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Writer:

Emir Demirovic

Emir Demirović

(Writer's signature)

Faculty supervisor: Samindi Samarakoon

External supervisor(s): Cecilie Nødtvedt

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Life-Cycle Assessment of Buildings at the Design Stage: Case Study

Emir Demirovic

Master of science in Engineering Structures and Materials

Specialization Civil Engineering Studies

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Prewords

This work is written as a master thesis for a finished master's degree in construction and materials by the University of Stavanger under the institute for mechanical, constructional, and material science. The work accumulated 30 points and was written over the course of the entire spring semester 2021.

I have always been interested in technology and have over the course of my education grown an interest for environmental engineering and sustainability in construction. While my bachelor thesis focused on lightweight concrete, I wanted to have a master thesis that focused more on the logistics of green development in construction. The future of our planet is directly affected to construction, and I wanted a thesis that could possibly impact and shape the environmental view on construction.

The thesis was written with cooperation from JM, a large construction company in Norway, based in Sweden. They were very interested in my idea of performing a life-cycle assessment, and presented me with a task to compare steel and wooden studs in Langhus Gård through a life-cycle assessment.

Throughout this thesis I have used One Click LCA to perform my analysis, and I have received Revit model of Langhus Gård from JM. The challenges were to analyse the 3d-model and extract data to complete the LCA.

This thesis serves like a guide to perform LCA with Revit models and looks at the comparison of steel and wooden studs in outer walls in large residential buildings.

I wish to thank my supervisor from UiS, Samindi Samarakoon, for providing me with excellent literature, guidance, and patience during my thesis.

Furthermore, I wish to thank Cecilie Nødtvedt from JM for presenting the task to me and providing me with the model, EPDs and other information.

Lastly, I would like to thank my classmates and teachers for an excellent five years at the University of Stavanger.

Summary

There has been a huge focus on our planet’s future regarding sustainability and green production. With the construction sector standing for 40% of our total greenhouse gas emissions, there is much room for improvement.

In modern construction with low energy consumption, materials make up a large percentage of a projects net emission. Therefore, correct material selection can make a difference in the building’s environmental performance. The thesis will compare wood and steel studs in outer walls in a large residential building through a life-cycle assessment.

The BIM model of Langhus Gård, presented by JM, is in early design stage with projected construction beginning at the latter half of 2021. The challenges of early design stage involve lack of information and some approximations have been done. This thesis mainly looks at the integration between LCA and BIM in an early design stage. Since BIM programs cooperate badly with LCA tools, there is a challenge of extracting data from the model to perform the LCA.

To face this task a literature study regarding environmental engineering, stud comparison and performance of life-cycle assessment has been done. In early design stage, material volume is our largest concern to the LCA, and an analysis of the 3d-model of Langhus Gård was done. This included stud placement and extraction of material volume. The boundaries of LCA were done according to our limitations.

The data extracted needed to be placed in One Click to get results of the life-cycle assessment. This faced the challenge of what materials we had to work with and receiving precise EPDs.

The inputs gave us results for our LCA, which were presented in terms of 4 units of measurement: global warming potential, acidification, eutrophication, and energy consumption. The analysis also gave us information about carbon footprint and environmental classification. Since wooden and timber studs vary in volume, an equal part timber vs steel was performed next to the full analysis of the building.

The conclusion was based on the results of the One Click LCA, and many improvements to the LCA was examined about the merge between LCA and BIM.

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Abbreviations

LCA	-	Life-cycle assessment
BIM	-	Building information modelling
UiS	-	University of Stavanger
EPD	-	Energy Product Declaration
GWP	-	Global warming potential
CO_2	-	Carbon dioxide
SO_2	-	Sulphur dioxide
PO_4	-	Phosphate
IPCC	-	Intergovernmental Panel on Climate Change
UN	-	United Nations

Chapter 1: Introduction

2019 was the second warmest year on record coming off the warmest decade in recorded history (United Nations, 2020). Level of carbon dioxide was at an all time high as well as other greenhouse gases in our atmosphere. Reports from IPCC show that about a rise of 1°C is human-induced and is likely to reach 1.5 between 2030 and 2050 if it continues to rise at this rate (IPCC, 2018). A further rise can have detrimental impact on our planet. This includes instances such as melting of ice at the Poles and loss of biodiversity. Furthermore, release of particle matters such as NO_x can harm our air quality.

It is vital for our survival on earth to take steps into reducing pollution and build a sustainable future. The construction sector presents a large environmental impact on our planet, accounting for 35% of our global resources, 40% of our energy use, consume 12% of the worlds drinkable water and produce almost 40% of the CO_2-emissions (UK, 2018). This shows that there is great potential in reducing our human-induced environmental impact.

A life-cycle assessment (LCA) is an analysis performed to establish the environmental impact a material or project has in a lifetime perspective (One Click LCA, n.d.). This includes the full cycle from resource extraction, manufacturing, distribution, use and end-life. LCA was originally intended for single products but can be used for larger projects. By performing these analyses on large constructional projects, we can determine the carbon footprint and the impact each source has. This gives us an environmental profile for our project as well as showing us where improvements can be made. There are different tools and software to perform LCA, but for this project One Click LCA will be used.

1.1 Objectives

In this thesis the goal is to analyze Langhus Gård in Nordre Follo through a life-cycle assessment. The objective is to figure out if its more sustainable to have steel or timber studs in the outer walls. Langhus Gård is a residential building in Nordre Follo, in the early design stage. The building is a 5-story building with a façade of tile.

By performing a literature study on sustainability in construction sector, wall studs and premises of LCA we can perform a study to compare the two materials. As this is an early design stage building, the LCA will be mainly based off material selection.

Furthermore, the results will need to be further analyzed to draw conclusions as just the LCA will only give us an idea of the buildings environmental performance. Therefore, the studs will need to be categorized into two independent analyses and compared both in true part and equal parts. This will serve as a guide for further examinations of similar problems.

The life-cycle assessment performed relies heavily on data extraction from Revit (BIM software). As mentioned, material selection and volume are vital for the LCA in early design stage. First, we need to gather material volume to determine our input in One Click LCA. Material volume will only give us amount of certain material types, such as concrete or tile. We also need EPDs of said materials to get accurate results. EPD, environmental product declaration, is a code for each material that contains the environmental performance of a material. The database of EPDs is constantly increasing, but there are still many materials that lack EPDs.

1.2 Limitations of study

The study was met with a few problems for performance of LCA and data extraction. Extraction of data from Revit can sometimes be difficult as the plug-in from One Click LCA struggled to differentiate some materials from each other. This was due to the model involving JM’s own codenames in Revit data (for example JM_betong or JM_isolation). This led to some materials being hard to extract and some materials needed to be either manually measured or neglected (if materials had a low volume).

The life-cycle assessment was also met with certain limitations (also known as scope). This involved deciding which materials were involved in the thesis, boundaries of which stages and data was to be analyzed and which EPDs was chosen for the materials that did not have a known EPD.

Chapter 2: Sustainability in construction sector

2.1 Emissions from construction sector

Environmental engineering is a wide term used to describe the branch of engineering that involves protecting people and our earth from environmental effects. While environmental engineering can involve several engineering topics such as chemistry, biology, geology etc. we will be mainly looking into environmental engineering in construction and material science.

As previously mentioned, construction is the industry with the highest environmental impact in the world. Just Norwegian construction sites release annually 420 000 tons of CO_2 and 5.1 tons of NO_X (NTB, 2017). According to reports worked out by DNV-GL, can these pollutions be reduced by almost 99% with alternative energy fuel and better planning.

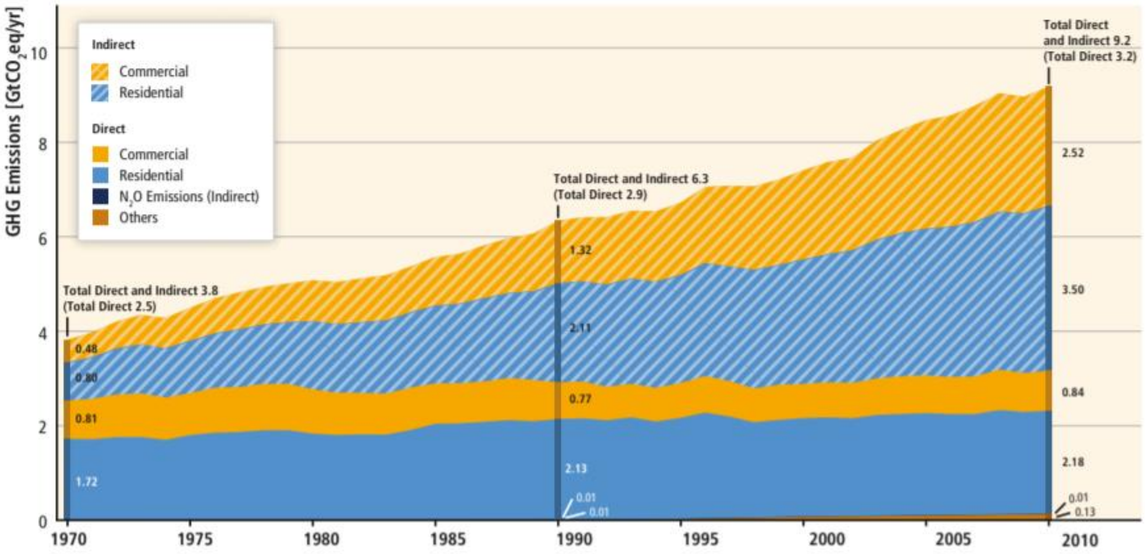


Figure 1: GHG Emissions over the years (Data from IPCC)

Worldwide, the construction sector, stands for a high share of environmental, economic, and social impacts. Therefore, it is important to control the development in the right direction. A milestone made to encounter by 2020 made that all constructions and renovations of buildings and infrastructure should be made to be zero-energy and highly material efficient (COMMISSION, 2011).

Our focus in construction needs to be resource management, planning, clean fuel, recycling, demolition, rehabilitation, education, and most of all – climate regulations.

By performing analyses of projects, we can determine what aspect of construction we can improve. This includes selection of material, planning and execution and end-of-life performance like waste disposal and recycling.

2.2 Effects

Buildings are responsible for a significant amount of the environmental effects on our planet (UK, 2018). They account for 35% of our resources, 40% of our energy use, consume 12% of the worlds drinkable water and produce almost 40% of CO_2-emissions. While buildings are vital for us, many of these parameters can, and should, be lowered.

We split environmental categories into three parts: environmental, social, and economical dimensions. Emissions from greenhouse gases (GHG) such as CO_2 are causing global warming. These are environmental effects as they contribute to destruction of our planet through the greenhouse effects. Chemicals such as phosphate (PO_4) and sulfur dioxide (SO_2) destroy our biodiversity, while other chemicals such as NO_x impact our air quality.

2.3 Greenhouse effects

As previously mentioned, any project regarding construction and infrastructure will emit greenhouse gases such as CO_2 (Kvamstø, 2015). Carbon dioxide (CO_2) is a greenhouse gas and will, due to the greenhouse effect, cause global warming.

The greenhouse effect is vital for our survival on earth. Without it, the average temperature on earth would be -18^oC (Kvamstø, 2015). In the natural greenhouse effect, heat from the sun breaks through our atmosphere with little problem, absorbs off our planet and back into space. The sun emits shortwaves of heat, which our planet releases back as longwave, or infrared radiation. The greenhouse gases absorb these infrared radiations, causing the temperature inside our atmosphere to rise.

While naturally this effect is vital for our survival, human impact has strengthened the atmospheres' ability to absorb heat radiation (Kvamstø, 2015). 99.96% of our atmosphere is made up of nitrogen, oxygen, and argon, but have little effect as they do not absorb and release infrared radiation. By definition, a greenhouse gas is a gas that absorbs heat radiation.

The most important greenhouse gases are carbon dioxide (CO_2), ozon (O_3), methane (CH_4), nitrous oxide (N_2O) and chlorine-fluorocarbons (CFCs).

The global median temperature has risen 1^oC in the last 140 years, and especially in the last 25 years (Løken, 2009). According to a report from IPCC (The Intergovernmental Panel on Climate Change) an increase to 2^oC will have severe consequences on eco-systems, humans, and society.

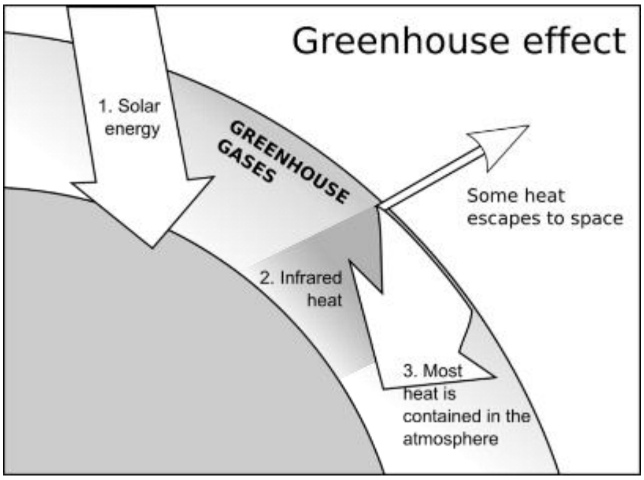


Figure 2: Greenhouse effect

2.4 Carbon dioxide (CO_2)

As mentioned, CO_2 is a greenhouse gas and exists currently at a concentration of around 0.04% (400 ppm) in our Earth's atmosphere and rising (Designing Buildings Wiki, 2021). While carbon dioxide occurs naturally all around us, our impact is increasing its release into the atmosphere.

Carbon dioxide is entrained in forests, minerals and oceans, and a lot of its emission is naturally (Designing Buildings Wiki, 2021). Material extraction can increase its emission and global warming is melting ice which again release CO_2. However, it is mainly emitted with burning of fossil fuel. Carbon dioxide is also release with burning of fossil fuel, which can be used in manufacturing of certain materials when high heat is wanted.

Carbon dioxide is considered the most important greenhouse gas as it contributes the most to our human impact on climate change (Miljødirektoratet, 2020). In 2019, CO_2 stood for 84% of all greenhouse gas emissions, which is a 19% increase from 1990.

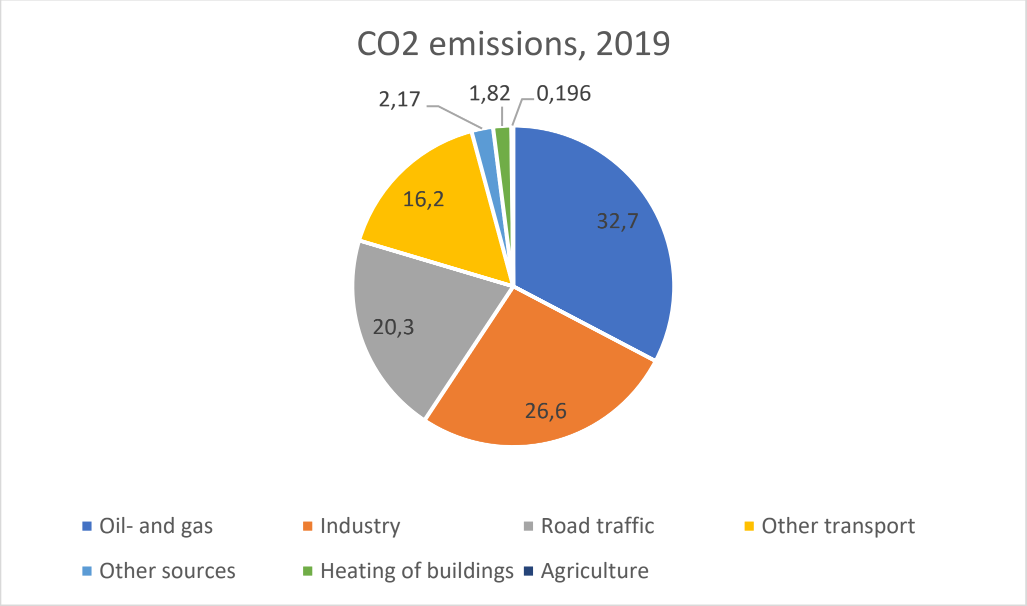
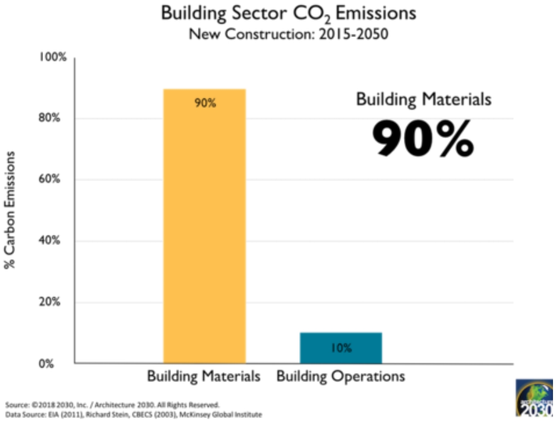


Figure 3: Source of CO2 emissions in Norway, 2019. (Miljødirektoratet)

According to an LCA performed by students at Høgskulen på Vestlandet 93.6 % of the CO_2 emissions came from the concrete (Martin Gulliksen, 2020). Steel and other metals stood for 5.8 % while both timber and isolation stood for 0.3 %. While concrete is represented highly in most buildings, its impact cannot be ignored.

Our analysis will focus on material selection, which make up 90% of CO_2 emission in the entirety of the project.



Source: ©2018 2030, Inc. / Architecture 2030. All Rights Reserved.
Data Source: EIA (2011), Richard Stein, CBECS (2003), McKinsey Global Institute

Figure 4: Carbon emission in a construction project (Building Green)

Concrete is the most used building material in the world (Bjørnstad, 2016). It is flexible, strong, and economical, but does come with a con: carbon footprint. Concrete is primarily made of water, cement, sand and stone aggregate. Cement is produced by burning limestone at a very high temperature, around 1450°C. The return is something called clinker, which combined with plaster becomes cement. Limestone is made up of pressurized corals and other carbon-based organism, that during heating, release CO_2 in a process called calcination. The combined CO_2-

emission from calcination is said to stand for around 6 % of our global CO_2 emission. However, during the hardening process of concrete, some CO_2 is taken up and entrained in the concrete due to a process called carbonation. Scientist have concluded that about 43 % of emission from calcination are taken up by carbonation, and these numbers are not currently included in the UN climate accounts.

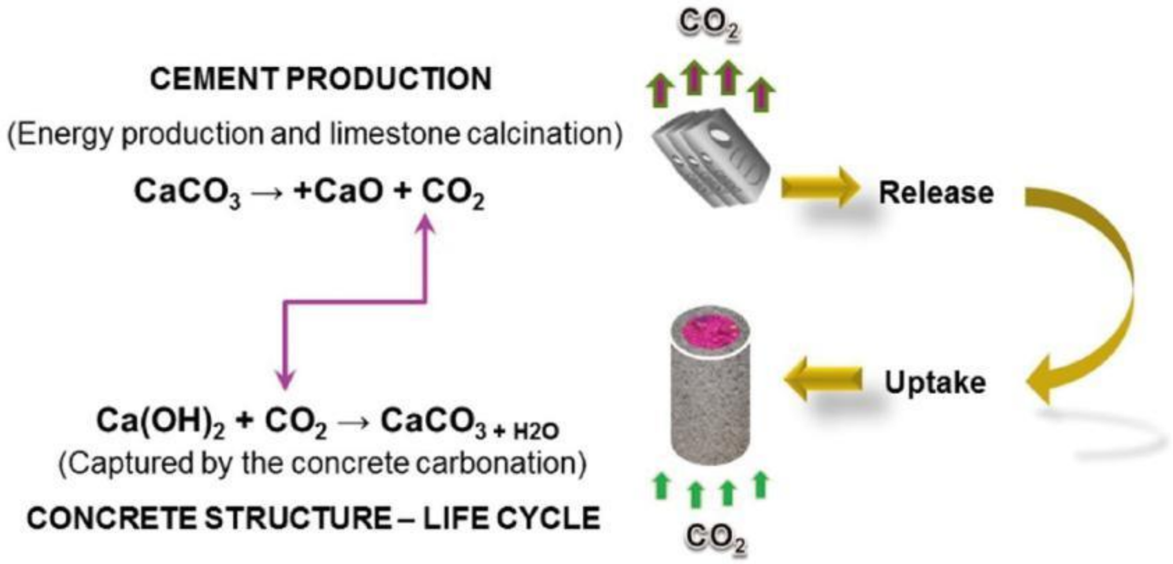


Figure 5: carbonation and calcination of concrete (SciELO)

CO_2 emissions from cement production are not only due to calcination, but also due to use of fossil fuel to reach the high temperature (Bjørnstad, 2016).

2.5 NO_X

The term nitrogen oxide, NO_x, are chemical compounds consisting of a nitrogen and oxygen molecule which can react in the air to create nitric oxide and nitrogen dioxide (Pickering, 2020). Per definition, nitrogen dioxide is not a greenhouse gas, but does come with health impacts. Combustion of fossil fuels from vehicles can produce oxides of nitrogen, NO_x, which can easily convert to nitrogen dioxide, NO_2, in the air. Diesel or gasoline fuelled engines in industrial machinery can also produce NO_2 by itself.

Exposure to NO_2 can cause airway inflammation and increased respiratory symptoms (Pickering, 2020). NO_x can also react with other elements and form particles that can have a negative impact on our lungs. During 2010, 9500 premature deaths were estimated to be from exposure to NO_2 and other particle matters in the air.

In 2014 a control of dust and emissions during construction and demolition supplementary planning guidance (SPG) was released (Pickering, 2020). This helped to control and manage emissions of dangerous particles, and among them NO_2. It forced construction sites to monitor air quality and alarm if limit was exceeded.

2.6 Regulations

The Intergovernmental Panel on Climate Change, IPCC, is the United Nations body for assessing the science related to climate change (Lucon & Ürge-Vorsatz, 2014). Their focus is to enlighten about climate impacts through scientific assessments, put forward regulations and mitigations options.

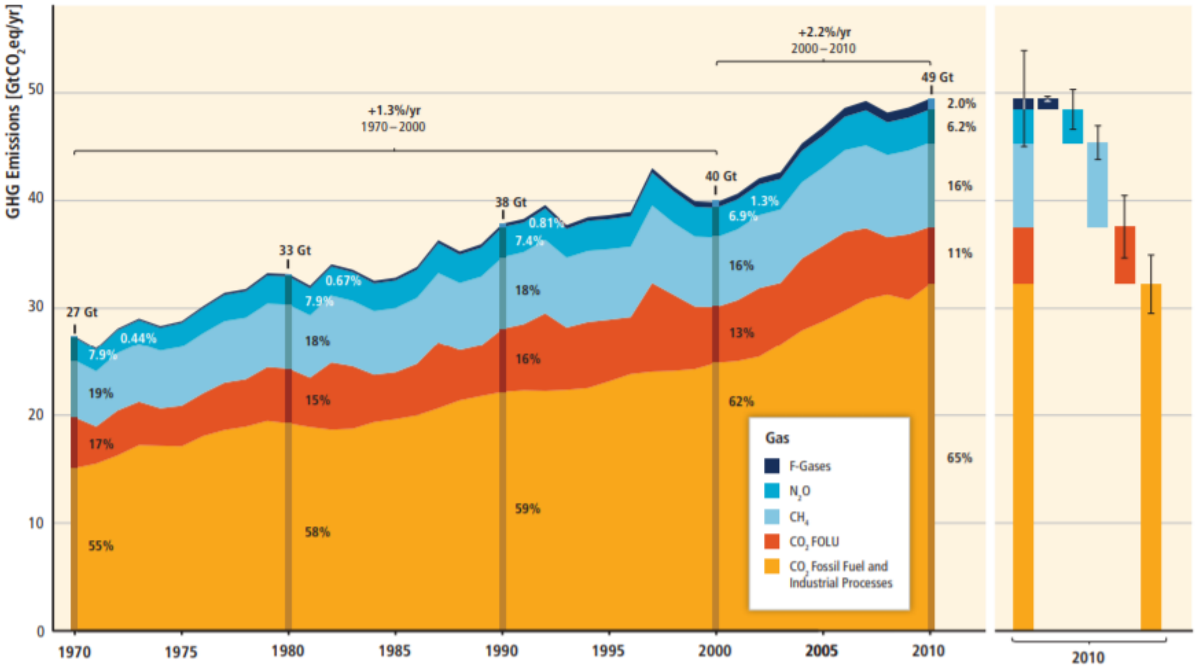
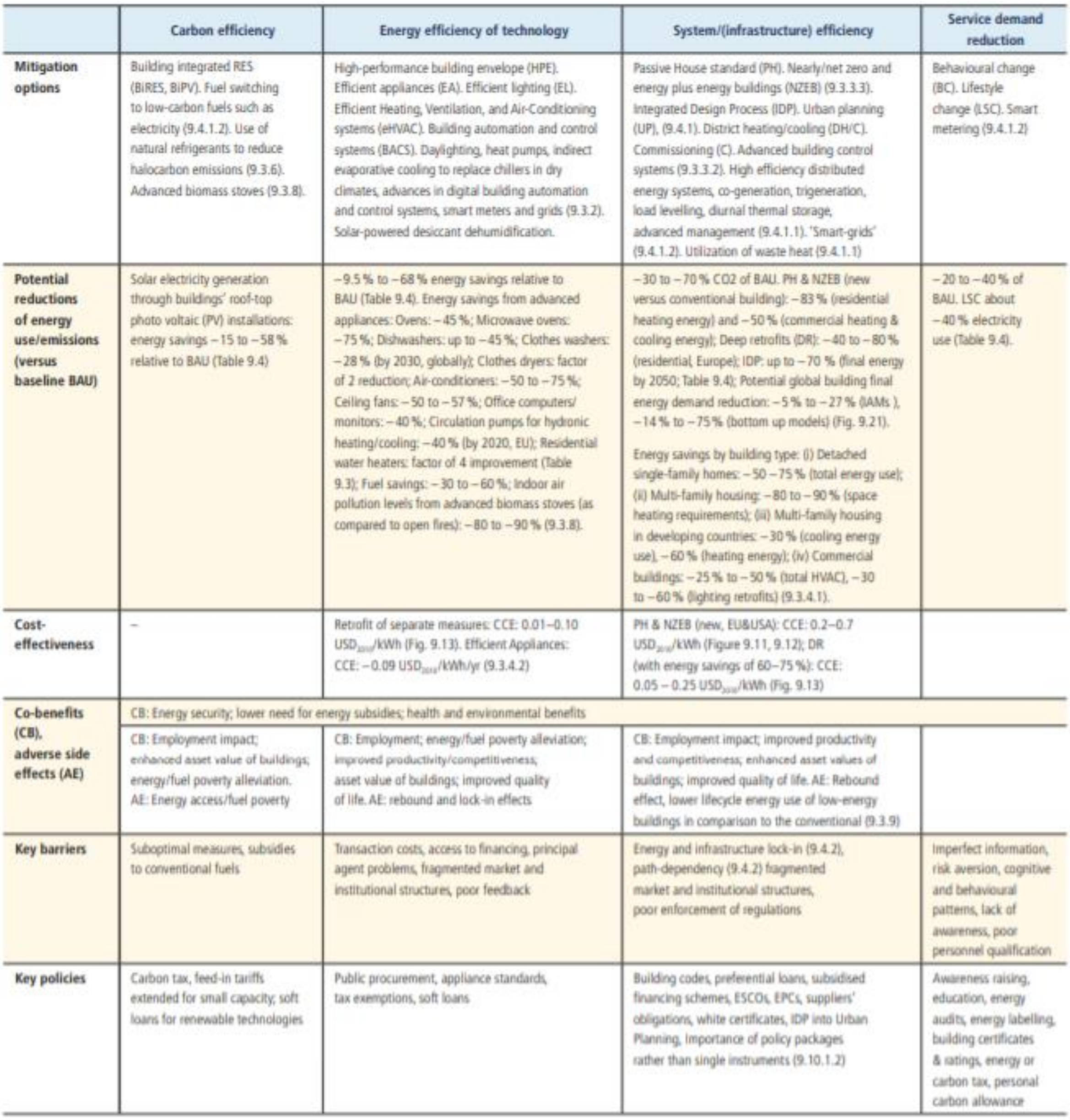


Figure 6: Total annual anthropogenic GHG emissions by groups of gases 1970 – 2010 by IPCC

Their report on buildings from 2014 made research on environmental impact of the building sector and setting forward mitigations and policies (Lucon & Ürge-Vorsatz, 2014). The report, prepared by over 20 authors, made guidelines for how regulations in the construction industry should be prepared and contained data on our global energy use and greenhouse gas emissions. It was also formed to help developing countries reaching the environmental targets set by UN, by setting lighter rules.



	Carbon efficiency	Energy efficiency of technology	System/(infrastructure) efficiency	Service demand reduction
Mitigation options	Building integrated RES (BiRES, BiPV). Fuel switching to low-carbon fuels such as electricity (9.4.1.2). Use of natural refrigerants to reduce halocarbon emissions (9.3.6). Advanced biomass stoves (9.3.8).	High-performance building envelope (HPE). Efficient appliances (EA). Efficient lighting (EL). Efficient Heating, Ventilation, and Air-Conditioning systems (eHVAC). Building automation and control systems (BACS). Daylighting, heat pumps, indirect evaporative cooling to replace chillers in dry climates, advances in digital building automation and control systems, smart meters and grids (9.3.2). Solar-powered desiccant dehumidification.	Passive House standard (PH). Nearly/net zero and energy plus energy buildings (NZEB) (9.3.3.3). Integrated Design Process (IDP). Urban planning (UP), (9.4.1). District heating/cooling (DH/C). Commissioning (C). Advanced building control systems (9.3.3.2). High efficiency distributed energy systems, co-generation, trigeneration, load levelling, diurnal thermal storage, advanced management (9.4.1.1). 'Smart-grids' (9.4.1.2). Utilization of waste heat (9.4.1.1)	Behavioural change (BC). Lifestyle change (LSC). Smart metering (9.4.1.2)
Potential reductions of energy use/emissions (versus baseline BAU)	Solar electricity generation through buildings' roof-top photo voltaic (PV) installations: energy savings −15 to −58 % relative to BAU (Table 9.4)	−9.5 % to −68 % energy savings relative to BAU (Table 9.4). Energy savings from advanced appliances: Ovens: −45 %; Microwave ovens: −75 %; Dishwashers: up to −45 %; Clothes washers: −28 % (by 2030, globally); Clothes dryers: factor of 2 reduction; Air-conditioners: −50 to −75 %; Ceiling fans: −50 to −57 %; Office computers/monitors: −40 %; Circulation pumps for hydronic heating/cooling: −40 % (by 2020, EU); Residential water heaters: factor of 4 improvement (Table 9.3); Fuel savings: −30 to −60 %; Indoor air pollution levels from advanced biomass stoves (as compared to open fires): −80 to −90 % (9.3.8).	−30 to −70 % CO2 of BAU. PH & NZEB (new versus conventional building): −83 % (residential heating energy) and −50 % (commercial heating & cooling energy); Deep retrofits (DR): −40 to −80 % (residential, Europe); IDP: up to −70 % (final energy by 2050; Table 9.4); Potential global building final energy demand reduction: −5 % to −27 % (IAMs), −14 % to −75 % (bottom up models) (Fig. 9.21). Energy savings by building type: (i) Detached single-family homes: −50 −75 % (total energy use); (ii) Multi-family housing: −80 to −90 % (space heating requirements); (iii) Multi-family housing in developing countries: −30 % (cooling energy use), −60 % (heating energy); (iv) Commercial buildings: −25 % to −50 % (total HVAC), −30 to −60 % (lighting retrofits) (9.3.4.1).	−20 to −40 % of BAU. LSC about −40 % electricity use (Table 9.4).
Cost-effectiveness	–	Retrofit of separate measures: CCE: 0.01–0.10 USD_{2010}/kWh (Fig. 9.13). Efficient Appliances: CCE: −0.09 USD_{2010}/kWh/yr (9.3.4.2)	PH & NZEB (new, EU&USA): CCE: 0.2–0.7 USD_{2010}/kWh (Figure 9.11, 9.12); DR (with energy savings of 60–75 %): CCE: 0.05 – 0.25 USD_{2010}/kWh (Fig. 9.13)	
Co-benefits (CB), adverse side effects (AE)	CB: Energy security; lower need for energy subsidies; health and environmental benefits			
	CB: Employment impact; enhanced asset value of buildings; energy/fuel poverty alleviation. AE: Energy access/fuel poverty	CB: Employment; energy/fuel poverty alleviation; improved productivity/competitiveness; asset value of buildings; improved quality of life. AE: rebound and lock-in effects	CB: Employment impact; improved productivity and competitiveness; enhanced asset values of buildings; improved quality of life. AE: Rebound effect, lower lifecycle energy use of low-energy buildings in comparison to the conventional (9.3.9)	
Key barriers	Suboptimal measures, subsidies to conventional fuels	Transaction costs, access to financing, principal agent problems, fragmented market and institutional structures, poor feedback	Energy and infrastructure lock-in (9.4.2), path-dependency (9.4.2) fragmented market and institutional structures, poor enforcement of regulations	Imperfect information, risk aversion, cognitive and behavioural patterns, lack of awareness, poor personnel qualification
Key policies	Carbon tax, feed-in tariffs extended for small capacity; soft loans for renewable technologies	Public procurement, appliance standards, tax exemptions, soft loans	Building codes, preferential loans, subsidised financing schemes, ESCOs, EPCs, suppliers' obligations, white certificates, IDP into Urban Planning, Importance of policy packages rather than single instruments (9.10.1.2)	Awareness raising, education, energy audits, energy labelling, building certificates & ratings, energy or carbon tax, personal carbon allowance

Figure 7: Summary of IPCCs report on construction sector with mitigations

Regulations in a more all-round scale of environment was worked out through the Paris Agreement, which is a legally binding international treaty on climate changes. The aim of the agreement is to limit global warming to below 2^{o}C. This heavily relies on gaining control of our GHG-emissions (United Nations, 2021).

To handle the environmental impacts the construction industry has had, the UN has launched the Sustainable Buildings and Climate Initiative (SBCI) in 2006. This program promotes sustainability practices in building with focus on energy efficiency and reducing GHG-emissions.

Target 9.4: By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities.

Target 11.6: By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management.

2.7 Indicators for measuring sustainable construction materials

To measure sustainability in construction we use a system called sustainability assessment (Danso, 2018). This system gives us importance of each indicator has and is branched into three main routes: economic sustainability, environmental sustainability, and social sustainability. Figure 8 shows an example of the system for construction materials. Furthermore, it places different sub-categories (factors/indicators) and weighs the importance of the categories. The purpose of this division is to provide for long and short-term perspectives for decision-makers.

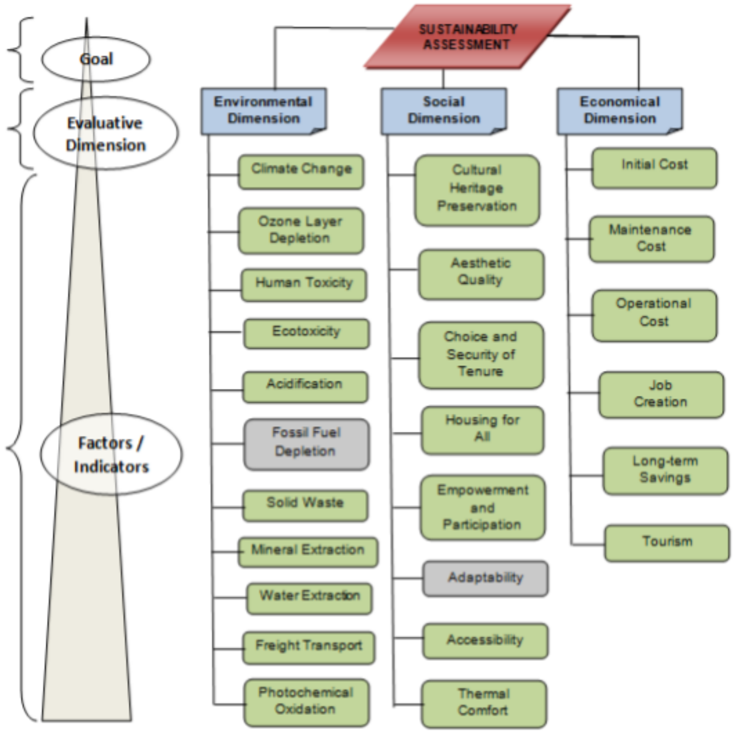


Figure 8: Hierarchical structure for construction materials sustainability assessment (Danso, 2018)

The program used to perform the life-cycle assessment is called One Click LCA. In One Click LCA there are environmental categories which your results can get presented by. One of the boundaries of the thesis is to two decide which categories are selected based on their contributions to our understanding of the problem.

These categories include:

- Global warming potential, GWP
- Acidification potential, AP
- Eutrophication potential, EP
- Energy consumption

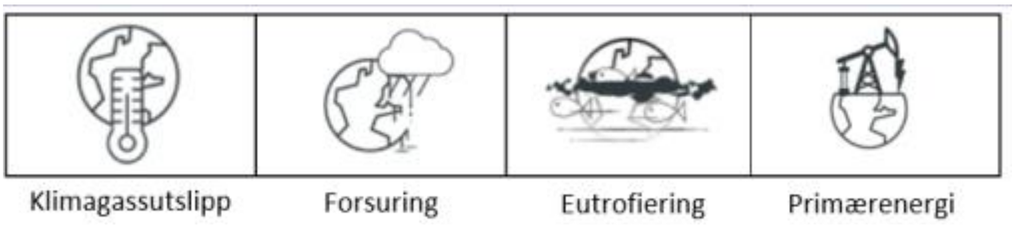
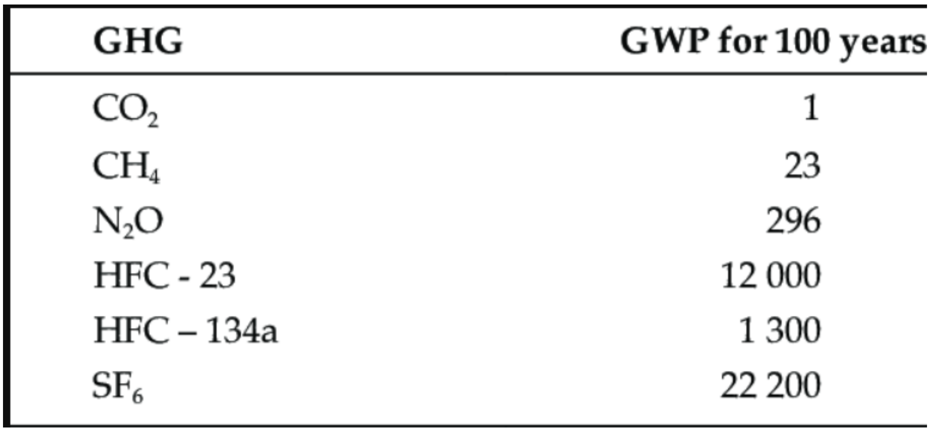


Figure 9: Environmental categories

2.7.1 Global warming potential (GWP)

The global warming potential (GWP) is a category developed to measure the heat absorbed in the atmosphere by different gases (EPA, 2020). GWP's unit of measure uses carbon dioxide (CO_2) as a reference. GWP is measured as how much energy the emissions of 1 ton of gas will absorb over a given time, relative to the emissions of 1 ton of carbon dioxide (CO_2). Specifically, it calculates the impact of different greenhouse gases as CO_2-equivalents over a given time (usually 100 years). The larger the GWP a gas has, the more it heats up the earth compared to CO_2. For example, methane (CH_4) has a GWP of 23, which means 1 kg of methane heats up the earth 23 times more than 1 kg of carbon dioxide (Toldnæs, 2019). By that definition, CO_2 has a GWP of 1.



GHG	GWP for 100 years
CO_2	1
CH_4	23
N_2O	296
HFC - 23	12 000
HFC – 134a	1 300
SF_6	22 200

Figure 10: GWP of different GHG

GWP is our main category in the LCA and will give us an accumulated result of emissions from greenhouse gases as CO_2-equivalents. The emission of greenhouse gases has huge impact on our planet and has long been a prime indicator of our sustainable treatment of earth.

Carbon dioxide comes from many sources, most of them being burning of fossil fuel. Many materials require high temperature for production and most of these materials are vital in buildings.

2.7.2 Acidification potential (AP)

Acidification measures the potential contribution a material has on the increase of acidity in the environment (Dincer & Abu-Rayash, 2020). This effect comes as air pollution, acid rain or emission of ammonium from industry. When the nature is affected by acidity it can cause damage to plant and wildlife.

Acidification potential uses sulphur dioxide (SO_2) as a reference and gives results in SO_2-equivalents (Dincer & Abu-Rayash, 2020). Other materials that contribute to acidification are nitrogen oxides (NO_x), nitrogen monoxide (NO) and nitrogen dioxide (N_2O). These acid gases are usually released into the atmosphere through fuel combustion.

Luckily, the amount of sulphur dioxide in the construction sector has massively dropped in the last 30 years (Gillette, 2012). This is due to our ever-growing regulations of air quality in construction and more sustainable machines and vehicles.

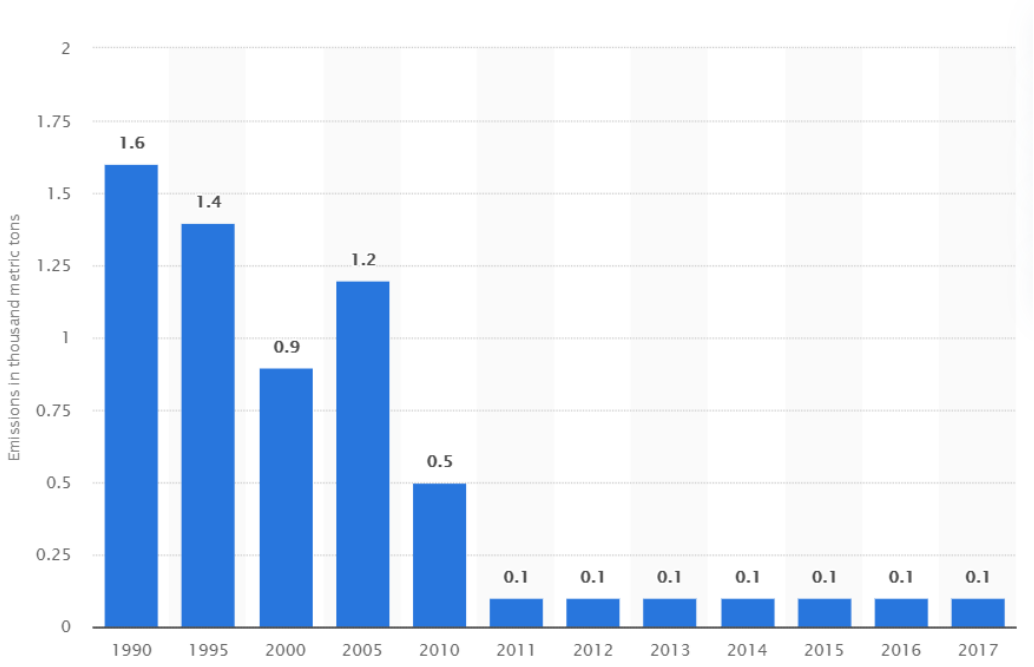


Figure 11: Sulfur dioxide (SO_2) emissions from buildings and construction work in the UK from 1990 to 2017 (Statista).

2.7.3 Eutrophication potential (EP)

Eutrophication is a term used to explain the increased plant production due to unwanted nutrition in the soil (Kjensmo & Hongve, 2019). This excess growth of plants can cause oxygen depletion in the soil and can eradicate natural plants and promote unwanted bacteria and organisms.

Eutrophication is measured against waste disposal and will benefit materials that are easy to recycle or not deemed as toxic waste. Eutrophication is measured in phosphate (PO_4)-equivalents and can contain other substances such as nitrogen and ammonia.

2.7.4 Energy consumption

Energy consumption measures the amount of electric energy is used in terms of joule. This category involved both energy consumption in production and after-life. For example, some materials have high R-value which means they have better insulating performance, giving us lower heat loss, and requiring less energy to warm up inside.

2.8 Recycling

There are great potential economic and environmental rewards for implementing more focus on recycling construction waste (Pettersen, 2020). A study for the Metropolitan Region of Amsterdam, calculated that 2.6 million ton of construction waste would have a value of 688 million euro if reused or recycled properly.

From 2020, the EU has stated that 70% of non-toxic construction waste should be reused or recycled (Pettersen, 2020). However, current standards make a claim that new buildings such be built using new, improved materials, and that recycling is still in the start-phase. Technology is however evolving, and our focus on recycling is vital for the future of environmental engineering.

2.8.1 Cobuilder collaborate

A big problem for recycling has always been lack of information regarding products and materials used. A product cannot be recycled if information about its strength or durability is lacking.

Cobuilder collaborate is a Norwegian company founded in 1997 which provides a digital tool allowing us to keep track of all materials and products used on a project (Cobuilder Collaborate, 2021). Some companies already provide automatic direction of products used into the cobuilder collaborate file regarding the project.

2.8.2 Concrete

Concrete is the most used material in construction and is also the one with the highest environmental impact (European Cement Research Academy, 2015). Concrete can be recycled but would have to serve a different use than structural. By crushing concrete to debris, we can produce an aggregate with a given particle size. Magnetic separators remove the reinforced steel while the concrete is crushed several times until the desired particle size is achieved.

The recycling rate of concrete in Europe greatly varies but is seen to be highest in countries with limited resources of natural gravel, such as the Netherlands.

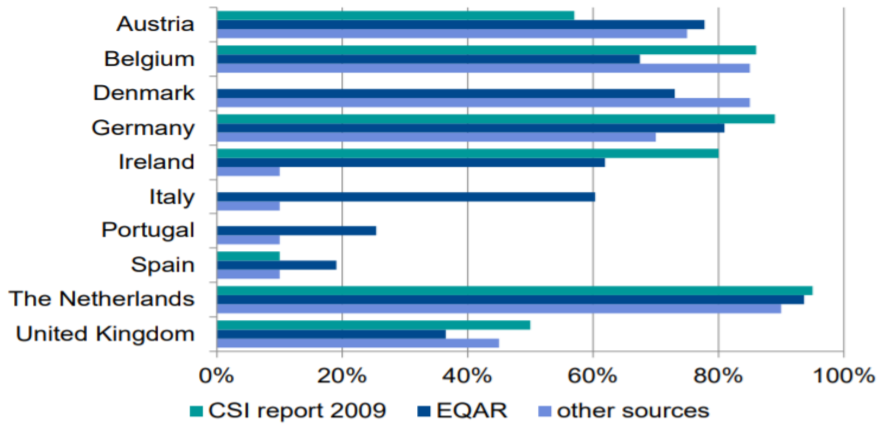


Figure 12: Recycling rate of European countries (Gervasio, 2018)

When concrete is recycled it usually serves either as:

- sub-base or base for road constructions
- as course or fine aggregate in new concrete.

	Germany	*Netherlands*	*UK*
sub-base or base for road constructions	*81%*	*86%*	*93%*
as course or fine aggregate in new concrete.	*19%*	*14%*	*7%*

Table 1: recycled concrete usage

Crushed, recycled concrete serves best use in road construction, as production of new concrete is limited according to current regulations.

2.8.3 Steel

Steel is greatly used in construction as reinforcement to concrete or framework. It is also the one of the most recycled materials in the world.

Product	***% reused***	***% recycled***	***% lost***
Heavy structural sections/tubes	*7*	*93*	*0*
Rebar (in concrete superstructures)	*0*	*98*	*2*
Rebar (in concrete sub-structure or foundations)	*2*	*95*	*3*
Steel piles (sheet and bearing)	*15*	*71*	*14*
Light structural steel	*5*	*93*	*2*
Profile steel cladding (roof/facade)	*10*	*89*	*1*
Internal light steel (plaster profiles, door frames)	*0*	*94*	*6*
Other (e.g. stainless steel)	*4*	*95*	*1*

Table 2: steel recycling

2.8.4 Wood

Unlike steel and concrete, wood is a limitless source, and by efficiently handling wood in a full life cycle we can be sustainable in this department (Leblanc, 2018). In the US, 70.6 million tonnes of wood waste were produced in 2010, about half coming from construction. Only around 15-20% of this wood was recycled or reused. Most of recycled wood from construction comes from pallets, crates, beams, windows and doorframes, fences, and panels.

Recycling of wood comes with a few limitations, making it harder to recycle, especially for further constructional use (Northern Ireland Environment Agency, n.d.).

Limitation to recycling wood:

- Limited waste management
- Unknown levels for contamination
- Low profitability
- Limited marketplace
- Practical difficulties – e.g. glue or screws
- Government policies.

Recycled wood can serve other purposes that are not constructional-related such as:

- Chipboards
- Beddings
- Remanufactured products – e.g. fibre composites
- Logs, fuel chips, biofuel
- Liquid fuel (ethanol)

2.9 Demolition

In 2020 the EU launched an ambitious target for the building sector: 70% of non-hazardous construction and demolition waste will be recycled (Gervasio & Dimova, 2018). Across Europe, about 25-30% of all waste generated comes from construction and demolition waste (C&DW).

When a building is to be demolished and taken apart, waste management is very important (EPA, 2020). Often heavy and bulky items need to be extracted, sorted, and analysed for either re-use or recycling. These materials can be concrete, wood, drywall, metal, bricks, glass, and plastic.

EPA’s waste characterization report, the Advancing Sustainable Materials Management: 2018 fact sheet, says that 600 million tons of C&DW waste was generated in the 2018, more than twice the amount of municipal solid waste (EPA, 2020). However, just over 75% of this waste was either re-used or recycled, a lot of it as aggregate in concrete. Other material waste was used as fuel, re-manufactured products, compost, and soil. Asphalt recycled from demolition can be used as asphalt mixture.

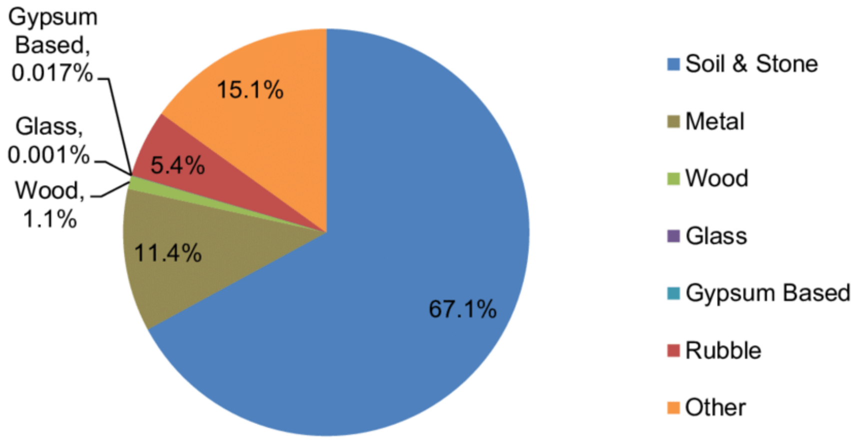


Figure 13: Composition of demolition waste (McCoole, 2013)

2.10 Rehabilitation

The term rehabilitation of building is to increase or ensure a building’s functional requirements (Qualharini, 2019). The reason for a certain rehabilitation depends on the definitions:

- **Restoration:** action set to preserve a structures architectural or historic view.
- **Renovation:** alteration of conditions inside an existing building, like habitability, usability, or safety.
- **Maintenance:** actions set out to conserve or recover the functional capacity of the building, to satisfy needs

2.11 Rehabilitation vs Demolition and Construction

When deciding between rehabilitation or demolition of a building a lot of factors play a role. Obviously, we cannot tear down a historical building and re-construct it, but we can renovate it for structural reasons and mainly requirements for its use (Trabucco, 2013).

An old building will rarely suffer from structural decays, but rather struggle to meet standard requirements for the tenants, like internal comfort, functionality, and environmental performance. Especially if the old building serves as a hotel or a bank, it requires certain standard for both the workers and customers (Trabucco, 2013).

Usually rehabilitation is best choice (both environmentally and economically), but demolition and construction occur when no other option is available (Trabucco, 2013). Inappropriate technical aspect such as very low floor-to-ceiling height can make new installations difficult and expensive. Sometimes the expected value of the new building will exceed the demolition and construction costs, making it a higher value option.

Generally renovating tall buildings can cost 50-90% less than the demolition and construction of a new one, and the restoration can take downwards to half the time to complete (Trabucco, 2013). Tall buildings are usually served in dense urban areas, where explosives for demolition are not an option as well.

When discussing the challenge of rehabilitation vs demolition, we usually think of both as large projects (Trabucco, 2013). However, rehabilitation comes in smaller batches. A study from 2013 was looking at tall building (200 m+ US/Canada, 100 m+ Europe), and saw that around 10% of these buildings had received significant renovations. A building must meet the user's expectations as vacant buildings are losing money. Tenants, who can be large firms, have leverage to modify the building to their needs.

Renovation	***%***
Facade renovation	*41*
Alterations of building mass or internal space	*21*
Heating, ventilation, and air conditioning	*15*
Removal of asbestos	*11*
New tenant needs, system upgrades	*7*
Structural issues	*4*

Table 3: Examples of renovations

From the table above, façade renovation is seen to be the most common renovation. Heat stresses, solar radiation, and weather effects such as rain and wind can cause decreased performance.

One hidden threat to this debate is asbestos. Previously used as an electric insulator, it was discovered as a cause of cancer. Removal of asbestos in old building can be very expensive and a very long process.

Chapter 3: Applications of Wall Studs

Wall studs are vertical pieces of either wood or metal positioned in closely intervals to form the framework of the wall (Wiki, 2020). Studs may carry structural loads but can also be part of a partition wall and carry no load. Typically wall studs are made of timber, but steel is increasingly popular.

A wall stud is fastened by nail and hammer, but modern technique can involve use of screw fasteners, clips, and ties as to increase wind and seismic resistance. Studs can hold windows, door, isolation, interior and so on in place, and can sometimes be bundled together to hold for example intersecting walls. There are different types of studs followed their use, such as:

- **King stud:** used on either side of door or window, from bottom plate to top plate.
- **Trimmer or jack:** used on either side of door or window, from bottom plate to underside of header.
- **Cripple stud:** used either above or below a framed opening.
- **Post or column:** groups of studs fastened side-by-side.

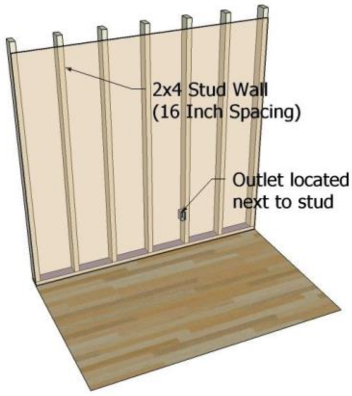


Figure 14: Timber studs

Figure 15: Steel studs

3.1 Timber Studs

Timber studs are looked at as a more traditional and safer choice (Sebring, 2016). Wood can provide good support for variety of different structures. Not long-ago, before development of modern metal applications, timber studs were the most available and by far most common choice of material for studs. Still to this day, many professionals prefer wood over steel, especially to blend in with an already complete wooden structure. If you are working with windows and doorway, timber studs allow for modification as they can easily be nailed onto doors and window frames at later points.

Timber studs come in a variety of sizes from 2”x4” to 2”x8” (Sebring, 2016). Timber can also vary in material as we have light structural timbers such as softwood trees like pine and pruce. There is also higher quality timber such as cedar or hardwood.

What makes timber studs so applicable? For once, wooden studs can support a lot of weight and can bear loads of walls, cabinets, doorways, and frames. Timber studs are easy to modify and cut to our liking if modifications are needed. Wood lasts long, and if needed can easily be replaced at an affordable cost. It does, however, face the challenge of moisture and humidity. Wood can warp and rot and can be difficult to protect during wet months. While it does vary from carpenter and home-fixers, some can find it difficult to work with and install wooden studs.

3.2 Steel Studs

As mentioned before, development of modern metal application has made us see an increase in popularity of steel studs (Sebring, 2016). They are more and more common in hardware stores but can face a challenge for home-fixers. Metal studs are primarily composed of steel, but initially made popular for use in basement walls. They are used to support non-load-bearing walls. Framing with steel is a simple, quick, and affordable process. Steel studs can also be applied in a structure with a framework of timber. Steel is much more lightweight than wood and would not cause the timber to be worn or stretched down.

When working with steel studs it is important to select proper screws (Sebring, 2016). As steel cannot be penetrated with screws, drywall screws should be selected as they are easy to insert and modify. Steel studs comes in different sizes ranging from 2½” to 14” and above.

While steel studs can corrode, they are usually safe from wear over time, and not affected by humidity and moisture (Sebring, 2016). This means that steel studs are reliable for a very long time. Steel is also generally a light metal which is easy to store and easy to maintain. With steel studs you avoid the worry of termites. While steel studs have many great traits, it does face a difficulty in modification.

3.3 Timber vs Steel Studs

When choosing between timber and steel studs there are many things to take into consideration. Here it is important to split between environmental and general properties.

3.3.1 Strength

Generally, steel is placed in a higher spacing (600mm) than wood (400mm) due to its higher strength and stability (Klippstein, 1992). Decreasing spacing slightly increases the shear strength.

Steel has both higher compressive strength and modulus of elasticity. Studs need to withstand both vertical forces and shear stresses due to natural forces (Klippstein, 1992). This makes steel better in areas where earthquakes are a threat, as the integrity of steel can prevent structural damage. Since the strengths are different for these two materials, we usually use less material of steel with a higher spacing. This allows us to use longer spans and larger windows, which is wanted especially in bigger office buildings.

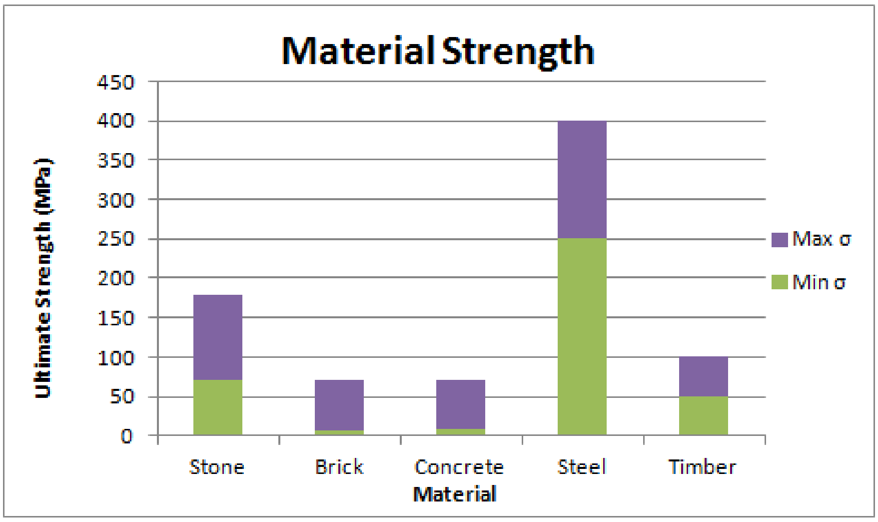


Figure 16: Material strength (Drexel University)

3.3.2 Maintenance

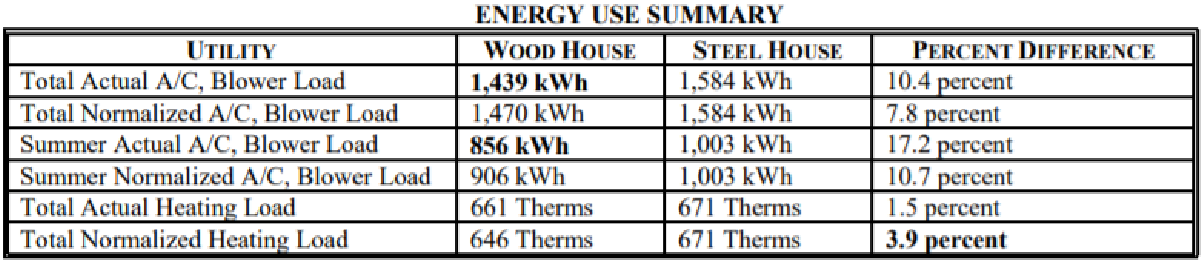
Steel is generally less maintenance than wood (Klippstein, 1992). Steel frames are galvanized in manufacturing and should be protected from corrosion, but it is important track that no damage has been done to the frame as it can be exposed to corrosion. Timber, however, faces the challenge of rotting, especially when the moisture is high. Therefore, it needs to be painted regularly to keep it safe from mold, rot and pests. If the level of humidity gets high wood can warp and rot, or even worse, get attacked from termites. This greatly reduces its strength and can even cause structural difficulties. Repairing a termite-infested frame is a costly process. Insurance companies take these risks into account as steel is less risky with a longer lifespan.

3.3.3 Installation

Steel is prepared for exact precision and cannot face warping (Klippstein, 1992). It is also easier to transport steel due to its lower weight, without facing possible small defections. While wood is easier to replace partly, it requires many different tools to install, but is easier to cut and modify on sites if there is need for it. The labour costs for wood are normally higher than for steel.

3.3.4 Thermal conductivity

Steel is a conductor and can be a liability if any live wires encounter the framing (NAHB Research Center, 2002). It is required to install circuit breakers to prevent potential lethal crisis. Wood on the other hand, is a natural insulator that can absorb heat and release it slowly during the day. Energy use is marginally lower in houses with mainly wood frames.



ENERGY USE SUMMARY

UTILITY	WOOD HOUSE	STEEL HOUSE	PERCENT DIFFERENCE
Total Actual A/C, Blower Load	**1,439 kWh**	1,584 kWh	10.4 percent
Total Normalized A/C, Blower Load	1,470 kWh	1,584 kWh	7.8 percent
Summer Actual A/C, Blower Load	**856 kWh**	1,003 kWh	17.2 percent
Summer Normalized A/C, Blower Load	906 kWh	1,003 kWh	10.7 percent
Total Actual Heating Load	661 Therms	671 Therms	1.5 percent
Total Normalized Heating Load	646 Therms	671 Therms	**3.9 percent**

Figure 17: energy use summary

3.4 Environmental impact of steel vs timber studs

When comparing environmental impacts of steel and timber we need to split into three categories: manufacturing (resource extraction and production), operational impact, and waste and recycling.

3.4.1 Manufacturing

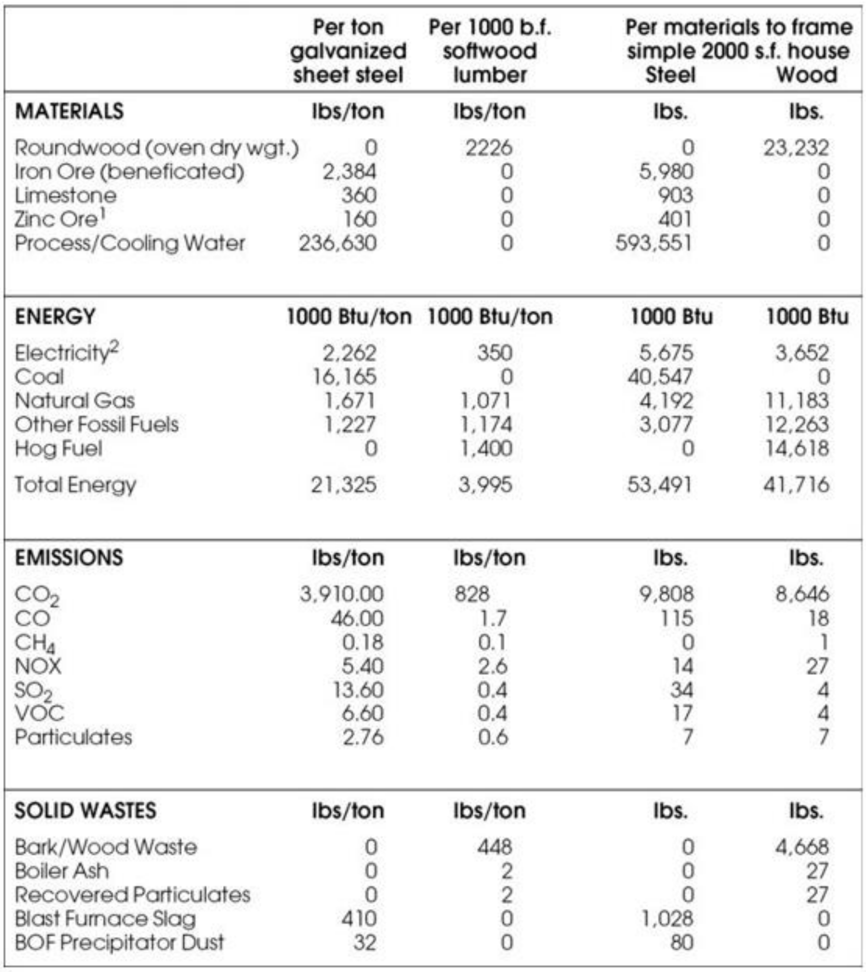
When we discuss the environmental impact a material has when being produced we have to consider resource extraction and manufacturing process.

Timber

We know that timber is extracted from trees, primarily spruce, fir and pine (Malin, 1994). And we also know that tree is naturally a renewable and theoretically ‘infinite’ source. The impact of harvesting lumber varies, where inappropriate practices can lead to habitat destruction, loss of biodiversity, and siltation of streams. Wayne Trust, a project manager who leads a research on sustainable building materials, said: “You can renew trees, but not forests.”

Trees take a long time to grow before being ready to harvest (Kinver, 2013). Most trees can be ready for 10 to 20 years, but some trees can take up to 50 years. By excess harvesting of trees, faster than re-growth, there can be huge environmental impacts. Deforestation in an un-timely manner can cause loss of biodiversity. When mass amounts of tree are removed, the soil will lose its support from roots and can become saturated. This can cause flooding and cause severe damages. Trees can, through photosynthesis, turn carbon monoxide to oxygen and are needed to keep our level of global warming more stable.

The manufacturing process of timber is not without risks (Malin, 1994). Making lumber from logs consists of debarking, sawing, surface treatment and drying the lumber in the kiln. Additional preservation is needed in case of termites, and arsenic based treatments such as CCA and ACZA retain an environmental and hazardous risk.



	Per ton galvanized sheet steel	Per 1000 b.f. softwood lumber	Per materials to frame simple 2000 s.f. house	
			Steel	Wood
MATERIALS	**lbs/ton**	**lbs/ton**	**lbs.**	**lbs.**
Roundwood (oven dry wgt.)	0	2226	0	23,232
Iron Ore (beneficated)	2,384	0	5,980	0
Limestone	360	0	903	0
Zinc Ore[1]	160	0	401	0
Process/Cooling Water	236,630	0	593,551	0
ENERGY	**1000 Btu/ton**	**1000 Btu/ton**	**1000 Btu**	**1000 Btu**
Electricity[2]	2,262	350	5,675	3,652
Coal	16,165	0	40,547	0
Natural Gas	1,671	1,071	4,192	11,183
Other Fossil Fuels	1,227	1,174	3,077	12,263
Hog Fuel	0	1,400	0	14,618
Total Energy	21,325	3,995	53,491	41,716
EMISSIONS	**lbs/ton**	**lbs/ton**	**lbs.**	**lbs.**
CO_2	3,910.00	828	9,808	8,646
CO	46.00	1.7	115	18
CH_4	0.18	0.1	0	1
NOX	5.40	2.6	14	27
SO_2	13.60	0.4	34	4
VOC	6.60	0.4	17	4
Particulates	2.76	0.6	7	7
SOLID WASTES	**lbs/ton**	**lbs/ton**	**lbs.**	**lbs.**
Bark/Wood Waste	0	448	0	4,668
Boiler Ash	0	2	0	27
Recovered Particulates	0	2	0	27
Blast Furnace Slag	410	0	1,028	0
BOF Precipitator Dust	32	0	80	0

Figure 18: Emissions in production of steel and timber (Malin, 1994)

Steel

Steel is produced from the raw materials iron ore, limestone, coal, and zinc (World Steel Assocation, 2018). Today's steel can be produced by two main methods: basic oxygen process (BOP) which uses a blast furnace and electric arc furnace (EAF).

Production of steel involves melting lime, coke (extracted from coal) and iron ores in a furnace (World Steel Assocation, 2018). Later, they are blasted with pure oxygen to remove impurities and get liquid steel, which is then casted and formed.

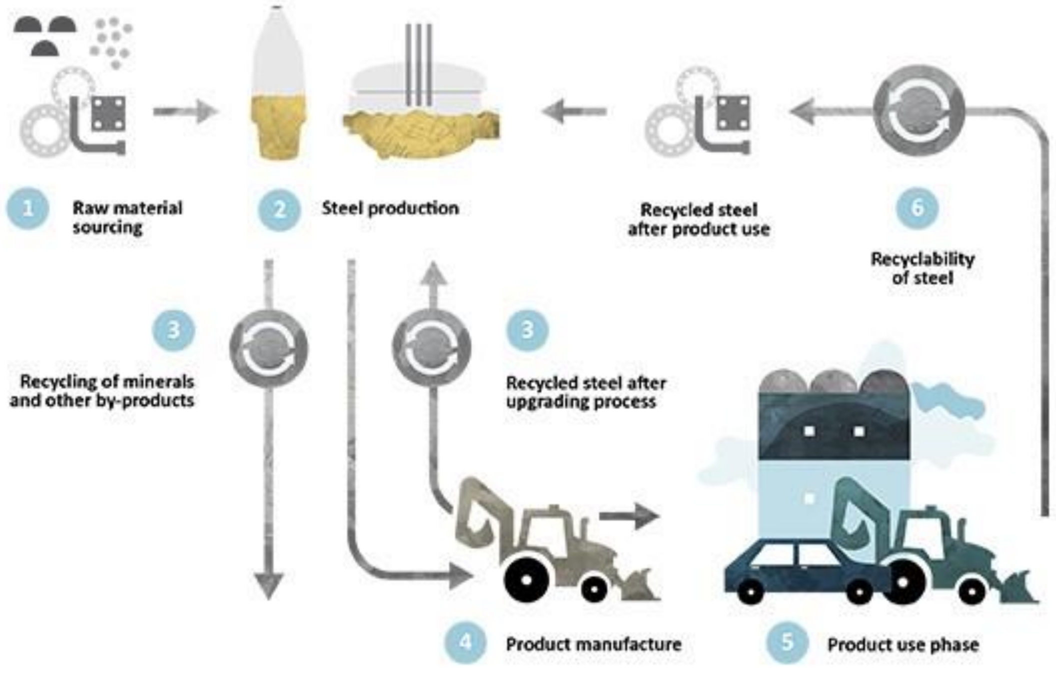


Figure 19: steel production cycle (SSAB)

All these materials are non-renewable, mined from earth (Liu, 2020). The main ingredient, iron ore, is mined at a rate of 2000 million tons a year, 95% of which is used in the steel industry. Steel manufacturing is a highly energy intensive and air polluting process. Steel production requires a large input of coal: a material that release great amounts of CO_2 during heating (Axelsson, 2018). Coal stands for 90% of the CO_2 emissions in steel industry. Emissions of NO_x is also normal in the heating process during fuel combustion, as well as sulphur dioxide (SO_2).

A life-cycle inventory assessment made on steel production saw that for every ton of molten steel, 358.84 kg of CO_2 was produced, 1.96kg of SO_2 and 0.42 kg of $PM_{2.5}$ (Liu, 2020). However, the same research compared a cleaner production of steel, involving less iron and therefore less fuel and ore. The results showed that iron ore has the biggest environmental impact in steel production, accounting for 70% of total impact.

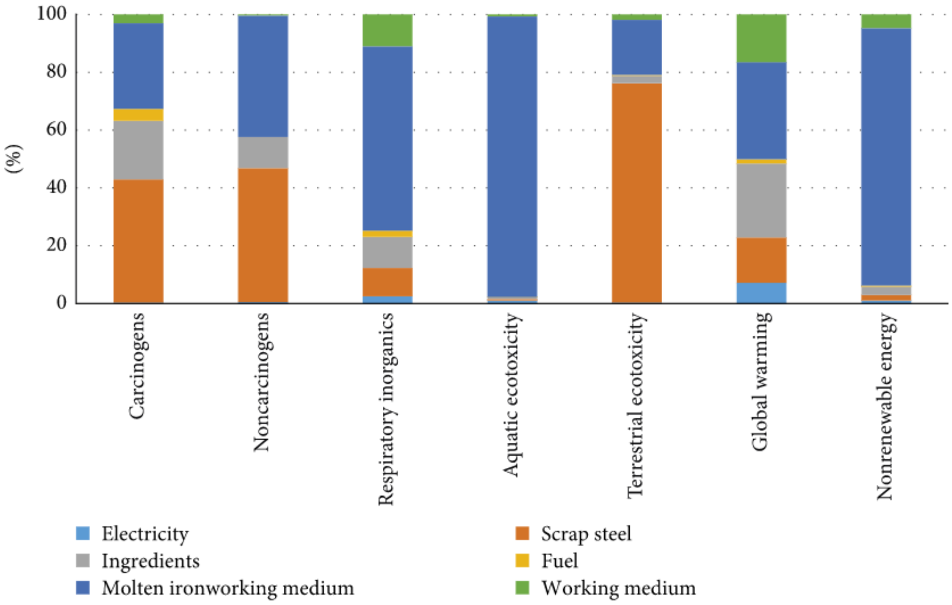


Figure 20: steel environmental impact distribution (Liu, 2020)

3.4.2 Operational Impact

Steel is 400 times more conductive of heat than wood and can pose as a liability in areas with high need of cooling or heating (Malin, 1994). This is an important environmental factor to consider. The high conductivity of steel cause thermal bridging, which is movement of heat through a material.

We measure a materials resistance to heat flow as thermal resistance, or R-value. This is the materials insulation. A high R-value is desired for a building material to keep temperature inside stable. Wood has a significantly higher R-value. While steel have great strength, its thermal characteristics can be a problem when using a full framework of steel.

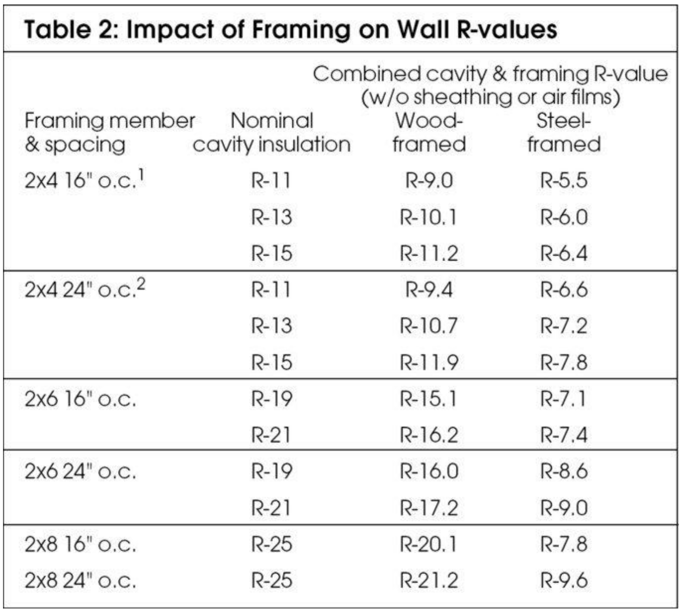


Table 2: Impact of Framing on Wall R-values

		Combined cavity & framing R-value (w/o sheathing or air films)	
Framing member & spacing	Nominal cavity insulation	Wood-framed	Steel-framed
2x4 16" o.c.[1]	R-11	R-9.0	R-5.5
	R-13	R-10.1	R-6.0
	R-15	R-11.2	R-6.4
2x4 24" o.c.[2]	R-11	R-9.4	R-6.6
	R-13	R-10.7	R-7.2
	R-15	R-11.9	R-7.8
2x6 16" o.c.	R-19	R-15.1	R-7.1
	R-21	R-16.2	R-7.4
2x6 24" o.c.	R-19	R-16.0	R-8.6
	R-21	R-17.2	R-9.0
2x8 16" o.c.	R-25	R-20.1	R-7.8
2x8 24" o.c.	R-25	R-21.2	R-9.6

Figure 21: impact of framing on wall R-values (Malin, 1994)

3.4.3 Waste and recycling

When comparing the endgame for these two materials, we usually consider steel to be a better choice. While manufacturing of steel provides significant environmental challenges, the fact that it be can easily recycled or re-used allows us to circulate the material for a long time. Steel also has a generally higher lifetime in building (Malin, 1994).

Wood is generally biodegradable, but treatment of constructional wood will cause it not to be, forcing us to treat it as hazardous waste. Since wood characteristics can decay over time, wood can be re-used into different lower-grade materials.

Chapter 4: Methodology

The problem I faced in the beginning required a lot of planning on how to tackle the problem. The chapter of methodology explains which methods are used and why. A combination of methods was needed to get information and results.

4.1 Quantitative or qualitative research

Finding the suitable research method for a task depends on many factors. Research methods are usually divided into two subcategories: quantitative and qualitative research.

When a task requires large amount of data to be analysed, a **quantitative research** is the optimal method. Quantitative research focuses on deducting empirical data to find patterns. This can include graphs, counting, measurements and calculations to make up a conclusion.

Qualitative research focuses more on non-numerical information such as reports and text to find the optimal solution. It is a more natural approach to a subject and can require lots of research on reports and conducting interviews.

For my thesis it was required a mix of these both quantitative and qualitative research to get optimal results. While a quantitative research involved the main part of my analysis, a qualitative research was essential to explain and understand my results.

4.2 Information gathering

To get a better understanding on how to handle my problem, a literature study was performed first. This included mainly gathering information through scientific reports. While the prime focus was information, empirical data was important for providing me with an understanding of the different subjects.

My focus was to get a wide understanding of the problems we are facing, what is causing the problems and what are the potential solutions.

The literature study involved:

- **Environmental engineering in construction sector**
    - Environmental effects
    - Challenges in construction
    - Greenhouse gases and
    - Regulations
    - Recycling, demolition, and rehabilitation
- **Studs**
    - Stud selection and placement
    - Steel studs
    - Wooden studs
- **Life-cycle assessment**

    - Performance
    - Scope
    - Standards
    - Boundaries

4.3 Perform the life-cycle assessment

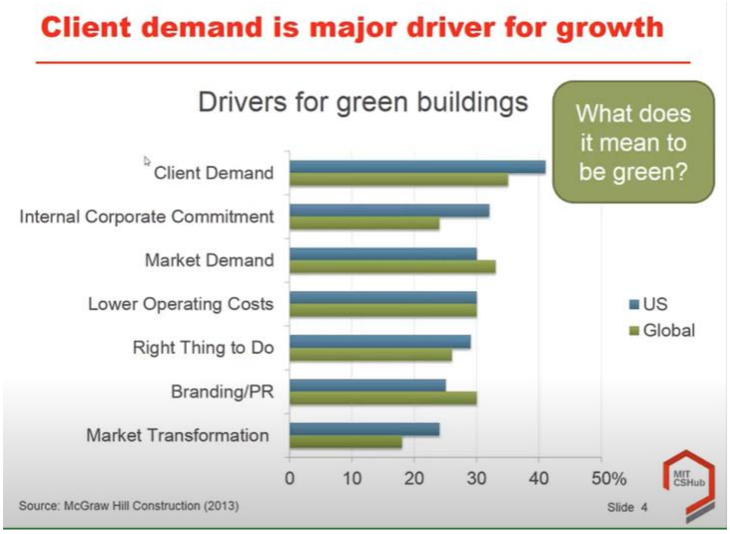
The performance of the life-cycle assessment was a challenge, as little information was present regarding merging BIM with LCA. By researching One Click LCA and other video guides I was able to get an idea on how it could work. With help from my supervisors, co-students and emails with One Click LCA, I was able to conduct an LCA.

It was important to present the data in a specific way for a better overview. This included having three separate analyses for reference and comparison. While the LCA of the building was presented, the focus was the comparison of material selection in studs. This was conducted in a way to show optimal solution in a way combining the parts of steel and timber in their own analyses, both with true and equal parts.

Chapter 5: Life-cycle assessment

A life-cycle assessment, shortened LCA, is a method to review the environmental impact a product has had from extraction of resources to its very end (Constructionlca, 2012). LCAs was primarily for simpler products but has been used in construction to review entire projects. There are many ways to carry out an LCA, but it requires full overview of the project from model, transportation, machinery etc.

It is easy to see why the use of LCA is becoming growingly popular as the demand for green buildings are drastically rising. Globally client and market demand are pushing for buildings that are more environmentally friendly as well as regulations from for example the United Nations.



Client demand is major driver for growth

What does it mean to be green?

Source: McGraw Hill Construction (2013)

Figure 22: Drivers for green buildings (MIT CShub)

5.1 Life-cycle assessment (LCA)

A life cycle assessment can be performed at any time during a project. Doing it at early stage can be most beneficial but faces the challenge that a lot of details regarding products and management are not available at the early design stage. Performing the LCA too late in process can make the cost of change expensive.

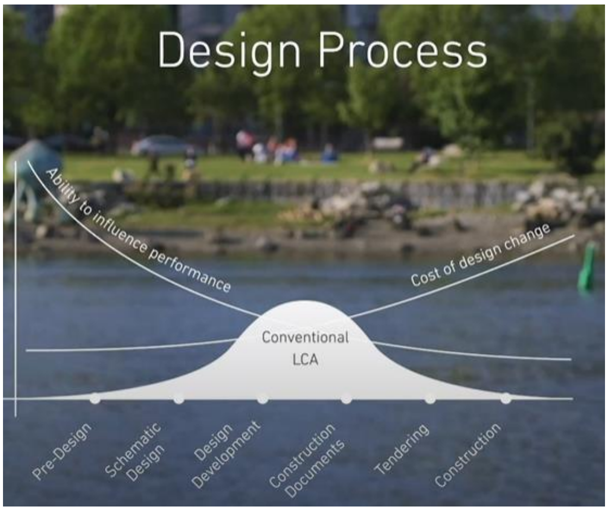
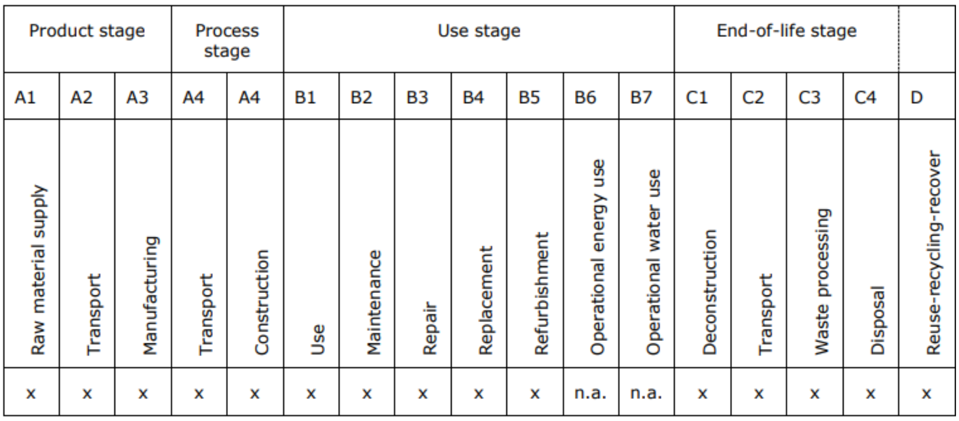


Figure 23: Design process of LCA (MIT CShub)

Figure 24: Flow chart of LCA

5.1.1 Scope

When performing an LCA, it is important to define scope and boundaries (Thøgersen, 2019). The first step is to define the purpose of the analysis. This consists of deciding system boundaries and level of detail to the analysis. The system boundaries decide which phases of the life cycle is to be considered. In some cases, the product and process stage (A1-A5) are sufficient, but in our case, we must consider End-of-life stage as well, as recycling and waste disposal are main factors to our comparison of material choice. In this phase of the LCA it is also decided which functional unit is to be used, for example CO_2-emission per volume (kg/m^3).



Product stage			Process stage		Use stage							End-of-life stage				
A1	A2	A3	A4	A4	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction	Transport	Waste processing	Disposal	Reuse-recycling-recover
x	x	x	x	x	x	x	x	x	x	n.a.	n.a.	x	x	x	x	x

Figure 25: stages of LCA (One Click LCA)

The next part is to decide detail of materials to be used in the analysis (Thøgersen, 2019). By using One Click LCA, we can decide which materials will be considered in the analysis and on what terms. When performing an analysis of a residential building, structural components make up the most important part and modelled pipe systems and furniture are neglected. In One Click LCA, materials are extracted from Revit into the website. The website has different categories but are normally subjected into:

1. **Ground and foundations**
2. **Vertical structures and facades**
3. **Horizontal structures: beams, floors, and ceiling**
4. **Other structures and materials**

Our wall studs will be placed into vertical structures and facades. The rest of the materials that are important for the analysis are all concrete, steel and wood structures, as well as cement, aluminium, mortar, tile, asphalt, glass, all types of iron as well as most types of isolation (glass, wool).

5.1.2 Environmental product declaration (EPD)

An EPD, environmental product declaration, is used to determine the environmental performance of a product (Bionova, 2021). The EPD of a product is found in standards, but different manufacturers can have different EPDs for a product. The higher the accuracy of the EPD, the higher the accuracy of the LCA will be.

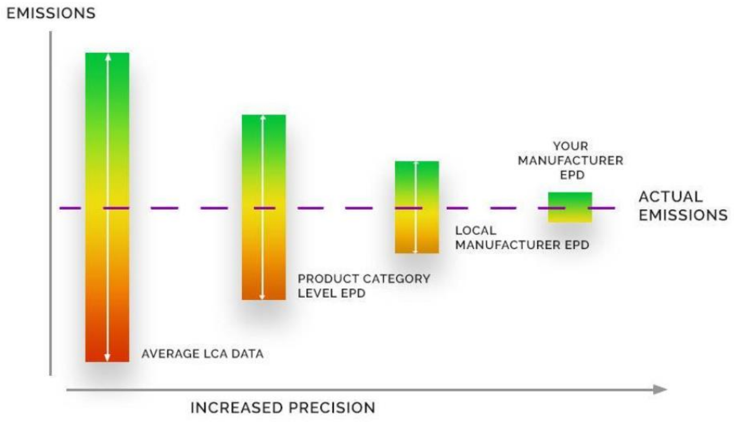


Figure 26: importance of correct EPD (One Click LCA)

When we are trying to determine the carbon footprint of an entire building project, it is important to know what materials we are using (Bionova, 2021). For an LCA it is not sufficient to just know where the material came from. We need data regarding its manufacturing, life cycle and potential environmental impact. This information comes in the form of an EPD.

One Click has a wide range of data with different EPDs for an accurate analysis (Bionova, 2021). This can for example include whether materials have been recycled before (thus lowering its carbon footprint). The necessity for such a database of EPDs has been widely recognized by many countries and there are many such databases, most of which are integrated into One Clicks database.

When choosing a material for an LCA, the order of preference should be as:

1. **Product EPD from your manufacturer.**
2. **Technically similar product EPDs from a local manufacturer.**
3. **Product category level EPD**
4. **Average LCA data for the product in question.**

While exact EPDs provide for more accurate results, the average LCA data is a good option when EPDs are not available.

5.1.3 Data input

Our product of the analysis is in this case a large residential building in Nordre Follo. The project has been given the name Langhus Gård and is built by JM.

The building is modelled in Revit by JM and shared with me so the LCA can be performed. By looking at the categories One Click LCA has for material inputs, we have everything covered by the Revit model.

Figure 27: Revit model of Langhus Gård

In Revit you can use the function ‘schedule’ to get an overview of the different materials used. By sectioning for each category, we can determine what material and the volume of each structural component in each sub-category. This can easily be plotted into the One Click website for a life-cycle assessment.

Before we plot in the data, we need to determine the EPDs (as much as possible) for a more correct and accurate analysis. These EPDs can be found by using mainly using Cobuilder Collaborate or from the suppliers.

Lastly, for the studs to be a part of the analysis we need to determine the volume of non-bearing wooden walls. The reason for this is that these walls are to be dimensioned with studs. By adding the total length of non-bearing walls in the entire building we can determine that volume of the studs. By adding a stud for every spacing (600mm), we can determine the volume of the studs and add them into the analysis. The results of these two analyses will give us an overview of which kind of studs are better environmentally.

5.2 Standard/guidelines for LCA

LCA is defined by standardized indicators provided by guidelines. These standards contain information about product categories and environmental classifications of materials. These classifications provide environmental information on materials, so called EPD (Environmental product declaration).

There are many ways to carry out an LCA according to different standards. These standards consider definition of the goal and scope of LCA.

Our LCA is carried out by focusing on the structural components rather than building physics. The LCA is carried out using One Click LCA, which performs an analysis of material components that are plugged in from the Revit model. This analysis is done according to requirements from EN 15978, ISO 21931-1 and ISO 21929 standards. The EPDs for the different materials are already defined within, and we need to define goals and scope for the LCA.

Norwegian guidelines for LCA are standardized through ISO14040 and ISO14044.

Standards	***Title***
CEN TC 350	*Sustainability of construction works*
EN 15978	*Sustainability of construction works – assessment of environmental performance of buildings*
ISO 21931-1	*Sustainability in building construction*
ISO 21929	*Sustainability in building construction*
ISO 14040	*Environmental management – Life cycle assessment – Principles and framework*
ISO 14044	*Environmental management – Life cycle assessment – Requirements and guidelines*
NS 3720	*Method for greenhouse gas calculations for buildings*

Table 4: Standards for LCA

Chapter 6: Langhus Gård

Langhus Gård is a project carried out by the large entrepreneur JM. It is a long-term project in Nordre Follo, Viken. The project takes on a large area and consists of multiple residential buildings and houses, about 300 apartments and 80 houses.

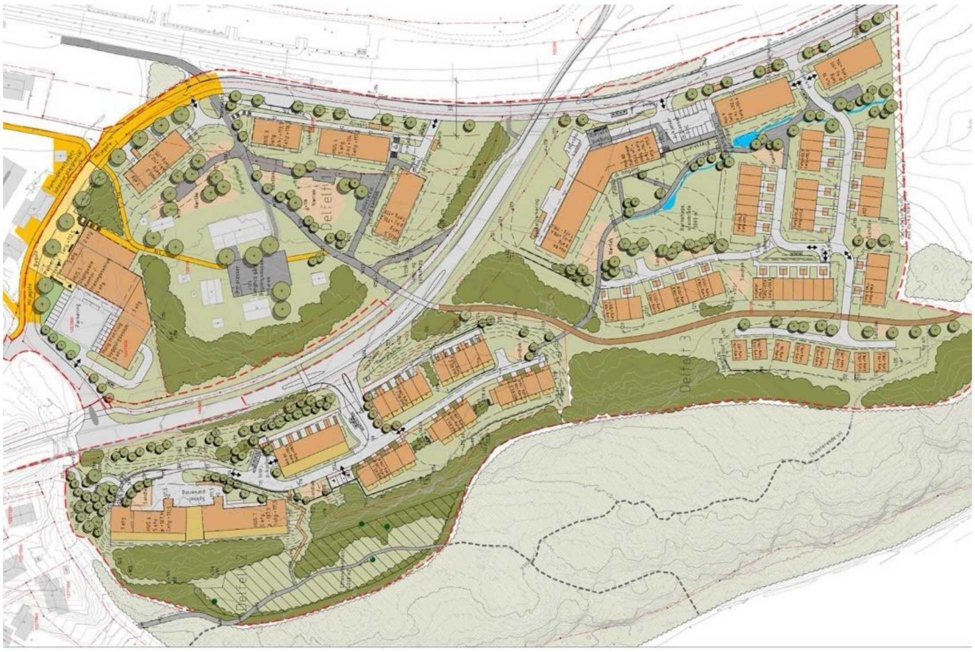
The first step in development of this area consists of two multiple-story residential buildings, Langhus Gård – Utsikten 1 & 2. These apartments will vary from 44 – 114 sqm and are projected completion October 2021 to February 2022. JM is a company that has high focus on green buildings and the project is swan labelled.

The buildings are currently past the design stage, but the consideration of wall studs is to be considered and decided between steel and wood. An analysis of the project is to be performed to get a better understanding of the GWP, resource depletion, acidification, eutrophication, and energy consumption. Furthermore, the analysis of the steel and wood studs will give us a better indication of which materials are better in green building. While the pros and cons are discussed in chapter 3, the analysis will give us a more specific answer to the environmental impact.

Langhus Gård, façade 1.

Langhus Gård, façade 2.

Langhus Gård, area 1. Utsikten 1 & 2 in bottom left corner.



Langhus Gård, 2d map.

Langhus Gård, a smart home with good solar conditions.

6.1 One Click LCA

To perform the LCA of the residential building in Langhus Gård, the website One Click LCA will be used. This website is easy to use, have a large database of EPDs and give results in End-of-life stage (A1 to C4) and waste disposal (D), which is a requirement for us.

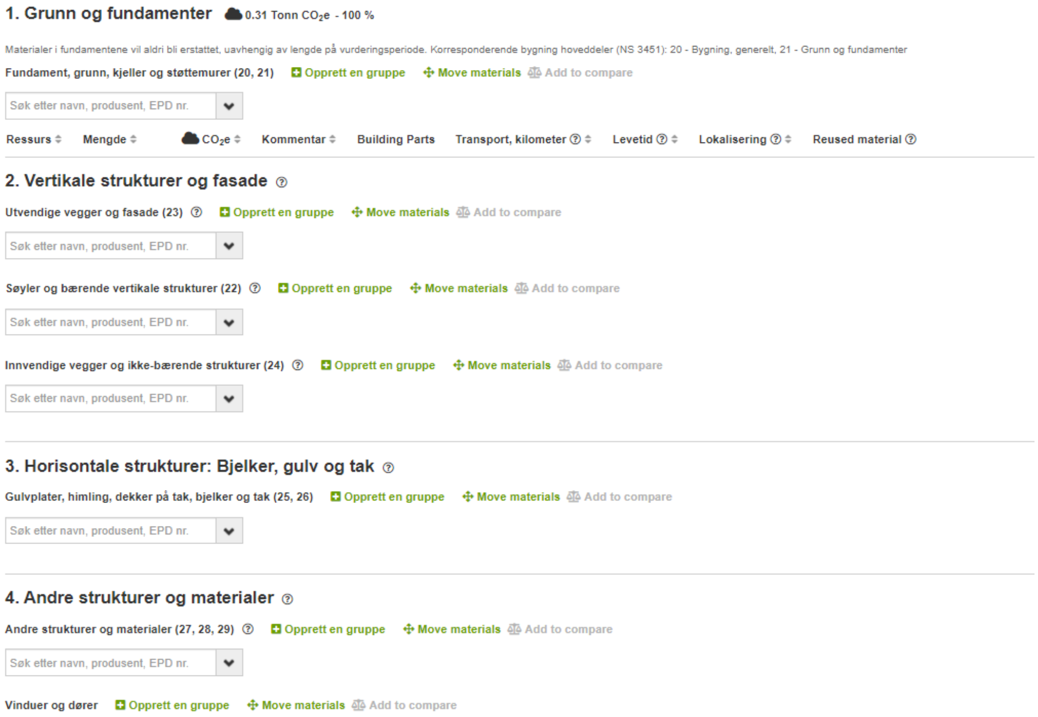
When all these parameters are fulfilled, as well as some basic information about the building, the carbon footprint of the project will be presented.

6.1.1 Building materials

When carrying out an LCA at the website the first we need input of materials. By using a materials EPD and adding the volume [m^3] the material will be considered into the analysis. This is where we put all our materials: concrete, steel, wood and more. If we do not have the EPD, a similar product can be used.

Next, we need to determine the transport distance for the material and the service life, which we will put 100 years for the entire project.

Furthermore, there is a possibility to state if the material is reused or recycled. This will lower the materials carbon footprint.



1. Grunn og fundamenter 0.31 Tonn CO_2e - 100 %

Materialer i fundamentene vil aldri bli erstattet, uavhengig av lengde på vurderingsperiode. Korresponderende bygning hoveddeler (NS 3451): 20 - Bygning, generelt, 21 - Grunn og fundamenter

Fundament, grunn, kjeller og støttemurer (20, 21)

2. Vertikale strukturer og fasade

Utvendige vegger og fasade (23)

Søyler og bærende vertikale strukturer (22)

Innvendige vegger og ikke-bærende strukturer (24)

3. Horisontale strukturer: Bjelker, gulv og tak

Gulvplater, himling, dekker på tak, bjelker og tak (25, 26)

4. Andre strukturer og materialer

Andre strukturer og materialer (27, 28, 29)

Vinduer og dører

Figure 28: Material input in One Click LCA

6.1.2 Energy/water consumption

For a fully complete LCA, energy and water consumption need to be considered. In this category the inputs are electricity, fuel consumption, district heating, energy export.

However, this is very hard for us to consider as the project is in early design stage. We can only make assumptions based on average use, but it is fine to leave out of the total equation.

6.1.3 Construction site operation

Construction site operation are also important for a complete LCA, and considers inputs such as energy consumption, material use (that are not part of the building), water consumption, waste disposal and transports regarding construction site. These parameters are unknown, and can only be based on standard assumptions.

6.1.4 Calculation period

The building has a calculation period of 100 years, which is standard for residential buildings.

6.2 Studs in LCA

The wall studs are dimensioned in the Revit file, but incorrectly as some walls have both steel and wooden studs. Our focus is on outer walls, and here we need to find out if steel or wooden studs in outer walls are more optimal from an environmental view. The reason for only focusing on outer walls is because wooden studs can face challenge from wet outer environments.

Firstly, we need to decide spacing. Most common spacings are 12, 16 and 24 inches (300, 400 and 600mm). We will use 600mm spacing and we will use it for both steel and wood. This means that the centre of one stud needs to be 600mm apart from the next stud. The easiest way is to calculate the total length of non-bearing walls and place studs accordingly every 600 mm, but it is not that simple. There will be deviation in the spacing because of obstacles and since few walls are perfectly divided by 600mm.

If there are “obstacles” like windows and doors, studs need to be placed on the beginning and end of the obstacle. This means that some spaces are not going to be fully 600 mm, some might even be larger. For windows and doors, studs need to be placed above as well if there is a load-bearing wall. When an element of wood cladding continues another element, studs are placed on the “bridge”.

- Spacing 600mm from centre of stud to the next centre
- Before and after every window, door, and other obstacles. Double on each side and above windows and doors if the wall is a load-bearing wall.
- Every outer corner needs three studs to reduce stiffness and easier placement of nails.

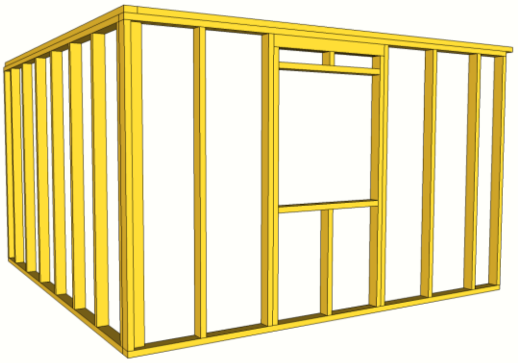


Figure 29: Studs in framework

The second, third and fourth floors are identical, which makes stud placement similar in these floors. The fifth floor differs from the other three floors with more open space and less walls, resulting in fewer studs. The garage needs studs in outer walls on the south and west side, but the rest of walls are either made of concrete or does not need studs.

Floor	***Studs***
Ground floor / garage	*115*
2nd floor	*146*
3rd floor	*146*
4th floor	*146*
5th floor	*157*
Total	*710*

Table 5: outer wall studs

Wood studs have a thickness of 48 mm and the width can vary. We will use width 148mm. The height is as high as the wall, which is 2400mm.

Steel studs come in a great variety of shapes and our hollower than wood studs, and therefore have a smaller volume. The standard size of steel studs used is 200mm which makes dimensions 2000x50x30 mm.

Figure 30: Steel stud (Byggmax)

Figure 31: Pendulum rail (Elektroimportoren)

6.3 Materials

Material	*Vertical [m^3]*	*Horizontal [m^3]*
Betong plasstøpt (Norbetong, vibrerbar)	*329.86*	*767.95*
Betong element (Thomas betong)	*0*	*295*
Stål stender	*2.13*	
Tre stender	*12.1*	
Tre		*25.53 (Tak bjelkelag)*
Tegl (wienerberger)	*77*	
Gips (gyproc)	*69.56*	
Isolasjon	*80.38*	*389.04*

Table 6: material volume

The rest of the materials had missing EPDs or were not part of the analysis for several reasons. Most of materials are neglected because of their un-importance to the analysis (like pipes and furniture).

As you can see the studs make up a small part of the volume, and steel studs even more so because of their hollow outline.

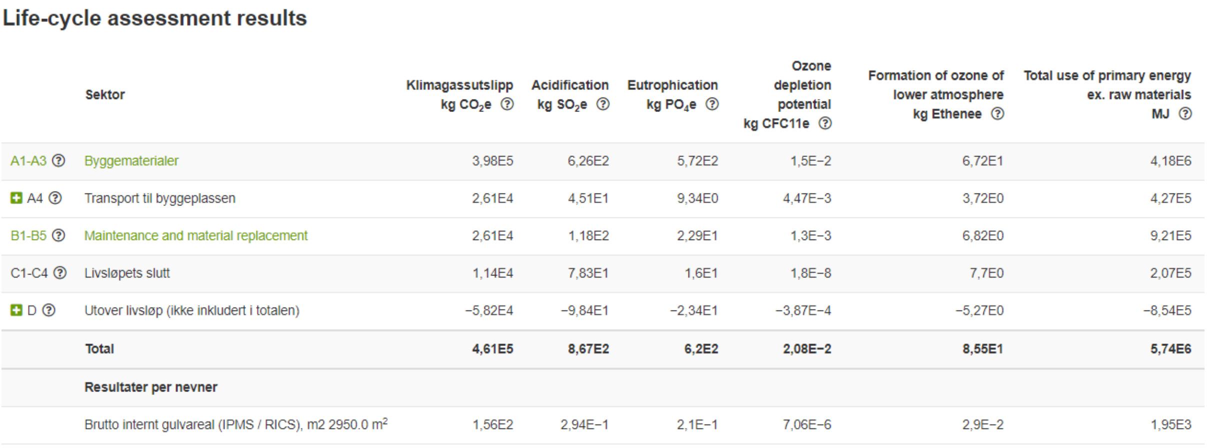
Chapter 7: Results

The life cycle assessment does calculations based on materials lifecycle. Since this is an early-stage design, we can only make assumptions based on energy and water consumption and construction site pollution. Materials make up most of our analysis. The analysis is split into two parts: one analysis with wooden studs and one analysis with steel studs. Since studs make up a small percentage of materials the differences in the results are going to be minimal.

	Wooden studs	*Steel Studs*
CO_2-emission ***[tons]***	*462*	*461*
Yearly release ***[kg/m^2/year]***	*1.56*	*1.56*
Social cost from carbon footprint ***[$]***	*23 077*	*23 074*

Table 7: Full analysis with wooden studs vs steel studs.

These are the base numbers of the comparison, and while they do give us an indication, it is important to note that the studs make a very small percentage of the total picture. To get a clear understanding of the analysis we need to look at the building without studs and isolate wooden and steel studs in their own analysis.



Life-cycle assessment results

	Sektor	Klimagassutslipp kg CO_2e ⓘ	Acidification kg SO_2e ⓘ	Eutrophication kg PO_4e ⓘ	Ozone depletion potential kg CFC11e ⓘ	Formation of ozone of lower atmosphere kg Ethenee ⓘ	Total use of primary energy ex. raw materials MJ ⓘ
A1-A3 ⓘ	Byggematerialer	3,98E5	6,26E2	5,72E2	1,5E−2	6,72E1	4,18E6
⊞ A4 ⓘ	Transport til byggeplassen	2,61E4	4,51E1	9,34E0	4,47E−3	3,72E0	4,27E5
B1-B5 ⓘ	Maintenance and material replacement	2,61E4	1,18E2	2,29E1	1,3E−3	6,82E0	9,21E5
C1-C4 ⓘ	Livsløpets slutt	1,14E4	7,83E1	1,6E1	1,8E−8	7,7E0	2,07E5
⊞ D ⓘ	Utover livsløp (ikke inkludert i totalen)	−5,82E4	−9,84E1	−2,34E1	−3,87E−4	−5,27E0	−8,54E5
	Total	**4,61E5**	**8,67E2**	**6,2E2**	**2,08E−2**	**8,55E1**	**5,74E6**
	Resultater per nevner						
	Brutto internt gulvareal (IPMS / RICS), m2 2950.0 m^2	1,56E2	2,94E−1	2,1E−1	7,06E−6	2,9E−2	1,95E3

Figure 32: Life-cycle assessment of Langhus Gård (without studs)

This is an overview of the parameters and the different stages with how much impact each stage has. These specific numbers above are without studs. In a large residential building project, the building materials are going to make up the largest impact on every parameter, especially in an early design stage.

7.1 Global warming potential (GWP)

This unit of measure is called global warming potential and gives us an accumulated release of CO_2 of the project in the period. As mentioned earlier, concrete is a large producer of CO_2 due to the calcination process, which stands for around 6% of the world's total CO_2-emission (Bjørnstad, 2016).

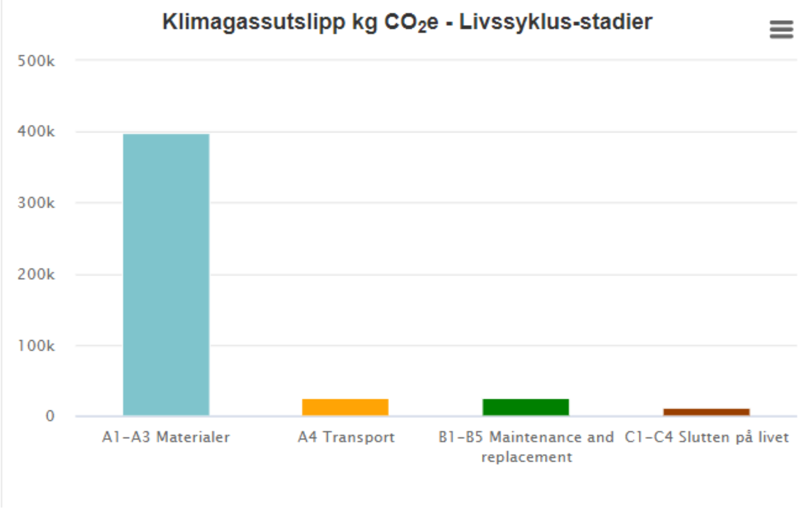


Figure 33: Distribution of CO2-emission from stages (without studs)

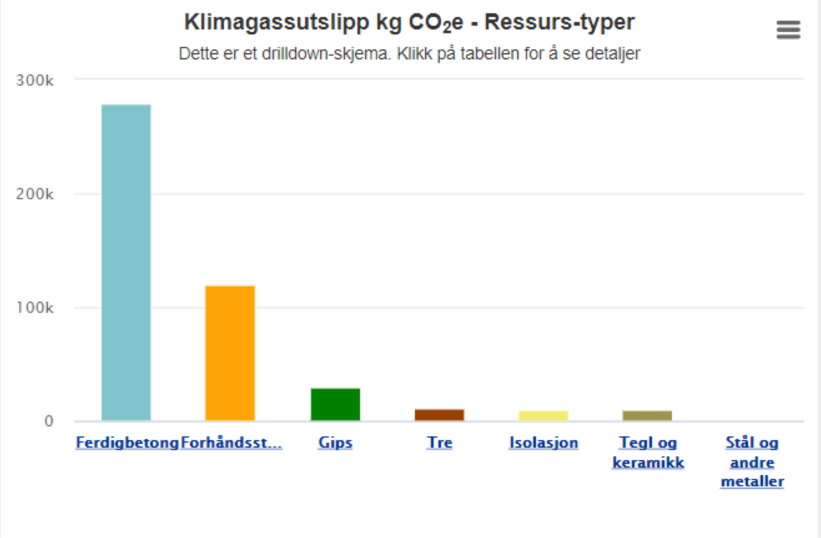


Figure 34: Distribution of CO2-emissions from materials (without studs)

As we can see, concrete stands for a large amount of the emissions. While concrete is highly represented in our analysis, they make up a large percentage of materials in every building and will therefore usually make up the largest amount of emission.

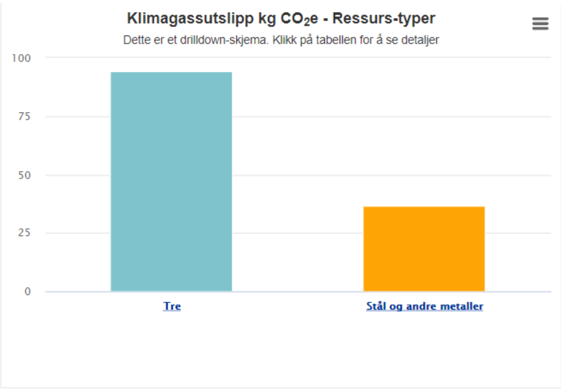


Figure 35: True parts wood vs steel (left)

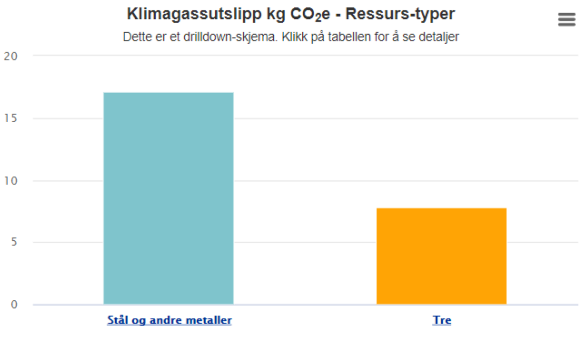


Figure 36: Equal parts (1m3) wood vs steel (right)

The comparison of the studs show that wood has about three times the amount of CO_2-emission than steel. When two generic values of EPDs are chosen, this naturally occurs as wooden studs are larger in volume than steel, and the smaller amount of material needed makes a difference in our results.

However, when we have equal amount of wood and steel, for example a 1 m^3 each, our results show that steel would have more than twice the GWP. While steel is a material that is easy to recycle, its manufacturing impact is what makes the difference.

7.2 Acidification potential (AP)

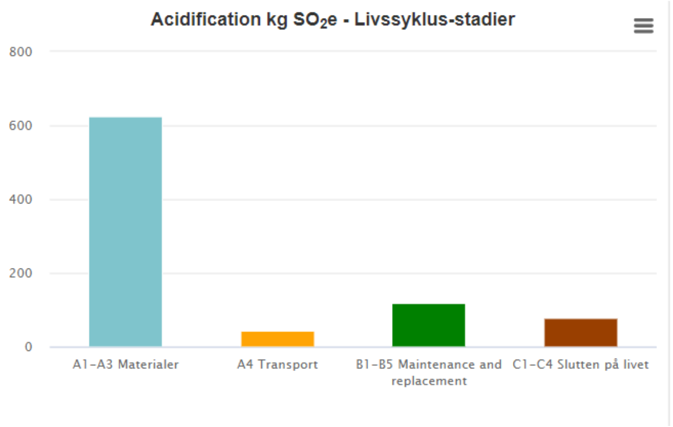


Figure 37: Analysis of stages (without studs)

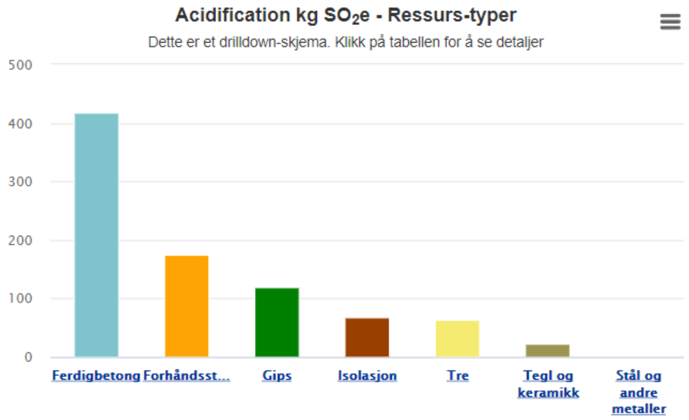


Figure 38: Analysis of materials (without studs)

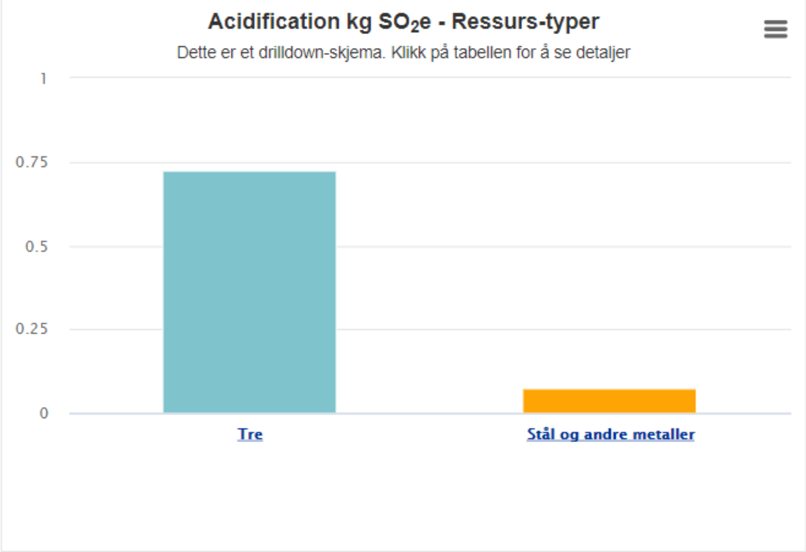


Figure 39: Acidification (SO2) of studs (true part)

Decomposition and waste disposal of wood contributes to larger acidification than steel. When doing the analysis of equal parts, wood has just under double the amount of acidification than steel.

7.3 Eutrophication potential (EP)

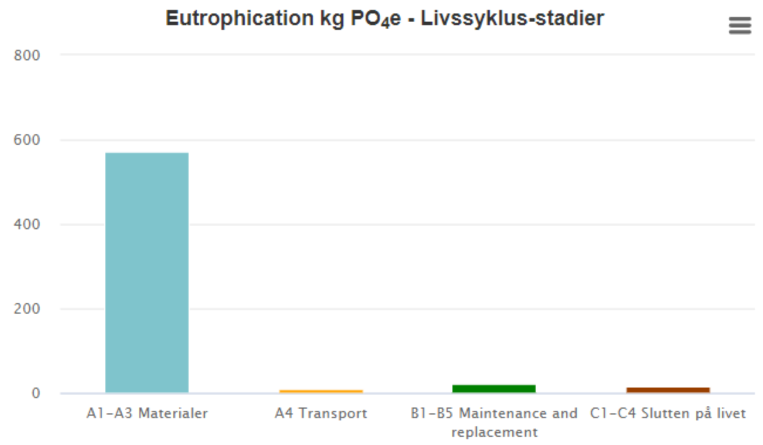


Figure 40: Analysis of building (without studs)

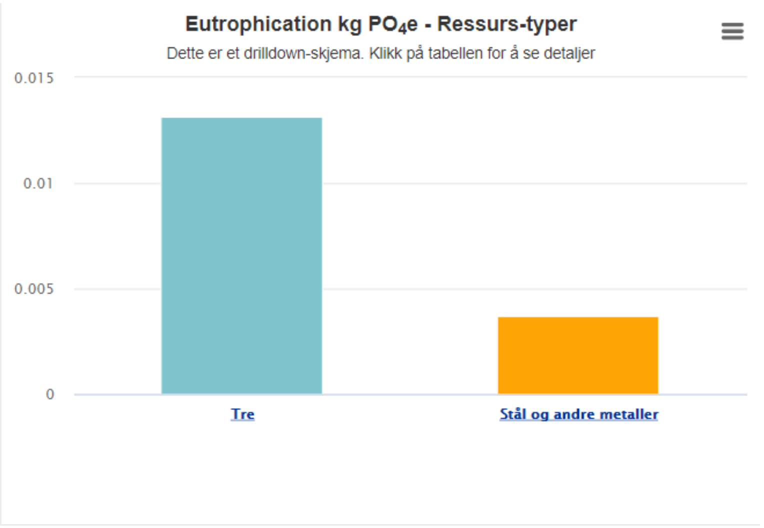


Figure 41: Equal parts wood vs equal parts steel

When compared to equal parts we can see that wood produce 3.5 times phosphate that steel does. This is due to resource extraction concerning wood. Wood also has a very high maintenance charge on phosphate and produce high amount of phosphate in the B1-B5 stages, while steel does not produce any maintenance charges. This is mainly due to steel not facing the challenge of having to be replaced.

7.4 Energy consumption

Energy consumption is the last category in the LCA. The unit is measured in megajoule [MJ].

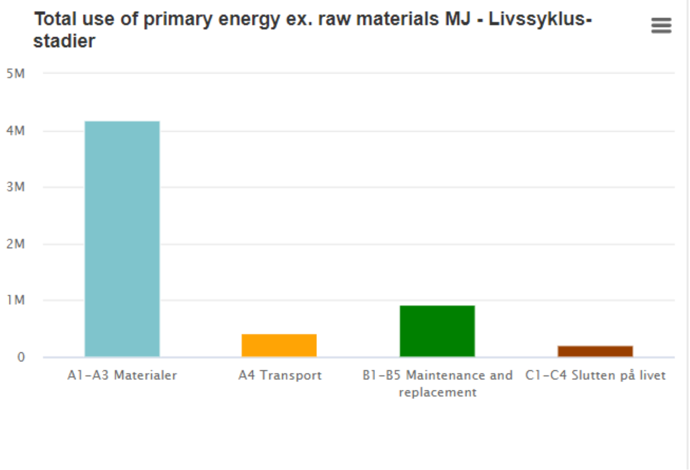


Figure 42: Building (without studs)

For pure resource extraction, steel produces about double the amount of energy as wood, but the generic renewable percentage of steel is considered, lowering it energy use. The figure below shows the steel vs woods in equal parts each, and shows wood have higher energy use, mainly due to maintenance charges.

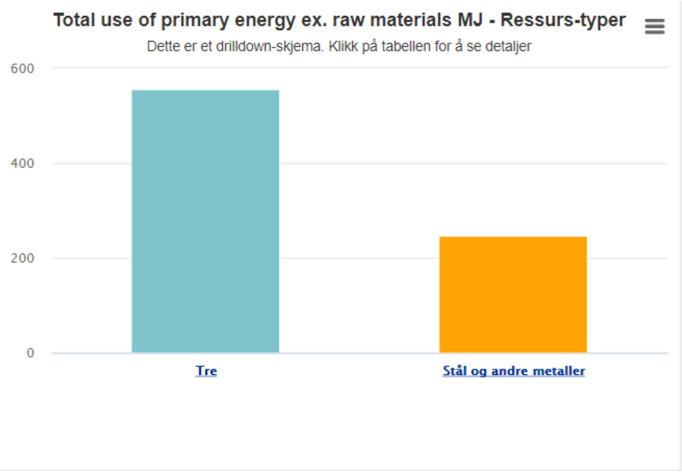


Figure 43: Equal parts (m3) wood vs steel

7.5 Carbon Heroes Benchmark

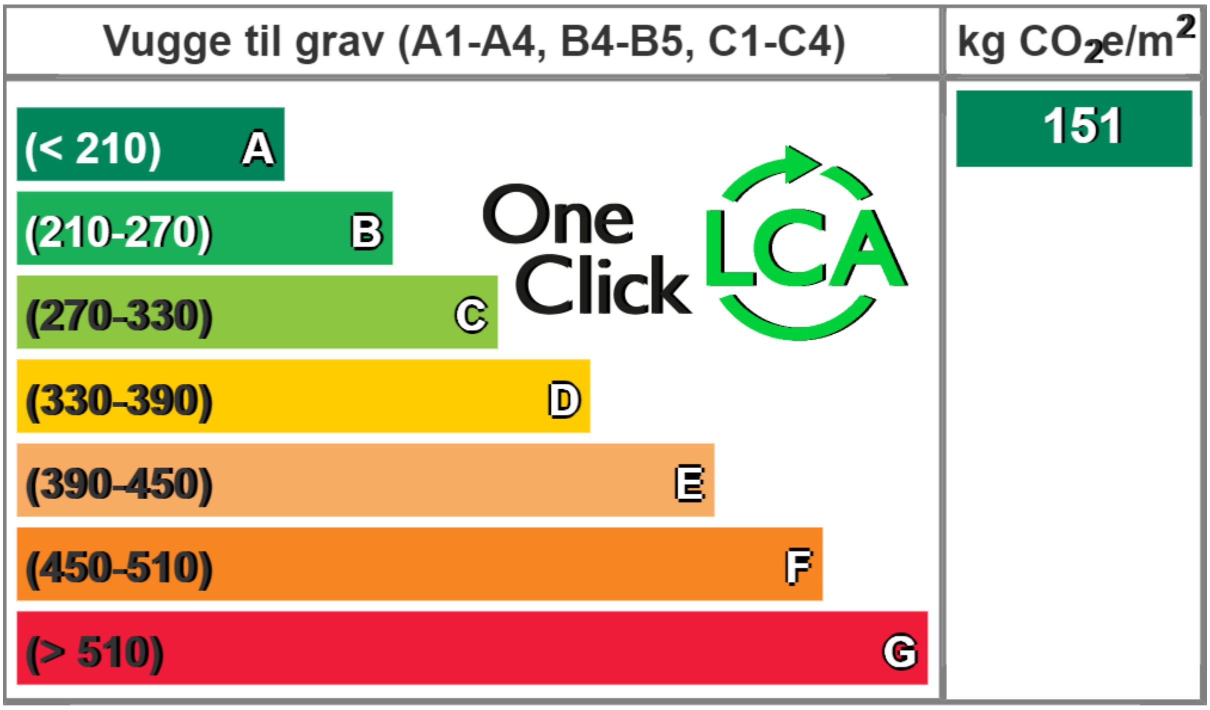


Figure 44: Carbon heroes benchmark of Langhus Gård, classification A

A carbon heroes benchmark gives an overall view of the building according to material selection, transportation, and material replacement. This is calculated over a period and neglects recycled materials. Carbon heroes benchmark gives us a classification on our project and calculates the CO_2 per m^2 in the building.

In our analysis, not every material was selected. However, over 90% of the materials used are considered, and the project received **classification A**, with a good margin to B. The end results show that Langhus Gård will have **151 kg CO_2 per m^2.**

Chapter 8: Discussion

8.1 Life-cycle analysis

From what we can see from our results, steel seems to be a better option, mainly for the lower volume of materials being used. This mainly comes from steel being a stronger and more stable material, thus allowing it to have a hollow shape.

Normal parts

	Wooden Studs	*Steel studs*
GWP – [kg CO_2]	*94.22*	*36.44*
AP – [kg SO_2]	*0.725*	*0.075*
EP – [kg PO_4]	*0.159*	*0.00795*
Energy consumption – [MJ]	*6725*	*527*

Table 8: True part wood vs steel comparison

Equal (1m^3) parts

	Wooden Studs	*Steel studs*
GWP – [kg CO_2]	*7.79*	*17.1*
AP – [kg SO_2]	*0.06*	*0.035*
EP – [kg PO_4]	*0.013*	*0.0037*
Energy consumption – [MJ]	*555.8*	*247.4*

Table 9: Equal part wood vs steel comparison

However, when comparing equal parts, we get a better understanding of the materials environmental impact. While steel is better in 3 out of 4 categories, it does emit more CO_2 than steel, which is the most vital category.

Steel is highly recyclable but does have high manufacturing impact. Timber on the other hand, has a low impact on the early stages (A1-A3), but has marginally higher transportation impact and greatly higher maintenance impact (B1-B5). This is due to timber being exposed to more treats (termites, humidity, defects).

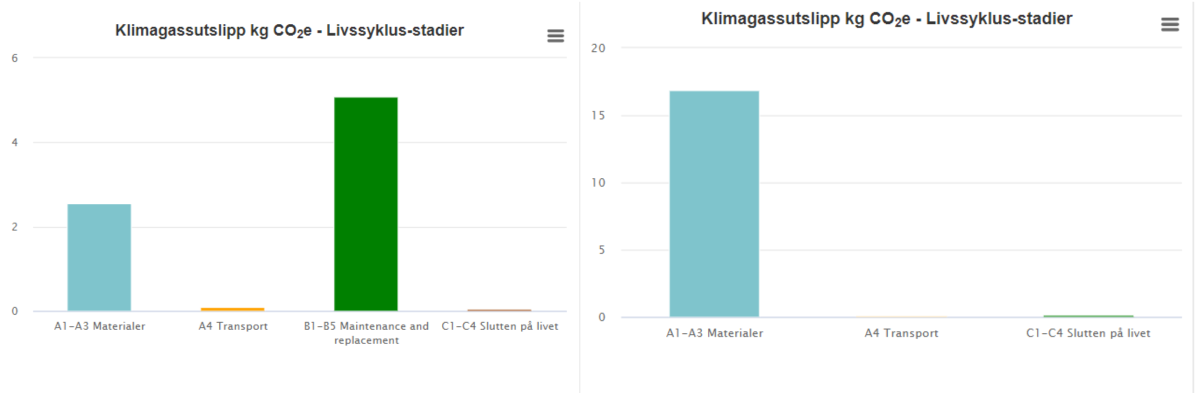


Figure 45: LCA of 1 m3 of timber (left) and 1 m3 of steel (right)

Despite steel emitting more CO_2 than timber, it is important to consider how much material will be used. In studs, one steel stud is less than 5 times the volume of a wooden stud and therefore will have 1/5 the impact.

8.2 Improvements to LCA

Performing life-cycle assessments on buildings is a relatively new technology and our methods have yet to be fully optimized. While the technology to perform reasonably accurate analyses is in place, the lack of EPDs is a problem. Just five years ago marks the date of the first EPD for cold-formed steel studs (Specifier, 2016).

The additions to our world-wide database of EPDs is growing, which leads to easier performance of analyses. From figure 24, we can see that our accuracy in LCA will increase with more accurate EPDs. We can use generic LCA data in certain points, but when comparing vital data, our manufacturers EPD is the one providing us with the best insight. More and better EPDs will guide us to achieve better precision in our analyses.

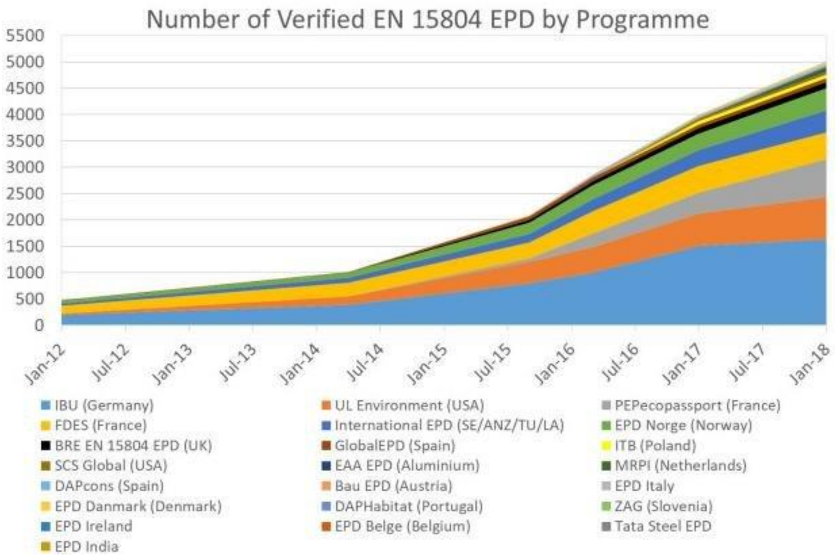


Figure 46: Increase in EPDs (LCA.no)

There are many ways to perform LCA, most of which requires software that have built in EPD database. One Click LCA, Umberto and SimaPro are all software that handles data and executes LCAs. However, these programs do not mesh well with Revit model, especially from JM who makes models using their own name codes (e.g. JM_betong, JM_stender). The plug-in from One Click recognized only 3% of the materials used in the entire building. This can be improved by using co-builder collaborate to store information regarding products. If we have accurate information on the scale of each material used in a building, we can perform LCA using solely materials and their EPDs. The results would be very accurate if we have the correct manufacturers EPD and the amount of each material.

Another idea would be to store EPDs within Revit models. If we had EPD for every material value within a Revit file, it would take less than a minute to perform a full LCA. This would lead to more sustainable buildings as we have the active impact of influencing our structure. The merge between LCA software and BIM software would improve our performance and understanding of life-cycle assessments drastically.

Chapter 9: Conclusion

In a building where we analyse studs, steel will in almost every case beat timber in terms of sustainability. While the material volume-for-volume give us an indicator that steel produce more CO_2, every other category is in favour of steel. When talking about studs, there will always be need for more material in timber than steel, because of steels hollow shape and lighter material, making it easier for storage. Steel's recyclability is also a massive advantage over wood, showing that if we have 2.2 times the amount of wood, steel will win in every category.

- Steel produces more CO_2 than timber when equal parts, but produce less energy, SO_2 and PO_4.
- A timber stud has more than 5 times the volume of a steel stud.
- Steel studs are easier to manage, transport and store.
- Steel studs can be mounted on a wooden framework, but not the other way around.

Life-cycle assessments is a great way to analyse and rate buildings in terms of sustainability. While this is relatively new technology, the ever rise of the EPD database is making LCA very easy to perform. The merge between LCA and BIM software is good at identifying volume of material, given that the materials in the BIM are generic materials. If we can build models with built-in EPDs of our material selection, LCA will be very easy to perform.

- LCA has come a long way and is very simple to use.
- The biggest challenge so far is lack of correct EPDs.
- A merge between BIM and LCA software in terms of built-in EPDs will be a huge improvement in LCA studies.

References

Axelsson, H. (2018). Environmental impact of the processes. *Jernkontoret*, 1. Retrieved from https://www.jernkontoret.se/en/the-steel-industry/production-utilisation-recycling/environmental-impact-of-the-processes/

Bionova. (2021). *https://www.oneclicklca.com/epds-for-building-lca/*. Retrieved from One Click LCA: https://www.oneclicklca.com/epds-for-building-lca/

Bjørnstad, L. (2016). Kan vi bruke betong med god klimasamvittighet? *Forskning.no*, 1. Retrieved from https://forskning.no/bygningsmaterialer-klima/kan-vi-bruke-betong-med-god-klimasamvittighet/379248

Cobuilder Collaborate. (2021, 01 01). *Cobuilder Collaborate*. Retrieved from https://cobuilder.com/: https://cobuilder.com/nb/cobuilder-collaborate/

COMMISSION, E. (2011). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS.* Brussels: EUROPEAN COMMISSION. Retrieved from https://www.europarl.europa.eu/meetdocs/2009_2014/documents/com/com_com(2011)0571_/com_com(2011)0571_en.pdf

Constructionlca. (2012, 02 20). *https://constructionlca.co.uk/2012/02/20/centc-350-and-en-15804/*. Retrieved from Construction LCA: https://constructionlca.co.uk/2012/02/20/centc-350-and-en-15804/

Danso, H. (2018). *Dimensions and Indicators for Sustainable Construction Materials: A review.* Kumasi: Department of Construction and Wood Technology. Retrieved from https://crimsonpublishers.com/rdms/pdf/RDMS.000568.pdf

Designing Buildings Wiki. (2021, 03 11). *https://www.designingbuildings.co.uk/*. Retrieved from Design Buildings Wiki: https://www.designingbuildings.co.uk/wiki/Carbon_dioxide_in_construction

Dincer, I., & Abu-Rayash, A. (2020). Energy Sustainability. In I. Dincer, & A. Abu-Rayash, *Energy Sustainability* (pp. 119-164). Oshawa: Elsevier. Retrieved from https://www.sciencedirect.com/topics/engineering/acidification-potential

EPA. (2020, 09 09). *https://www.epa.gov/ghgemissions/understanding-global-warming-potentials*. Retrieved from https://www.epa.gov: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

EPA. (2020, 11 12). *Sustainable Management of Construction and Demolition Materials*. Retrieved from epa.gov: https://www.epa.gov/smm/sustainable-management-construction-and-demolition-materials

European Cement Research Academy. (2015). *Closing the loop: What type of concrete re-use is the most sustainable option?* Dusseldorf: European Cement Research Academy. Retrieved from https://www.theconcreteinitiative.eu/images/Newsroom/Publications/2016-01-16_ECRA_TechnicalReport_ConcreteReuse.pdf

Geographic, N. (Director). (2017). *Causes and Effects of Climate Change | National Geographic* [Motion Picture]. Retrieved from https://www.youtube.com/watch?v=G4H1N_yXBiA&ab_channel=NationalGeographic

Gervasio, H., & Dimova, S. (2018). *Model for Life Cycle Assessment* . EU: JRC Science Hub.

Gillette, D. G. (2012). *Sulfur dioxide and material damage.* U. S. Environmental Protection Agency. Retrieved from https://www.tandfonline.com/doi/pdf/10.1080/00022470.1975.10470202

IPCC. (2018). *IPCC.* Retrieved from ipcc.ch: https://www.ipcc.ch/sr15/

Kinver, M. (2013). European forests near 'carbon saturation point'. *BBC,* 1. Retrieved from https://www.bbc.com/news/science-environment-23712464

Kjensmo, J., & Hongve, D. (2019). *Store Norske Leksikon.* Retrieved from https://snl.no: https://snl.no/eutrofiering

Klippstein, T. J. (1992). *Shear resistance of walls with steel studs.* Missouri: Missouri University of science and technology. Retrieved from https://scholarsmine.mst.edu/cgi/viewcontent.cgi?article=1062&context=ccfss-aisi-spec

Kvamstø, N. G. (2015, 05 01). Drivhuseffekten og jordens klima. *Bjerknes*, 1. Retrieved from https://www.bjerknes.uib.no/artikler/fns-klimapanel/drivhuseffekten

Leblanc, R. (2018, 11 26). The Importance of Wood Recycling in C&D Management. *Wood Recycling in the Construction Waste Stream,* p. 1. Retrieved from https://www.thebalancesmb.com/wood-recycling-construction-2877760

Liu, L. L. (2020). *Life Cycle Assessment of Environmental Impact of Steelmaking Process.* Shandong: National Science Foundation of China. Retrieved from https://www.hindawi.com/journals/complexity/2020/8863941/#abstract

Løken, I. (2009). *Zero Emission Construction.* Høvik: DNV GL Energy. Retrieved from https://www.klimaoslo.no/wp-content/uploads/sites/88/2019/06/Perspectives-on-zero-emission-construction.pdf

Lucon, O., & Ürge-Vorsatz, D. (2014). *IPCC Report Buildings.* Geneva: IPCC.

Malin, N. (1994). Steel or Wood Framing: Which Way Should We Go? *Building Green,* 1. Retrieved from https://www.buildinggreen.com/feature/steel-or-wood-framing-which-way-should-we-go

Martin Gulliksen, M. B. (2020). *Green concrete expertise - a case study of the county building in Bergen.* Bergen: Høgskulen på Vestlandet.

Miljødirektoratet. (2020, 11 13). *Karbondioksid (CO2)*. Retrieved from https://miljostatus.miljodirektoratet.no/: https://miljostatus.miljodirektoratet.no/tema/klima/norske-utslipp-av-klimagasser/co2/

NAHB Research Center. (2002). *Steel vs wood, Long-term thermal performance comparison.* Marlboro, Maryland: NAHB Research Center. Retrieved from https://www.huduser.gov/Publications/pdf/steelval_rpt.pdf

Northern Ireland Environment Agency. (n.d.). *Northern Ireland Business Info*. Retrieved from https://www.nibusinessinfo.co.uk/: https://www.nibusinessinfo.co.uk/content/recycling-wood-construction-projects

NTB. (2017, May 22). *Norske byggeplasser slipper årlig ut 420.000 tonn CO2*. Hentet fra https://e24.no/naeringsliv/i/naMyA5/norske-byggeplasser-slipper-aarlig-ut-420000-tonn-co2

One Click LCA. (n.d.). *One Click LCA*. Retrieved from oneclicklca.com: https://www.oneclicklca.com/life-cycle-assessment-explained/?utm_source=google&utm_medium=cpc&utm_campaign=NO%202021%20Search%20LCA&gclid=Cj0KCQjw8IaGBhCHARIsAGIRRYr94iw0hNP402xucMN76MtWgsayPWKv_k_yTcM1GKuGehO6huaTagwaAvbYEALw_wcB

Pettersen, M. M. (2020). Ombruk av byggematerialer. *Gjenvinningsbloggen*, 1. Retrieved from https://blogg.norskgjenvinning.no/ombruk-av-byggematerialer

Pickering, P. (2020). Part 1: Why monitor NO2 and PM at construction sites? *Aeroqual*, 1. Retrieved from https://www.aeroqual.com/why-monitor-no2-and-pm-at-construction-sites

Qualharini, O. a. (2019). Rehabilitation of buildings as an alternative to sustainability in Brazilian constructions. *Degruyter*, 1. Retrieved from https://www.degruyter.com/document/doi/10.1515/eng-2019-0017/html

Sebring, B. (2016, 01 26). THE BIG DEBATE: METAL STUDS VS WOOD STUDS. *Sebring*, 1. Retrieved from https://sebringdesignbuild.com/the-big-debate-metal-studs-vs-wood-studs/

Specifier, T. C. (2016, 02 26). *Construction Specifier*. Retrieved from https://www.constructionspecifier.com: https://www.constructionspecifier.com/steel-industry-releases-epd-for-cold-formed-steel-studs-and-track/

Thøgersen, S. N. (2019). *Hvordan reduseres bygningers miljøpåvirkning med LCA og BIM.* Trondheim: NTNU.

Toldnæs, J. P. (2019, 07 17). *https://snl.no/globale_oppvarmingspotensialer*. Retrieved from SNL: https://snl.no/globale_oppvarmingspotensialer

Trabucco, D. (2013). *Confronting the question of demolition or renovation.* Venice: University of Venice. Retrieved from https://global.ctbuh.org/resources/papers/download/245-confronting-the-question-of-demolition-or-renovation.pdf

UK, M. C. (Director). (2018). *How do buildings affect the environment* [Motion Picture]. Retrieved from https://www.youtube.com/watch?v=ap65Hnddfv4&ab_channel=MultiComfortUK

United Nations. (2020). *United Nations*. Retrieved from un.org: https://www.un.org/sustainabledevelopment/climate-change/

United Nations. (2021). *The Paris Agreement.* Paris: United Nations. Retrieved from https://unfccc.int/: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

Wiki, D. B. (2020, 09 25). *Stud*. Retrieved from https://www.designingbuildings.co.uk/: https://www.designingbuildings.co.uk/wiki/Stud

World Steel Assocation. (2018). *Sustainable Steel.* Brussels: World Steel Assocation. Retrieved from https://www.worldsteel.org/en/dam/jcr:ee94a0b6-48d7-4110-b16e-e78db2769d8c/Sustainability%2520Indicators%25202018.pdf