takeoff in Solibri, imported the report into One Click LCA and did the LCA without edit any data					
		Cold formed aluminium sheet, 2700 kg/m3 (GAA)	15,34	m3	Obtained .ITO tamplate from One Click LCA, performed information takeoff in Solibri, imported the report into One Click LCA and did the LCA without edit any data					
		Solid Timber Panels (Cross-Laminated Timber, CLT) (Stora Enso)	2,86	m3	Obtained .ITO tamplate from One Click LCA, performed information takeoff in Solibri, imported the report into One Click LCA and did the LCA without edit any data					
		Steel hot rolled, I, H, U, L, T and wide flats, FI average (Ruukki)	1,8	m3	Obtained .ITO tamplate from One Click LCA, performed information takeoff in Solibri, imported the report into One Click LCA and did the LCA without edit any data					
		Ready-mix concrete, normal-strength, generic, C30/37 (4400/5400 PSI), 10% (typical) recycled binders in cement (300kg/m3)	1,1	m3	Obtained .ITO tamplate from One Click LCA, performed information takeoff in Solibri, imported the report into One Click LCA and did the LCA without edit any data					
		Cold formed aluminium sheet, 2700 kg/m3 (GAA)	0,505	m3	Obtained .ITO tamplate from One Click LCA, performed information takeoff in Solibri, imported the report into One Click LCA and did the LCA without edit any data					
					Obtained .ITO tamplate from One Click LCA, performed					

Appendices F: One Click LCA Certifications With ISO and EN Standards

Instytut Techniki Budowlanej

00-611 Warsaw, Filtrowa 1

Thermal Physics, Acoustics and Environment Department

02-656 Warsaw, Ksawerów 21

DECLARATION Nº 043/2016

ITB hereby confirms that the software:

One Click LCA® and 360optimi® developed by Bionova Ltd

has been audited and verified to be compliant with the following standards:

EN 15804+A1:2014 - Sustainability of construction works.
Environmental product declarations.
Core rules for the product category of construction products
EN 15942:2012 - Sustainability of construction works. Environmental product declarations.
Communication format business-to-business
ISO 21930 - Sustainability in building construction - Environmental declaration
of building products

The software was found to be in conformance with the provisions and requirements of listed international standards

This declaration is valid from the date of issue for the year in which it is signed and 5 full calendar years after that

Head of the Thermal Physic, Acoustics and Environment Department

Michał Piasecki, PhD

INSTYTUT TECHNIKI BUDOWLANEJ

Deputy Director for Research and Innovation

Krzysztof Kuczyński, PhD

Warsaw, 10 November 2016

Appendices G: One Click LCA Verification

70 YEARS ITB

Building Research Institute

together to the future

00-611 Warsaw, Filtrowa 1

Department of Thermal Physic, Sanitary Systems and Environment

02-656 Warsaw, Ksawerów 21

DECLARATION № 031/2015

ITB hereby confirms that the software:

360optimi® and One Click LCA™ developed by Bionova Ltd

has been audited and verified to be compliant with the following standards:

EN 15978 Sustainability of construction works - Assessment of environmental performance of buildings Calculation method

ISO 21931-1 Sustainability in building construction - Framework for methods of assessment of the environmental performance of construction works - Part 1: Buildings

ISO 21929-1 Sustainability in building construction - Sustainability indicators Part 1: Framework for the development of indicators and a core set of indicators for buildings

Conformity with the above standards was verified in consideration of the data quality requirements of the following standards:

ISO 14040 Environmental management - Life cycle assessment Principles and framework

EN 15804 Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products

The software was found to be in conformance with the provisions and requirements of listed international standards

This declaration is valid from the date of issue for the year in which it is signed and 5 full calendar years after that

Head of the Department of Thermal Physic, Sanitary Systems and Environment

Robert Geryło, PhD

Deputy Director for Research and Development

Michał Wójtowicz, PhD

Warsaw, 1 April 2015 r.

Mats Nilsen

Evaluation of BIM-based LCA in the early design phase (low LOD) of buildings

NTNU
Kunnskap for en bedre verden