GWP of multi-storey timber buildings

State-of-the-art review

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Thesis to obtain the Master Degree in Civil Engineering

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I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Abstract

Building high-rise buildings using timber has been suggested as a strategy to reduce the buildings sector's GHG (greenhouse gas) emissions. Several researches already have shown that when a multi-storey building is redesigned using mass timber as the load-bearing structure, a smaller carbon footprint can be achieved. However, the existing studies are always focused on a definite timescale for one specific case. This study performs a meta-analysis on the existing literature concerning the potential reductions in GHG emissions achieved by timber multi-storey buildings. This is both done at the level of the material and at the level of the building. For this 36 comparative LCA's, 60 EPD's and additional relevant literature were collected. The parameter used to make the comparison in GHG emissions is the GWP (global warming potential). For the operational phase the energy consumption is also used.

The outcome was unanimously that for all the cases that focuses on the overall GWP, the timber variant of the multi-storey building caused the least carbon emissions. The reduction in GWP between the reinforced concrete and timber benchmark of the building ranged from 1,22% to 219,92%. Between steel and timber, the GWP reduction varied between 1,20% and 144,11%. The proportion of this carbon reduction seems to be highly dependent on the chosen end-of-life scenario of the construction waste. However, the latter seems to be a matter where a lot of uncertainty remains making further research into the waste processing required.

Keywords: CLT, Glulam, LCA, EPD, High-rise, Multi-storey building

Resumo

A construção de arranha-céus utilizando madeira tem sido sugerida como uma estratégia para reduzir as emissões de GEE (gases de efeito estufa) no setor de edifícios. Várias pesquisas já mostraram que, quando um edifício de vários andares é reabilitado utilizando madeira como estrutura de suporte, provoca de uma pegada de carbono menor. No entanto, os estudos existentes estão sempre focados em uma escala de tempo definida para um caso específico. Este estudo realiza uma meta-análise da literatura existente sobre as potenciais reduções nas emissões de GEE obtidas pelo arranha-céus de madeira. Isso é efetuado tanto no nível do material quanto no nível do prédio. Para isso, 36 ACVs comparativas, 60 DAPs e literatura relevante adicional foram coletadas. Os parâmetros utilizados para fazer a comparação nas emissões de GEE são o potencial de aquecimento global (PAG) e o consumo de energia.

Os resultados evidenciam que o PAG em para todos os edifício com madeira de vários andares tem menores emissões de carbono. A redução do PAG entre o a solução de betão e o melhor desempenho de madeira nos edifícios variou de 1,22% a 219,92%. Entre o aço e a madeira, a redução do PAG variou entre 1,20% e 144,11%. A proporção dessa redução de carbono parece ser altamente dependente do cenário de final de vida escolhido para os resíduos de construção. No entanto, este último parece ser uma questão onde a incerteza é elevada, continuando a ser necessária mais investigação sobre o processamento de resíduos.

Keywords: CLT, Glulam, ACV, DAP, Arranha-Céus, Prédios

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Acronyms

Name	**Description**
BF	Building Footprint
CLT	Cross Laminated Timber
CLST	Cross Laminated Secondary Timber
EAF	Electric Arc Furnace
EPD	Environmental Product Declaration
EWP	Engineered Wood Product
GHG	Greenhouse Gasses
GLT	Glued Laminated Timber/ Glulam
GWP	Global Warming Potential
HVAC	Heating, Ventilation & Airconditioning
LCA	Life Cycle Assessment
LFG	Landfill Gas
LVL	Laminated Veneer Lumber
MUF	Melamine-Urea-Formaldehyde
PSL	Parallel Strand Lumber
VHR	Ventilation Heat Recovery
WMC	Wooden Multi-Storey Construction

Chapter 1 – Introduction, objective and workingplan

This dissertation was carried out in order to receive the Master of Science degree in Civil Engineering Technology at the University of Ghent. This dissertation was developed during an Erasmus-semester at the Instituto Superior Técnico at the ULisboa in Lisbon, Portugal and accounts for 30 ECTS-credits.

1.1 Why there is a need for timber high-rise construction?

The reason for this increased interest in multi-storey buildings made from timber is the convergence of three main challenges Mankind will face in the upcoming decades: population growth, urbanization and global warming.

At the current time of writing[1], the world population totals a number of 7.708 billion (World population, n.d.). The last time a global survey was attempted [2], an estimated 100 million people were homeless worldwide and as many as 1.6 billion people lacked adequate housing (Global Homelessness Statistics, 2019). The prospects of the United Nations estimate that the global population will grow to 9.771 billion in 2050 and 11.184 billion in 2100 (World population 2017, 2017). This is shown in Figure 1.1. Not only do these extra people need proper housing, more workplaces and other infrastructure will need to be built as well. The amount of proper living units and work units will have to increase along with the growing population.

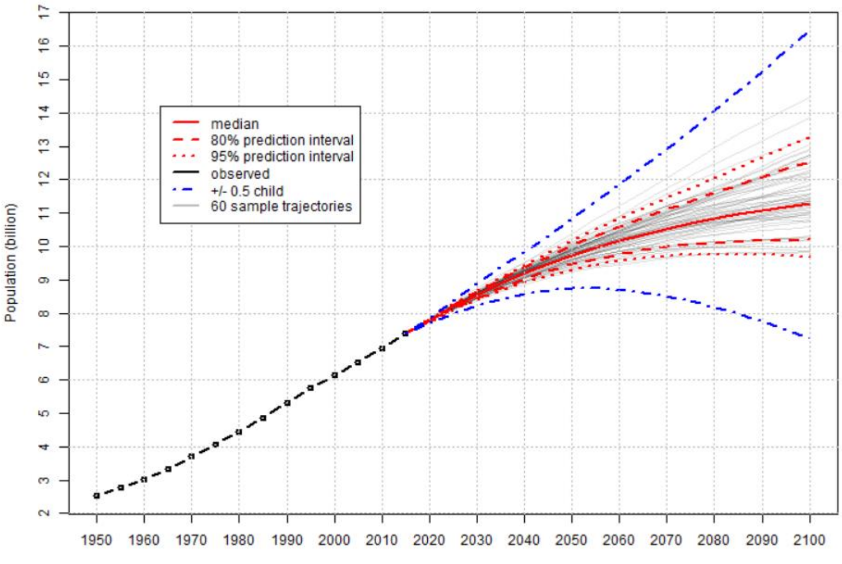

Figure 1.1: World population prospects (UN, 2017)

Not only should the number of living units and work units increase, they also have to be built more concentrated. Globally there can be a phenomenon observed in the population distribution, namely urbanization. The amount of people living in rural areas decrease and the amount living in urban areas increases. This tendency is likely to continue in the future. At the end of 2018, the UN estimated that 55.3% of the world population lived in urban settlements. According to the United Nations predictions,

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[1] 2 June 2019

[2] By the United Nations in 2005

this share will grow to 60% by 2030 and 66% by 2050. This is shown in Figure 1.2. The UN also states that nearly the complete global population growth between 2017 and 2030 will be absorbed by cities (UN, 2018) (World Urbanization Prospects, 2014).

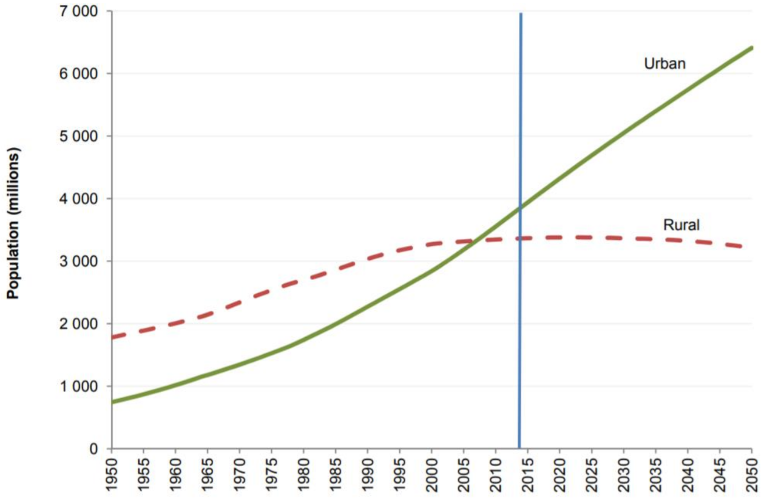

Figure 1.2: World's urban and rural populations, 1950-2050 (World Urbanization Prospects, 2014)

The problem of a growing population living on a smaller scale has been solved throughout history by building multi-storey constructions. Wherever cities emerged, high buildings arose with it. High-rise buildings create a more efficient use of the area by allowing a larger amount of people to live and to work on the same surface. Multi-storey buildings are mainly made with from building materials such as reinforced concrete and steel, two materials with a significant carbon footprint, which gets to the third and perhaps biggest problem, namely global warming.

Because of human activity, huge amounts of GHG's such as CO_2, CH_4 and N_2O are emitted into the atmosphere. The global construction sector has a significant share in this. The global construction sector emits 23% of the CO_2 emissions produced by the global economic activities (Huang et al., 2018). This is mainly due to the energy use for space heating and ventilation (Building Operations) in buildings and the CO_2 emissions during the production of building materials (Embodied Carbon) (Architecture2030, 2018). The latter is particularly large because of the production processes of steel and cement, which are needed for the production of reinforced concrete. The production of cement accounts for approximately 8% of the global CO_2-emissions (Lehne & Pretson, 2018). Since high-rise buildings contain more materials, their production emits more masses of CO_2, taken into account that materials as steel and reinforced concrete are very common in multi-storey buildings because of their strength. In order for the building industry to lower its carbon emissions it should shift to more ecological building materials with a lower carbon footprint. It is believed that this can be obtained by the use of timber materials. During its growth, timber sequestrates CO_2 from the atmosphere in the process of photosynthesis. Whereas steel and cement emit CO_2 during their production. So initially timber has a negative carbon footprint. However, manufacturing the timber to building materials together with the transport and assemblage at the building site creates carbon emissions as well, not to mention that incineration after usage causes the stored carbon to be released into the atmosphere again. The 4th assessment report of IPCC states: "*In the long term, a sustainable forest management strategy aimed at maintaining or increasing forest carbon stocks, while producing an annual sustained yield of timber, fiber, or energy from the forest, will generate the largest sustained mitigation benefit*.".

In the last two decades, the rising consciousness about global warming has led to the idea of building high-rise constructions using timber as the structural material. In Figure 1.3 are both realized and planned timber multi-storey buildings presented. In 2015 a residential building in Norway, Treet was completed. It is a 14-storey building with a load-bearing structure made up by wood reaching a height of 49 m (Treet, n.d.). In 2016 an 18-storey 53 m tall student residential tower was completed with a load-bearing structure consisting mostly out of wood. The first floor is still made up by reinforced concrete and the upper floors are supported by a reinforced concrete core. Currently research is being performed on hybrid wooden skyscrapers with an approximate height of 300 m (Ramage et al., 2017).

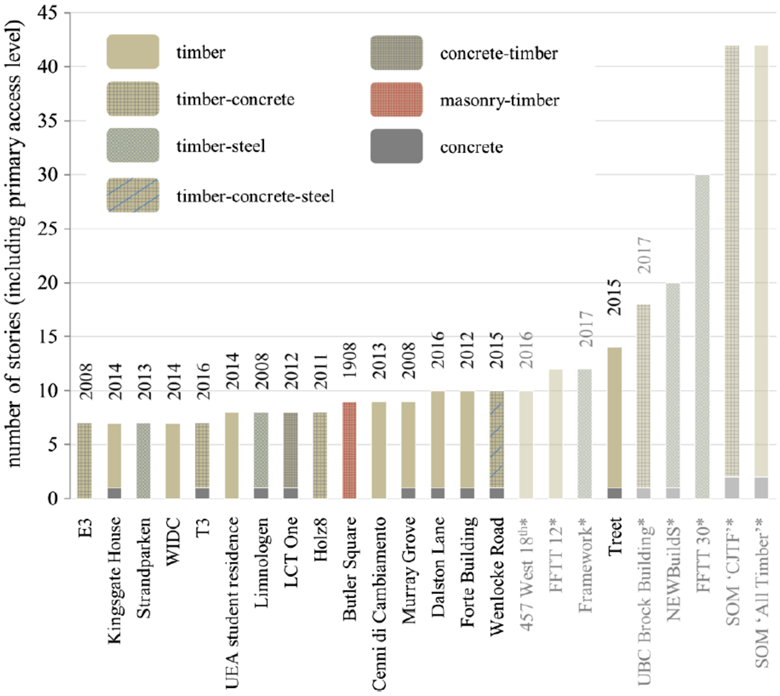

Figure 1.3: (Hybrid-)Timber multi-storey building projects, unrealized projects marked with * (Foster et al., 2016)

1.2 Reason for this dissertation

However, the benefits of switching from reinforced concrete and steel to timber for building multi-storey constructions in terms of GHG (greenhouse gas) reduction highly depends on several factors and assumptions. The last decade, research has been carried out on comparing the carbon footprint of timber buildings with its reinforced concrete and steel counterparts. Most of them are LCA's (Life Cycle Assessment) who compare the carbon emissions of a timber building with an equivalent building using steel or reinforced concrete. This means that the existing research on multi-storey timber buildings is focused on the climatic benefits of one specific case. Also some of the papers of the performed LCA's on timber buildings focus only on a share of these life stages (Robertson, 2007); (Li et al., 2019);

(Moncaster et al., 2018); (Peñaloza et al., 2013); (Cattarinussi et al., 2016); (Sandanayake et al., 2018); (Padilla-Rivera et al., 2018); (Guajardo, 2016); (Dodoo et al., 2012); (Khavari et al., 2016); (Dodoo & Gustavsson, 2016); (Pal et al., 2017); (Cole & Kernan, 1996); (Chen, 2012). The analysis of GWP of multi-storey timber buildings is one point that need further research.

1.3 Objective and working plan

So this dissertation wants to find out whether these founded reductions were only specific for several cases, or is it a general trend that multi-storey buildings have a lower carbon footprint when built with wood. This must consider the different life-stages and for the full lifecycle to see whether carbon reductions are achieved in the short-term and in the long-term. It will also be examined whether the potential carbon reductions are similar between the different buildings, and under what circumstances are these reductions greater/smaller? This will help project developers of multi-storey buildings to lower the carbon emissions of their future projects.

The main methodological steps are:

1) Comparing the GHG emissions from both timber materials and multi-storey buildings with their steel and reinforced concrete counterparts during the different life-stages of the LCA. The materials during their production (A) and end-of-life phase (C+D). Buildings will be compared during the production (A), operational (B) and end-of-life phase (C+D). For this comparison it will be verified whether multi-storey buildings emit less GHG's when realized in timber. The relative differences in GWP's for the 'C+D'-phase will be ranged according to their end-of-life scenario to determine which scenario results in the greatest reductions in GWP.
2) Comparing the GWP of both timber materials and buildings with their steel and reinforced concrete counterparts for their full lifecycle. It will be verified whether it can be stated if multi-storey buildings emit less GHG when realized with timber.
3) The relative differences in operational energy consumption will be ranged from cold to warm climates to examine the effect on the operational energy usage. Also the difference in energy usage for space heating and cooling when building with timber will be examined.
4) The relative differences in overall GWP will be ranged according to their end-of-life scenario to examine the effect on the full lifecycle GWP.

The criterium to determine whether one climatic region is colder/hotter than the other one is the monthly average temperatures of the warmest and coldest months. These data were obtained from the Climate data from the timeanddate.com who gives the average monthly temperature from the period of 1985-2015 (World temperatures, n.d.).

This dissertation makes a state-of-the-art review about the GWP and energy consumption of wooden multi-storey buildings. This dissertation performs no LCA on a specific building, but rather collects and compares the information of several LCA's and other literature about this topic to make a meta-analysis.

The LCA-stages relevant to greenhouse gas emissions and those that are affected by the application of wood in buildings are discussed within this dissertation. Figure 1.4 shows all the lifecycles that an LCA can include. Seeing the fact that some performed LCA's on timber buildings only cover a selected range of stages, every relevant stage is discussed separately.

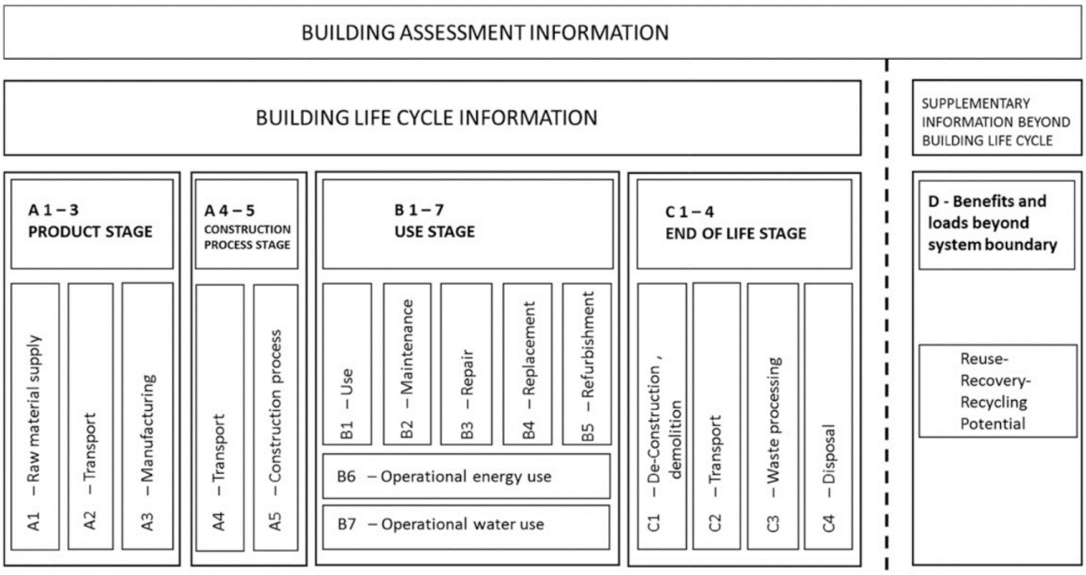

Figure 1.4: Life-stages analysed by an LCA according to EN 15804 (Hafner & Schäfer, 2017)

Several comparative LCA's have already shown how realizing a multi-storey building with timber instead of steel or reinforced concrete could be beneficial for the climate by having a smaller carbon footprint. A comparative LCA is when an existing building is redesigned using another structural material. Subsequently an LCA is performed on both the existing building and on the hypothetical building. At the end the results for both constructions are compared with each other. However, these studies are always specific for one case, and often limited in time by only taking a part of the lifecycle of the building into account.

In order to make a state-of-the-art review about the differences in the GWP of multi-storey buildings constructed with different materials, several LCA's and EPD's were collected. This dissertation investigates this matter both on a 'material-level' as on a 'building-level'. For the material-level the data from the EPD's are used, for the building level the LCA's are used. For this research EPD's and LCA's from different standards have been collected. In total there were 60 EPD's and 36 comparative LCA's collected.

In this dissertation the used declared units to compare materials are 'kg CO_2 eq/m^3' and 'kg CO_2 eq/metric tonne'. For buildings this is 'kg CO_2 eq/m^2', in case of the operational phase the energy consumption can also be compared by using 'kWh/m^2' as the functional unit.

The collected LCA's concern mid-rise buildings (3-10 floors) and high-rise buildings (>10 floors).

The comparison between the GWP's of the buildings will be made using bars. Their relative differences will be represented by a graph line. For the materials GWP's boxplots are plotted. To plot these bars, graphs and boxplots, Microsoft Excel 2016 is used.

The comparative LCA's collected for this state-of-the-art review were mostly found using the online library Web of Science. Others were suggested by the online library of Mendeley.

Within this state-of-the-art-review, the different parameters, aspects and phenomena influencing the GHG emissions of buildings will also be further discussed in detail. For this relevant literature concerning this matter of the GWP of timber multi-storey buildings were collected using the Web of Science and Mendely to provide insight in this matter.

1.3.1 Structure of the dissertation

This dissertation starts off by describing the timber materials that are suited to construct multi-storey buildings. It provides a small general explanation about the technical information of these products. It explains why these materials make multi-storey timber buildings possible. For this dissertation, three EWP's (Engineered Wood Products) were selected: CLT, glulam and LVL.

The following chapters follow the same order as the life-stages of the ones analyzed in an LCA. Throughout these chapters the energy consumption and GHG-emissions of the usage of timber is compared to its more conventional counterparts, steel and reinforced concrete.

In Chapter 2, the materials that make timber high-rise buildings possible are introduced.

The third chapter regards the production stage. In this paragraph the harvesting, transport and production process from raw material to construction element is described. The carbon-emissions and energy usage are given and compared to steel and reinforced concrete. There's also a subchapter concerning the fastening methods applied within wooden multi-storey buildings and their influence on the GWP of the building. At the end of this chapter, the GWP's at the level of the building for the production stage are presented in a table.

Chapter 4 examines the construction phase. Firstly, the transportation of the building elements to the construction site is discussed. In the LCA this is referred to as A4. The other half of this paragraph looks into the assemblage of the building on site, the A5-phase. This chapter focuses on both the level of the material as well as on the level of the buildings. Analogously with the former chapter the results of the collected EPD's and LCA's are put into a table.

The fifth chapter discusses the B-stages of the LCA's. The main parameters discussed here are the energy usages for space heating and cooling. The different required amounts of insulation materials are also described within this chapter. This chapter is solely discussed on the level of the building.

The end of the lifespan of the building and construction materials is discussed in chapter 6. First the differences between the demolition of timber buildings and buildings made up by steel and reinforced concrete are described. The three different end-of-life scenarios are discussed for all three materials, waste processing, disposal and recycling. To discuss the landfill and recycling of constructive timber waste, papers concerning the disposal of wood products were selected because of a lack of studies determining the GHG emissions caused by the disposal of CLT or other structural EWP’s.

The GWP of the found LCA’s and EPD’s that concern the entire lifetime were put together in the seventh chapter of this dissertation.

Chapter 8 is the representation and discussion of the results. The collected data of GWP’s and energy usage will be given in a way explained in the main goals of this dissertation in page 5. From the results of chapter 8, recommendations for future research and a conclusion on the current state-of-the-art will be drawn in chapter 9.

The appendices at the end add relevant material for this dissertation.

Chapter 2 – Materials suitable for wooden multi-storey buildings

Before the 1990’s, there weren’t any wooden high-rise constructions. Most high-rise buildings are carried by steel and reinforced concrete structures. This was mainly because of the lower strength and poor fire resistance of timber. Structural timber products such as GLT, LVL and PSL have been around for a longer period of time, but they are being produced as beams and columns. In other words, they could only provide the structural skeleton of the building. For high-rise buildings, this formed a problem since it was difficult to support the heavy reinforced concrete floor panels.

In the beginning of the 1990’s, a new timber product was developed: CLT (Cross Laminated Timber). CLT proofed to have higher fire resistance and better structural performances. But it was till the mid 1990’s the research was complete and CLT-products appeared on the market (Karacabeyli & Douglas, 2013). This newly development together with former structural engineered wood products made multi-storey buildings with timber possible.

This chapter provides a description of CLT, Glulam and LVL. It explains the structural properties and why these materials are suited for timber multi-storey buildings.

2.1 Cross laminated timber

CLT panels are made from layers of solid-sawn lumber glued together. Each layer of the board has an orientation perpendicular to the adjacent layers. This increases the inner friction of the material. CLT-boards mostly consists of an odd number of layers, this way the board is symmetric and the outer layers have the same orientation. Regular timber is an anisotropic material meaning its structural peformances depends on the direction of the applied load. But the different layers are glued at a perpendicular angle thus the anisotropy is reduced and the panels achieve better strucutral rigidity in both directions. CLT is used to make panels such as floors slabs and load-bearing walls. CLT is therefore used as a structural material in buildings with linear loads in closed-plan design. This causes CLT to be frequently applied in residential buildings. To glue the panels of the CLT adhesives such as MUF & PRF (Phenoplast and aminoplast), 1K-PUR (one component polyurethane) and EPI (Emulsion-polymer-isocyanate) are used. CLT is however vulnerable to moisture and biodeteriation. But this can easily be solved adding a non-porous, vapour, impermeable coating (Lepage et al., 2017).

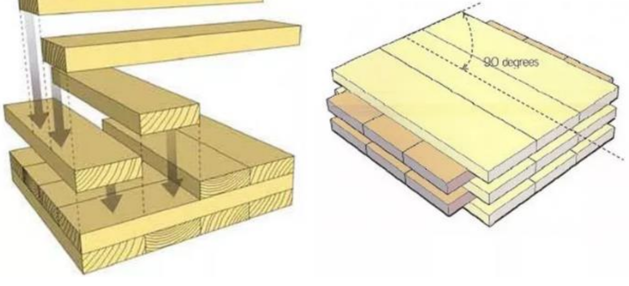

Figure 2.1: CLT-panels (International Framers, 2019)

CLT also has a high fire resistance. In contrast to steel, CLT remains its structural stability when exposed to high temperatures. The efficient fire resistance of CLT is obtained through charring. When exposed to fire, it's only the outer layer that starts burning forming a black layer of char. This way the char layer forms an insulating layer which prevents the temperature to rise within the unaffected core and also blocks the spreading of the fire. The heat-affected layer below the char is usually 20-40 mm (Östman & Tratek, 2014).

CLT is believed to be an eco-friendly construction material because timber sequestrates CO_2 during growth and the production of CLT doesn't require the burning of fossil fuels. It's also a material used in prefabrication which results in less waste produced during construction on site. Being made out of several layers of wood also increases the thermal insulation. CLT is a lighter building material which causes lower amount of emissions due to transport and besides allows the foundations to be smaller and contain less concrete (Wikipedia, 2018a).

Because of the low mass, the stiffness, the bearing capacity against in-plane and out-of-plane stresses and the ability to be prefabricated, CLT is starting to be applied for the construction of high-rise buildings. Several high-rise buildings using CLT as the loadbearing structure have already been built. The average Young's modulus of CLT is about 13.5 GPa parallel to the grain of boards (Danielsson et al., 2017) and about 370 MPa perpendicular to the grain of the boards (Sutton et al., 2011).

2.2 Glued laminated timber

Glued-laminated timber, also referred to as glulam, is very alike with CLT. It also consists of a number of layers of dimensioned lumber glued together by using durable, moisture-resistant structural adhesives. The main difference between CLT and GLT is that the grain of the different layers in CLT alternate at an angle of 90°, whereas the layers of GLT all have the same grain (Vicash, 2018). This is shown in Figure 1.2.

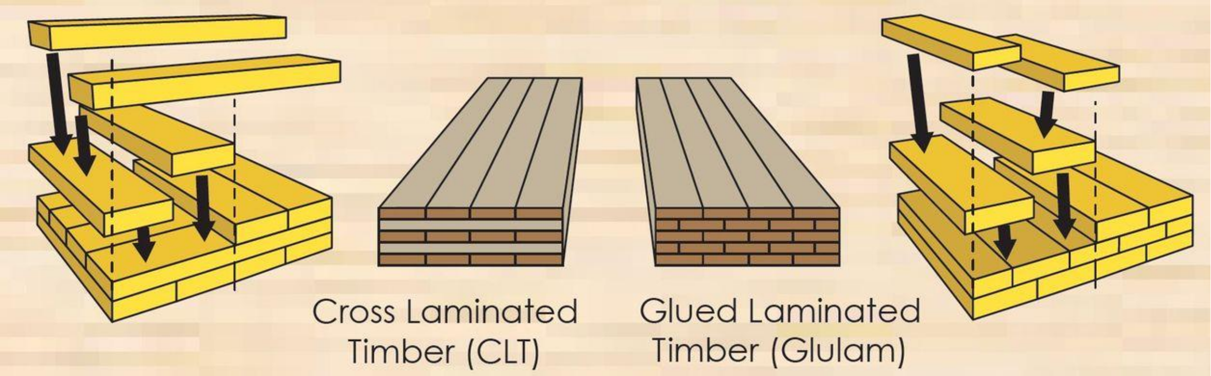

Figure 2.2: Difference between CLT and glulam (Brooshakian, 2016, 19 June)

Glulam can be used to build structural members such as vertical columns or horizontal beams or arches. In contrast to CLT, glulam is used in constructions with concentrated loads. This way glulam enables larger spans without intermediate columns, allowing a more flexible design and more open space. For this reason GLT can be applied in commercial buildings and offices (GLT vs CLT, 2018). As a structural material, it’s very efficient because of its low weight.

Because the layers in glulam components all have the same grain, it’s still an anisotropic material. This means that GLT-components should be positioned in a way the direction of the wood laminations accord to its stress-rated performance characteristics (Glue Laminated Timber, n.d.).

Analog with CLT, glulam also possesses a high fire resistance and is believed to have lower embodied carbon because of the carbon-sequestration during growth.

In 2015, in Bergen, Norway, a 49 m tall 14-storey residential tower was built by using a structural frame being made out of GLT beams and columns. The flats are prefabricated and modular and are also made from engineered timber. These modular flats are anchored to the glulam-frame (TDT, 2015).

2.3 Laminated Veneer Lumber

LVL is an EWP that is comparable to glulam. It also consists of thin wood layers assembled with adhesives. The main difference with glulam is that it has a higher allowable stress. LVL has an elastic modulus varying from 12 GPa to 14 GPa and an allowable bending stress varying from 19 MPa to 21 MPa. It is used to make headers, beams, rimboard and edge-forming material. In LVL the veneers all stack in the same direction. The grains of the lumber in LVL are all parallel to the longitudinal axis. LVL can be used in combination with glulam to increase the strength of the glulam beam (Wikipedia, 2018b).

Chapter 3 – Manufacturing phase

3.1 Raw material supply

This subchapter regards the GWP during the A1-phase of the EPD's collected for this dissertation. The A1-phase represents the extraction, harvesting and productions of the raw materials used for the production of the construction products. This is performed on timber, (reinforced) concrete and steel structural elements applicable in multi-storey constructions.

The subchapter of raw material supply in this dissertation solely regards the construction elements and not the building themselves. The values given in this subchapter apply to the level of the material, not the building. Also timber multi-storey buildings require an additional amount of concrete. This subchapter mainly highlights the cause of the assumed lower GWP of timber buildings then their steel or reinforced concrete equivalents.

3.1.1 Timber

The raw materials for timber construction products such as CLT, glulam and LVL are wood and the adhesives used for gluing the layers.

The processes included in the A1-phase for structural timber products are:

- The growth of the trees
- Forrest operations such as land fertilization, seeding, harvesting and cutting
- Transporting the tree logs from the forest
- Production of the adhesives

It is in this phase timber (multi-storey) buildings gain a great benefit in their GWP when compared to their significant steel and reinforced concrete counterparts. The main raw material is the wood from trees. The cultivation of this raw material consists of growing trees. During this growth-process trees sequestrate CO_2 from the atmosphere due to the process of photosynthesis. The majority of this CO_2 is stocked within the stem. The carbon that isn't being stocked in the stem is deposited to the soil. Seeing the fact that buildings (especially high-rise buildings) have a long life-span, building with timber creates an opportunity to store this carbon for a long period of time. This makes wooden buildings function as a carbon-sink. The designed life-span of high-rise buildings can vary from 50 to more than 100 years. This depends on the buildings function. The carbon-sequestration causes the timber constructive products to have a negative GWP within the A1-phase of an LCA.

It should be noted that in order for this to be climatological beneficial, a sustainable harvest of the wood is required. This means that when the tree gets cut down for manufacturing, a new tree is planted. Otherwise building with timber would contribute to deforestation. Re-growing the harvested trees would make timber a renewable construction material. In Europe the most commonly used structural timbers are derived from sustainably managed coniferous forests (Dickson et al., 2014). This sustainable harvest can be guaranteed by labels such as FSC and PEFC, this is shown in Appendix A.

Tree species that are suitable for constructive applications are Douglas fir, Larch, Hemlock-Fir, Spruce-Pine-Fir, Sitka spruce, Norway spruce, Southern Yellow Pine, Scots Pine, Yellow Cedar, Radiata pine, Sweet chestnut etc. (Skidmore et al., 2013).

Besides the CO_2-sequestration during harvest, there are also some GHG emissions inherent to this phase. This is due to the energy used during land fertilization, logging of the trees, cutting the unusable branches and the loading and unloading of the tree logs on the forwarder and the transportation of the forwarder itself. These are processes that can both use electricity or fossil fuels as energy source. If the trees are harvested in greenhouses the electrical energy required to operate forest nursery pumps and to keep seedlings cool for planting is included as well (Puettmann et al., 2013).

However most of the European forest plantations are pieces of existing forests that have been selected for timber harvest. This means that these forests are neither mechanically watered nor fertilized. The energy input for forestry growth is almost entirely solar (Ramage et al., 2017).

Eleven EPD's collected for this chapter of the state-of-the-art-review state that the total mass of CO_2 sequestrated from the atmosphere during growth varies between 741 – 874 kg for every m³ of wood. This is presented in Table 3.1. The CO_2-emissions from harvesting processes vary between several harvesters seeing the fact that they depend on a variety of factors such as energy source, equipment efficiency, stem size etc. But still they are relatively small in comparison with the stocked carbon within the trees. The CO_2 emitted during the logging and cutting can vary between 2.8 – 4 kg for every produced cubic meter of CLT (Prinz, 2018). The (un)loading and the transportation by the forwarder adds approximately 3 kg/m³ to this phase (Lijewski, 2017).

These products made for timber multi-storey buildings also contain a fraction of thermosetting synthetic adhesive resins that gets added in the manufacturing phase. For CLT this is a mass-fraction of 2 – 2.5%. Polyurethane, Phenol resorcinol formaldehyde (PRF) resin, phenol formaldehyde (PF) and melamine-urea-formaldehyde (MUF) are applied for the production of these products. They serve as the glue to keep the wood-layers together. These adhesives negatively impact the embodied energy burden of these products. The amount of needed adhesives is reduced when applying hardwood instead of softwood. The use of heavy timber in structurally glued elements could reduce the required adhesives to as much as 70% (Skidmore et al., 2013).

These adhesives are all synthetic products. Most of their raw materials are synthetic products as well. For example, the production of MUF requires methanol, urea, melamine, formic acid, sodium hydroxide, ammonium sulfate and molybdenum-iron oxide. Components such as urea and methanol are produced from natural gas processing. The GWP of 1 kg of MUF was estimated at 1.6 kg CO_2 (Aparecido Lopes Silva et al., 2015). Other adhesives applied in EWP's aren't further discussed in this dissertation because of the limited available information.

The data of the GWP from other resins weren't available. Therefore it couldn't be determined which share of the emitted greenhouse gasses during the A1-phase were caused by the production of the adhesives.

Recent innovations on welding of timber through high frequency oscillating or linear friction of adjacent wood surfaces could serve as an alternative for wet adhesives. The need for adhesives can be avoided, however only for small structures (Ramage et al., 2017), which makes this innovation irrelevant for this research.

In Table 3.1 is the GWP and energy-use during the A1-phase given for several timber construction products from eleven EPD's.

Table 3.1: GWP and energy consumption in the A1-phase for timber

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m³]	Primary energy-use non-renewable [MJ/m³]	kg CO2/m³ sequestrated during growth	Added resin [kg/m³]	kg CO2 eq/m³ emitted during A1-phase	A1 GWP [kg CO2 eq/m³]
CLT	2018	BSP Holz	Austria	8 440	882	801	9,93	102	-699
	2017	Egoin	Spain	26 656.86	2 824.83	-	3.73	-	-716
	2018	Nordic structures	Canada	9.32	573.3	741.36	4.46	37.88	-703
	2017	Stora Enso	France	7 430	647	739	-	33	-706
	2016	Stora Enso	Austria	9 120	1 000	866	9.83	135	-731
	2013	Structurlam	Canada	1 184.86	667.01	764.56	3.45	47.04	-729
	2013	Athena Sustainable Materials Institute	Canada	-	-	764.56	4.2	35.71	-728,9
Glulam	2013	North American Wood Association	USA/Canada	-	-	-	8	-	-683
	2013	BS Holz	Germany	9 195	1 055	874	10.46	119	-755
	2018	BS Holz	Germany	8 750	931	827	10.47	112	-715
	2018	Nordic structures	Canada	8.85	544.4	741.36	0.43	35.97	-705
	2018	Athena Sustainable Materials Institute		1 766.3	2 173.8	784.7	5.3	110	-674.7
LVL	2013	Metsä Wood	Finland	14 297	2 815	789	-	117	-672
	2018	Athena Sustainable Materials Institute	Canada	4 372.2	7.95	747.5	37.2	153.5	-594

3.1.2 Steel

The raw materials for steel production are scrap metal, iron ore, pig iron, lime (quicklime and dolomitic lime), coal, ferro-alloys, fluorite and calcium carbide.

The processes included in the A1-phase for structural steel are:

- Recycling and preparation of steel scrap
- Production of virgin materials, alloy elements and ancillaries
- Mining processes through the extraction of iron ore, coal, alloys and lime
- Generation of electricity and other fuels from primary and from secondary energy resources

Steel is a material that can be easily recycled. It is estimated that globally 85% of the steel used in construction is recovered for recycling (Steel and raw materials, 2018). Therefore scrap metal is one of its raw materials.

When there's no recycled steel applied, the main raw material for steel production is iron. Iron is made from iron ore which can be founded in the earths soil. In order to obtain this, the iron ore has to be minded. The extracting of the iron ore requires heavy machinery often energized by fossil fuels. The same applies to the coal, alloys and lime (Steel and raw materials, 2018).

In Table 3.2 is the GWP and energy-use during the A1-phase given for several steel construction products from seven EPD's.

Table 3.2: GWP and energy consumption in the A1-phase for steel

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m^3]	Primary energy-use non-renewable [MJ/m^3]	A1-GWP [kg CO_2 eq/m^3]	A1-GWP [kg CO_2 eq/metric tonne]
Structural steel	2016	Gerdau	USA	7 598.8	118 535	8 792	1 120
				6 688.2	112 255	8 242.5	1 050
Trusses and beams from hot-rolled plates, coils and sheet	2014	Ruukki	Finland	3 454	195 857.5	19 154	2 440
Trusses and beams from cold formed structural tubes	2014	Ruukki	Finland	4 867	206 455	20 017.5	2 550
Cold-Formed Steel Studs and Track	2016	SCSglobal	USA/Canada	8 580	218 400	17 160	2 200
Hot rolled steel sections for structural purpose	2015	AENOR	Spain	615.6	14 809.34	967.51	123.25
Hot rolled structural profiles and merchant bars	2017	AFV Beltram GROUP	Italy France Switserland	4 466.65	74 074.96	2 606.2	332

3.1.3 Reinforced Concrete

The raw materials for reinforced concrete are aggregates, cement, water, admixtures, potential chemicals to adjust the concrete behavior and reinforcing steel.

The processes included in the A1-phase for reinforced concrete are:

- Cement production
- Extracting and crushing of aggregates
- Production of admixtures
- Steel reinforcement production
- Generation of energy from primary and from secondary energy resources, mostly from fossil fuels

The main contributor to the embodied carbon of reinforced concrete is the production of cement, and the production for the steel reinforcement. During the production process of cement decarbonation of $CaCO_3$ occurs, forming CaO and releasing CO_2 in the atmosphere (Betontechnologie, 2015). Most of the energy used in cement production is used in the calcination process (Sjunnesson, 2005). Making the calcination process having a big impact on the GWP of reinforced concrete. The other carbon emissions from the production of reinforced concrete are mainly from the combustion from fossil fuels (Dodoo, 2014).

The most common kind of cement is Portland cement. 95% of all produced cement is of this type (Sjunnesson, 2005).

The aggregates are either macadam or gravel. Both kinds have to be extracted from the soil or the riverbed.

In Table 3.3 is the GWP and energy-use during the A1-phase given for several (reinforced) concrete construction-products from eleven EPD’s. The precast concrete elements are reinforced and therefore have a bigger GWP.

Table 3.3: GWP and energy consumption in the A1-phase for concrete

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m^3]	Primary energy-use non-renewable [MJ/m^3]	A1-GWP [kg CO_2 eq/m^3]	A1-GWP [kg CO_2 eq/metric tonne]
Precast concrete panel	2015	ASTM International	USA/Canada	-	-	-	265.1
Cast concrete C32/40	2018	Emirates Beton	UAE	38.8	2 320	217	89.34
Cast concrete C36/45	2018	Emirates Beton	UAE	39.2	2 380	226	93.39
Cast concrete C40/50	2018	Emirates Beton	UAE	39.7	2 425	232	95.55
Cast concrete C50/60	2018	Emirates Beton	UAE	39.8	2 447	235	97.03
Precast concrete	2015	ASTM International	USA/Canada	26.8	1 873.5	-	256.1
Prefabricated concrete C30/37	2013	SCANBET	Poland	47	1 696	287.4	121.63
Prefabricated concrete C35/45	2013	SCANBET	Poland	48	1 861	299.9	127.12
Prefabricated concrete C40/50	2013	SCANBET	Poland	54	2 120	347	146.03
Prefabricated concrete C50/60	2013	SCANBET	Poland	56.7	2 222.9	359	152.84
Hollow core	2017	Contiga	Norway	-	-	-	134
Concrete beam	2016	Contiga	Norway	-	-	-	195

3.2 Transport to the manufacturing plant

This subchapter regards the A2-phase of an LCA, the transportation of the raw materials from the place of extraction to the manufacturing plant. The GWP and energy-usage of this phase depends on three factors:

1) The distance between the forest and the manufacturing plant

2) The applied transport module (boat/ truck/ train; gasoline/ diesel)

3) The weight of the raw materials that needs to be transported

Because the A2-phase covers transportation, almost all GHG emissions origins from the combustion of fossil fuels.

However the A2-phase mostly only has a small contribution to the overall GWP of the building materials and also shows no significant differences among the three different structural materials. Tables 3.4; 3.5 and 3.6 represent the energy usage and GWP during the raw material transportation phase for respectively timber, steel and reinforced concrete.

The main raw materials for these structural elements (trees, iron ore, recycled steel and stone aggregates) are globally available. The distance between place of extraction and the manufacturing plant and therefore the GWP during the A2-phase is more inherent to the producer than to the material itself. For this reason the transport of the raw materials isn’t going to be further discussed into detail.

Table 3.4: GWP and energy consumption in the A2-phase for timber

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m³]	Primary energy-use non-renewable	A2 GWP [kg CO_2 eq/m³]	Mean distance [km]
CLT	2018	KLH	Austria	6.08	103	7.56	
	2017	Egoin	Spain	5.91	451.82	27.45	
	2018	Nordic structures	Canada	0.87	697.24	51.97	100
	2017	Stora Enso	France	6.14	205	12.4	
Glulam	2013	BS Holz	Austria	11.73	557.3	36.74	
	2018	BS Holz	Austria	24.7	468	32.1	
	2018	Nordic structures	Canada	0.83	662.08	49.35	100
	2018	Athena Sustainable Materials Institute	Canada	0	292.7	19.07	
LVL	2013	Metsä Wood	Finland	9	169	12	
	2018	Athena Sustainable Materials Institute	Canada	0	321.6	20.9	186

Table 3.5: GWP and energy consumption in the A2-phase for steel

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m³]	Primary energy-use non-renewable [MJ/m³]	A2-GWP [kg CO_2 eq/m³]	A2-GWP [kg CO_2 eq/metric tonne]
Structural steel	2016	Gerdau	USA	0	2 166.6	151.5	19.3
				0	2 166.6	151.5	19.3
Trusses and beams from hot-rolled plates, coils and sheet	2014	Ruukki	Finland	78	1 482	78	10
Trusses and beams from cold formed structural tubes	2014	Ruukki	Finland	78	1 482	78	10
Cold-Formed Steel Studs and Track	2016	SCSglobal	USA/Canada	0	3 432	280.8	36
Hot rolled steel sections for structural purpose	2015	AENOR	Spain	15.39	5 223.94	350.27	44.62
Hot rolled structural profiles and merchant bars	2017	AFV Beltram GROUP	Italy France Switserland	0	3 531.72	243.35	31

Table 3.6: GWP and energy consumption in the A2-phase for concrete

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ]	Primary energy-use non-renewable [MJ]	A2-GWP [kg CO_2 eq/m³]	A2-GWP [kg CO_2 eq/metric tonne]
Precast concrete panel	2015	ASTM International	USA/Canada	-	-	-	12.9
Poured concrete C32/40	2018	Emirates Beton	UAE	1.1	203	13	5.35
Poured concrete C36/45	2018	Emirates Beton	UAE	1.1	202	13	5.37
Poured concrete C40/50	2018	Emirates Beton	UAE	1.1	211	13	5.36
Poured concrete C50/60	2018	Emirates Beton	UAE	1.1	211	13	5.37
Precast concrete	2015	ASTM International	USA/Canada	-	-	-	13.8
Prefabricated concrete C30/37	2013	SCANBET	Poland	0	413	31	13.12
Prefabricated concrete C35/45	2013	SCANBET	Poland	0	413	31	13.14
Prefabricated concrete C40/50	2013	SCANBET	Poland	0	413	31	13.04
Prefabricated concrete C50/60	2013	SCANBET	Poland	0	413	31	13.2
Hollow core	2017	Contiga	Norway	-	-	-	5.57
Concrete beam	2016	Contiga	Norway	-	-	-	11.2

3.3 Production process

The A3-phase of an LCA regards the production of the element within the manufacturing plant. The end of this phase is referred to as ‘at the manufacturing gate’ while the three phases themselves are referred to as ‘cradle-to-gate’. The GWP at the manufacturing gate is the cumulative GWP of the phases A1, A2 and A3. The majority of the collected EPD's tend to give the GWP of the construction product at the manufacturing gate instead of separately for the three different stages.

3.3.1 Timber

The contributions to the GWP during the production of CLT, glulam and LVL are due to energy-usage of:

- The kiln drying of the wood
- Cutting of the lumber (Peeling in case of LVL)
- Adding of the adhesives
- Assembly pressing of the layers

In order for timber to be used in construction it needs to be dried. When arriving at the manufacturing plant, the wood can have a moisture content of 25 – 35%, depending on the species. The equilibrium moisture content within buildings is around 8 – 12%. This makes it necessary to dry the bound water of the timber in order to be applied in construction. Lowering the moisture content of timber improves mechanical properties and avoids shrinkage and attacks by fungi and bacteria. There are several methods to reduce moisture from timber including air, solvent, microwave and supercritical CO_2 drying, but the most common is the convective or condensing kiln drying. However convective drying is energy and equipment intensive. It offers the most accelerated means of drying dimensional timber for construction. The kiln is an enclosed structure that provides controlled heating, air circulation, humidification and ventilation. Heating is achieved by indirect (steam, hot water, thermal liquid, electricity) or direct means (gas/oil burner) (Ramage et al., 2017).

The dry process of timber is responsible for the majority of the energy-usage during the cradle-to-gate of wooden construction products. One LCI performed on residential wood building materials in the American Pacific Northwest and the American Southeast showed that the drying of the wood makes up respectively 92% and 91% of the overall energy-usage during the cradle-to-gate process (Puettmann & Wilson, 2005). The results of this study are added to this dissertation in appendix B.

The GWP caused by the drying process depends on the type of fuel used during the electricity production and the initial moisture content of the timber. The first is also highlighted by the LCI performed by Puettmann and Wilson on residential wood building materials (appendix B). For the residential timber industry in the Southeast of the US 72% of the total fuel used for electricity consumption was fossil-based of which 46% was from coal. This is in contrast to the Pacific Northwest, where 74% of the fuel used for electricity production came from hydro-power. As a result the GHG's emitted for every MJ of energy used for the production of the timber product during cradle-to-gate (expressed as CO_2 eq/m^3) decreases for glulam and LVL respectively 9.20% and 18.36%. When looking at the overall emissions to the air these values become 3.70% and 17.99%. It's also noticeable that the glulam and LVL in the Southeast has a significantly higher energy-usage when compared to the production in the Pacific Northwest. When looking at the amount of CO_2 eq emitted for every used MJ, the Pacific Northwest industry has a decrease of 9.98% and 20.22% for glulam and LVL respectively. For the total air-emission these values become 10% and 20.09% (Puettmann and Wilson, 2005). Because of the effect the share of (non-)renewable energy in the production process, the energy consumption mentioned in the EPD's is added to data of the tables.

The moisture content mainly depends on the tree species. For example, the energy consumption for the industrial drying of radiate pine requires 3 GJ/m³, while other species like mixed spruce suffice with only 1 GJ/m³ (Ananias, 2012).

Another factor that has a slighter influence on the energy-usage during the production stage is the type of pressing. The pressing of the timber layers can be performed by hydraulic pressing or vacuum pressing. Hydraulic pressing results in higher pressure. Vacuum pressing can press multiple CLT-panels at the same time making it more energy-efficient (Wikipedia, 2019).

In Table 3.7 are the GWP and energy usage given for several timber structural elements. These data were obtained from 23 EPD's.

Table 3.7: GWP and energy consumption in the A3-phase for timber

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m³] A1-3	Primary energy-use non-renewable [MJ/m³] A1-3	GWP [kg CO_2 eq/m³] A3	GWP [kg CO_2 eq/m³] A1-3	GWP [kg CO_2 eq/metric tonne] A1-3	Carbon sequestration
CLT	2018	BSP Holz	Austria	9 696.08	2 275	97	206.6 (-594.4)	439.6 (-1 264.9)	Excluded (included)
	2017	Egoin	Spain	26 664.12	3 353.38	3.2	-685,5	-1 305.7	Included
	2018	Nordic structures	Canada	887.52	1 899.23	32.04	121.9 (-619.5)	259.3 (-1 318)	Excluded (included)
	2017	Stora Enso	France	8 576.14	1 315	18.7	64.1 (-674.9)	136.4 (-1 436)	Excluded (included)
	2016	Stora Enso	Austria	10 810.37	3 393	122	264.2 (-601.8)	562.2 (-1 280.4)	Excluded (included)
	2013	Structurlam	Canada	510.39	983.58	51.53	86.3 (-678.3)	183,5 (-1443,2)	Excluded (included)
	2016	Cross timber systems	Norway	8 631	2 210	-	-567.3	-1 350.7	Included
	2018	Rubner	Italy	10 400	1 450	-	-664	-1 440.3	Included
	2013	UK National Industry	UK	10 600	4 570	-	-494	-1 202.3	Included
	2013	Athena Sustainable Materials Institute [3]	Canada	-	-	40.4	76.1 (-688.5)	161.8 (-1 464.9)	Excluded (included)
Glulam	2013	BS Holz	Germany	11 094.73	2 912.3	72.33	228.3 (-645.7)	449 (-1 270.2)	Excluded (included)
	2018	BS Holz	Germany	10 914.7	2 346	68.2	212.3 (-614.7)	439.4 (-1 272.1)	Excluded (included)
	2018	Nordic structures	Canada	1 447.23	812.55	15.07	127.09 (-614.3)	270.4 (-1 307)	Excluded (included)
	2013	UK National Industry	UK	10 400	4 760	-	-488	-995.9	Included
	2016	Moelven	Norwegian	10 653	1 638	-	62 (-656)	144.2 (-1 525.6)	Excluded (included)
	2018	Rubner	Italy	11 300	1 500	-	-646	-1 451.69	Included
	2018	Schilliger Holz	Switzerland	8 800	1 940	-	-615	-1 450.47	Included
	2017	WoodSolutions (softwood)	Australia	13 800	4 980	-	405 (-612)	652.2 (-985.5)	Excluded (included)
	2017	WoodSolutions (hardwood)	Australia	12 700	6 160	-	710 (-408)	1056.5 (-607.1)	Excluded (included)
	2018	Athena Sustainable Materials Institute [3]	Canada	1 766.3	2 240.9	55.1	204.2 (-580.5)	434.47 (-1 235.11)	Excluded (included)
LVL	2013	Metsä Wood	Finland	14 311	3 080	5	134 (-655)	243.6 (-1 190.9)	Excluded (included)
	2018	Roseburg	USA	2 700	5 538	-	274 (-600)	483.2 (-1 058.2)	Excluded (included)
	2013	UK National Industry	UK	10 600	5 200	-	-537	-1 100.4	Included
	2018	Athena Sustainable Materials Institute [3]	Canada	7 162.9	5 683.2	182.5	356.9 (-390.7)	780.9 (-854.9)	Excluded (included)

3.3.2 Steel

The GHG emissions during the production of steel are due to:

- Removing the carbon from the iron ore in the converter, forming CO_2.
- The energy usage for the heating of the cokes.
- The energy usage for the melting of pig iron and scrap steel.

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[3] Athena Sustainable Materials Institute didn't provided a density on their EPD, therefore a density of 470 kg/m³ was presumed.

- The energy usage for the transporting, crushing and mixing of the raw materials within the manufacturing plant.

Before the actual production of steel takes place, the cokes are heated up forming metallurgical cokes consisting of pure carbon. For this the coke needs to be heated up to a temperature of 1 100 °C (Steelmaking, 2009).

Iron ore consists of Fe_2O_3 and limestone ($CaCO_3$). To produce steel Fe is needed with a carbon level below 2%. For these cokes are added to the raw materials. In the blast furnace cokes react with the Fe_2O_3 forming iron and CO_2. To sustain this reaction hot air is preheated to a temperature of 1 250 °C (Steelmaking, 2009).

As mentioned in section '3.1.2 Steel' at page 13, 85% of the steel in construction is recycled. Steel scrap is loaded into a refractory-lined vessel and melted by using electric energy supplied through graphite electrodes, also known as the electric arc furnace. Instead of an EAF an oxy-fuel burner can be used as well. The GWP of an oxy-fuel burner can be 2 – 3 times higher than an EAF (ASIC, 2018).

In Table 3.8 are the GWP and energy usage given for several steel structural elements. These data were obtained from 20 EPD's.

Table 3.8: GWP and energy consumption in the A3-phase for steel

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m^3]	Primary energy-use non-renewable [MJ/m^3]	A3-GWP [kg CO_2 eq/m^3]	A3-GWP [kg CO_2 eq/metric tonne]	A1-3-GWP [kg CO_2 eq/m^3]	A1-3-GWP [kg CO_2 eq/metric tonne]
Structural steel	2016	Gerdau	USA	9 415.2	134 046.6	910.6	116	9 854.11	1 255.3
				7 504.6	127 766.6	910.6	116	9 304.61	1 185.3
Trusses and beams from hot-rolled plates, coils and sheet	2014	Ruukki	Finland	16 956	234 636.5	1 962.5	250	21 273.5	2 710
Trusses and beams from cold formed structural tubes	2014	Ruukki	Finland	16563.5	244 606	2 119.5	270	22 215.5	2 830
Cold-Formed Steel Studs and Track	2016	SCSglobal	USA/Canada	8 751.6	227 526	343.2	44	17 784	2 280
Hot rolled steel sections for structural purpose	2015	AENOR	Spain	8 809.74	68 343.75	2 690.9	342.79	4 008.68	510.66
Hot rolled structural profiles and merchant bars	2017	AFV Beltram GROUP	Italy France Switserland	5 156.67	90 883.38	2 205.85	281	5 055.4	644
Hot rolled structural sections	2016	AISC	USA	3 970.2	115 440	-	-	9 048	1 160
HISTAR steel sections	2017	Arcelor Mittal	Luxemburg	6 468.4	71 984.5	-	-	41 134	5 240
Hot rolled structural steel sections and merchant bars	2018	Arcelor Mittal	Luxemburg	9 106	98 125	-	-	8 949	1 140
Hot dip galvanised steel with Magnelis coating	2017	Arcelor Mittal	Luxemburg	8 375.96	182 392.4	-	-	20 039.68	2 560
Structural carbon steel	2016	Commercial Metal Company	USA	6 877	140 994	-	-	10 652.88	1 360
Structural steel (S235 - S960)	2010	Bauforumstahl	Germany	5 102.5	152 918	-	-	13 188	1 680
Structural steel (sections and plates	2018	Bauforumstahl	Germany	11 932	90 275	-	-	8 870.50	1 130
Structural section steel	2014	CELSA Group	Spain	9 106	66 175.5	-	-	66 175.5	632
Hot-rolled sections	2013	Contiga	Norway	47 414	127 170	-	-	10 362	1 320
Uncoated steel plate	2018	DanSteel	Denmark	14 915	222 155	-	-	24 492	3 120
Structural sections	2016	OneSteel	Australia	2 300	40 400	-	-	28 260	3 600
Structural sections	2016	OneSteel	Australia	7 693	141 300	-	-	11 775	1 500
Structural hollow sections	2017	Tata Steel	UK	4 278.25	200 175	-	-	19 625	2 500
H-beams S235	2018	Tokyo Steel	Japan	2 113.85	2 362.2	-	-	6 503.92	826
Welded beams and columns	2015	Bluescope	Australia	-	-	-	-	-	2 850
Hot rolled steel sections	2018	SULB Company	Bahrain	715.14	26 219	-	-	20 959.5	2 670

3.3.3 Reinforced Concrete

When compared to timber and steel, reinforced concrete has a fairly simple production process within the manufacturing plant. The raw materials are being proportioned and mixed. Ready-to-mix concrete gets immediately poured into the cement mixer after the mixing of the raw materials and send to the construction site. For prefabricated concrete elements the placing of the reinforcement and the pouring in the formwork are included in the production process. As a result the reinforced concrete elements have a lower GWP during the A3-phase.

It should be noted that once the concrete is hardened, it sequestrates CO$_2$ from the atmosphere when in contact with the atmosphere during its lifetime. This is due to the process of the carbonation reaction. This in included during the B-phase of the LCA.

In Table 3.9 are the GWP and energy usage given for several timber structural elements. These data were obtained from eighteen EPD's. Analogously with Table 3.3 the prefabricated concrete elements include the steel reinforcement.

Table 3.9: GWP and energy consumption in the A3-phase for concrete

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m^3]	Primary energy-use non-renewable [MJ/m^3]	A3-GWP [kg CO$_2$ eq/m^3]	A3-GWP [kg CO$_2$ eq/metric tonne]	A1-3-GWP [kg CO$_2$ eq/m^3]	A1-3-GWP [kg CO$_2$ eq/metric tonne]
Precast concrete panel	2015	ASTM International	USA/Canada	-	-	-	29.8	-	298.8
Cast concrete C32/40	2018	Emirates Beton	UAE	40.6	2 666	9	3.71	239	98.4
Cast concrete C36/45	2018	Emirates Beton	UAE	41	2 725	9	3.72	247	102.07
Cast concrete C40/50	2018	Emirates Beton	UAE	41.6	2 788	9	3.71	254	104.61
Cast concrete C50/60	2018	Emirates Beton	UAE	41.6	2 800	9	3.72	257	106.11
Precast concrete	2015	ASTM International	USA/Canada	-	-	-	29.8	-	299.7
Prefabricated concrete C30/37	2013	SCANBET	Poland	374.2	2 403	32.84	13.9	785.19	332.3
Prefabricated concrete C35/45	2013	SCANBET	Poland	375.2	2 568	32.79	13.9	813.45	344.8
Prefabricated concrete C40/50	2013	SCANBET	Poland	381.2	2 827	33.03	13.9	931.27	391.9
Prefabricated concrete C50/60	2013	SCANBET	Poland	383.9	2929.9	32.65	13.9	948.71	403.9
Hollow core	2017	Contiga	Norway	-	-	-	8.08	-	147.65
Concrete beam	2016	Contiga	Norway	-	-	-	7.32	-	213.52
Cast concrete C25/30	2018	Allied Concrete	New-Zealand	115	1377	-	-	281	119.07
Cast concrete C30/37	2018	Allied Concrete	New-Zealand	121	1462	-	-	303	125.73
Cast concrete C35/45	2018	Allied Concrete	New-Zealand	133	1597	-	-	338	139.67
Cast concrete C40/50	2018	Allied Concrete	New-Zealand	144	1770	-	-	387	159.92
Ekkomaxx cement concrete	2014	CERATECH	USA	-	-	-	-	82.6	-
Precast concrete	2018	Dubai Precast	UAE	-	-	-	-	-	271
Industry average benchmark of concrete 26-30 Mpa	2017	CRMCA	Canada	257.57	2 763.68	-	-	349.68	-
Industry average benchmark of concrete 31-35 Mpa	2017	CRMCA	Canada	307.77	3 229.68	-	-	417.05	-
Industry average benchmark of concrete 36-40 Mpa	2017	CRMCA	Canada	338.24	3 537.74	-	-	458.98	-
Industry average benchmark of concrete 41-45 Mpa	2017	CRMCA	Canada	314.14	3 309.63	-	-	426.33	-
Industry average benchmark of concrete 46-50 Mpa	2017	CRMCA	Canada	382	3 936.53	-	-	517.43	-
Industry average benchmark of concrete 51-55 Mpa	2017	CRMCA	Canada	354.15	3 688.44	-	-	480.33	-
Poured concrete 5000psi (34MPa)	2013	Titan Concrete	USA	-	-	-	-	408	-
Unreinforced concrete C30/37	2018	InformationsZentrum Beton GmbH	Germany	204	1 100	-	-	219	91.25
Unreinforced concrete C35/45	2018	InformationsZentrum Beton GmbH	Germany	229	1 200	-	-	244	101.67
Unreinforced concrete C45/55	2018	InformationsZentrum Beton GmbH	Germany	282	1 500	-	-	286	119.17
Unreinforced concrete C50/60	2018	InformationsZentrum Beton GmbH	Germany	292	1 510	-	-	300	125
Ready mix-concrete 4000psi	2014	Argos	Panama	33.9	2 612	-	-	432	-
Ready mix-concrete 8000psi	2014	Argos	Panama	50.4	3 628	-	-	633	-

3.4 Methods of fastening

Figure 3.1 gives the connection efficiency for several methods to connect the load-bearing members. The efficiency ratio can be defined as the ratio of the strength of the connection to the strength of the member it connects. It shows that glued finger joints are the connection with the greatest strength (Ramage et al., 2017). Since high-rise buildings carry greater loads, this form of connection is the most appointed to be applied.

With glued finger joints a zigzag-form is cut out at the edge of the timber element. An adhesive glue is applied at this edge, connecting the crossing members this way. These glue products bring along an environmental cost. Also these glued connections must be performed in a controlled environment which precludes their time on-site (Ramage et al., 2017).

Only the adhesives that are permitted for use in load-bearing timber structures according to 'EN 301 Adhesives, phenolic and aminoplastic, for load-bearing timber structures - Classification and performance requirements', 'EN 15425 Adhesives - One component polyurethane (PUR) for loadbearing timber structures - Classification and performance requirements' and the technical approvals are allowed. The main used substances for finger joint connection between timber members are 1K-PUR (1 component-Polyurethane) and MUF. MUF has already been discussed in section 3.1.1. It has an unfavorable effect on the GWP of timber buildings because of the emission of formaldehydes (Brandner, 2013). 1K-PUR is very beneficial for bonding within the woodworking industry because the substrate has a high water content, good water permeability and functional groups. For the production of 1K-PUR two isocyanate end groups are joined via a urea linkage, which results in the liberation of CO_2. During its further lifetime when 1K-PUR gets into contact with water (dissolved in the air) carbamic acid is formed which turns into amine by extracting CO_2 (Formulating Adhesives and Sealants, Müller &

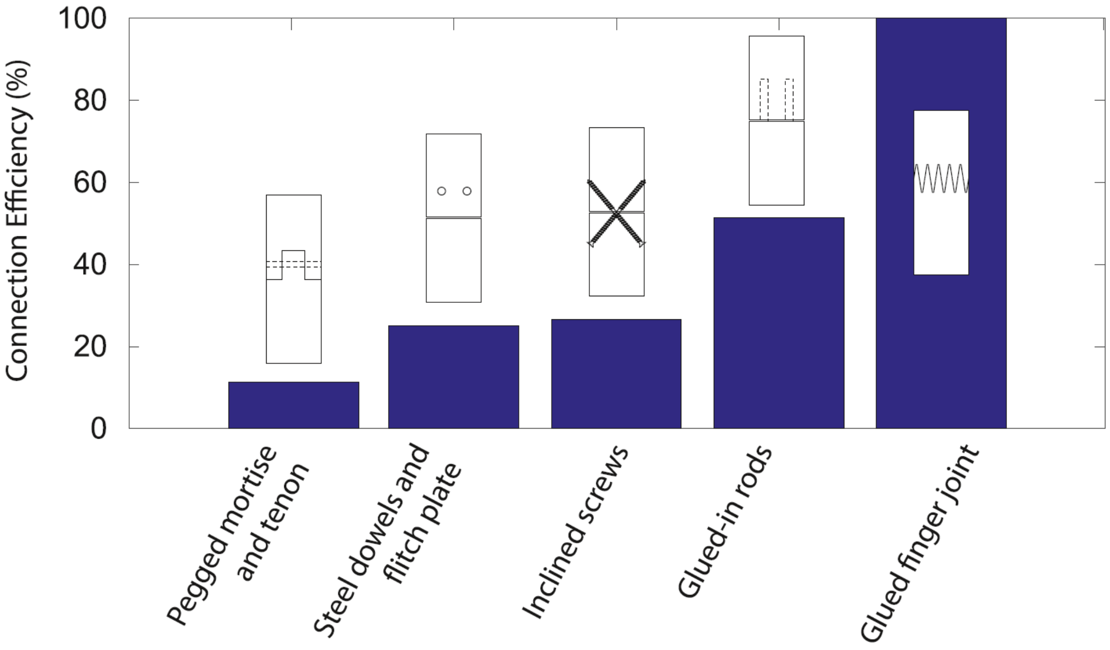

Figure 3.1: Efficiency of connections between 100 mm by 200 mm timber members transmitting a tensile axial force (Ramage et al., 2017)

Rath, 2010). The quantitative information specific about the GWP impact of 1K-PUR couldn't be obtained.

3.5 Additional materials

Timber buildings have a lighter weight than their structural counterparts reinforced concrete and steel. This adds advantages such as lighter foundations, less energy required for transport and greater resistance against earthquakes. However certain disadvantages rise along because of the reduced weight such as poor acoustic insulation, low mechanical resistance (for example against wind) and little thermal inertia. The latter will be further discussed in section 5.2. This is especially true when compared with reinforced concrete. It was not verified for this research if timber buildings have a poorer performance for these aspects when compared with steel.

3.5.1 Acoustic insulation

The mass law of sound insulation states that the sound insulation of a single wall is almost completely determined by its weight per unit area. A doubling of the surface weight of a solid element leads to an increase in sound insulation of approximately 5 dB (Steel Constructions, 2019). CLT has a density of 460 - 480 kg/m³ and reinforced concrete an average density of 2 300 – 2 500 kg/m³. This means that a wall or slab made out of CLT requires more acoustic insulation materials than their reinforced concrete counterpart to achieve an equal sound comfort.

In one study on a 4-storey student house, the CLT panels were layered with additional cementitious materials for acoustic separation (Moncaster et al., 2018). This additional cement can have a significant unfavorable impact on the GWP per surface area of the building. To improve the sound barrier between different stores, a reinforced concrete screed can be added to the floors (Ramage et al., 2017).

A group of researchers from the University of Trieste investigated the use of floating floors and walls separated by pads or layers to improve the acoustic insulation of timber buildings. A reduced sound transmission was achieved by applying polymer foams and wood fiber insulation boards (Caniato et al., 2017).

Materials such as plasterboards and mineral wool can help achieve timber buildings the required acoustic comfort. For example, when a mineral wool of 60 mm is placed between two CLT-panels who each have a thickness of 115 mm, and both CLT-panels are foreseen with a plasterboard of 12.5 mm thick at the outer face, an insulation of 57 dB is achieved. This is the same as with a masonry wall (Danihelovà & Gergel, 2016). The cradle-to-gate GWP of plasterboards and mineral wool is respectively around 3 kg CO_2 eq/m³ and 20-40 kg CO_2 eq/m³.

An eco-friendlier alternative to reduce the sound transmission is the use of cork flooring. Cork has prosperous sound insulating properties. For this reason cork is sometimes added to CLT-slabs. Cork is also a wooden material since its extracted from the bark from the cork oak tree, making it more environmentally friendly. A comparative LCA performed on a CLT-floor system with reinforced concrete and a CLT-floor system with cork as acoustic insulation showed a reduction in the GWP of 25% for the system using cork when built in Portland, Oregon, USA. It should be noted that most greenhouse gasses emitted for the cork are due to the transport seeing the fact that most cork has to be transported from Portugal while the reinforced concrete is produced locally (Lawrence et al., 2017).

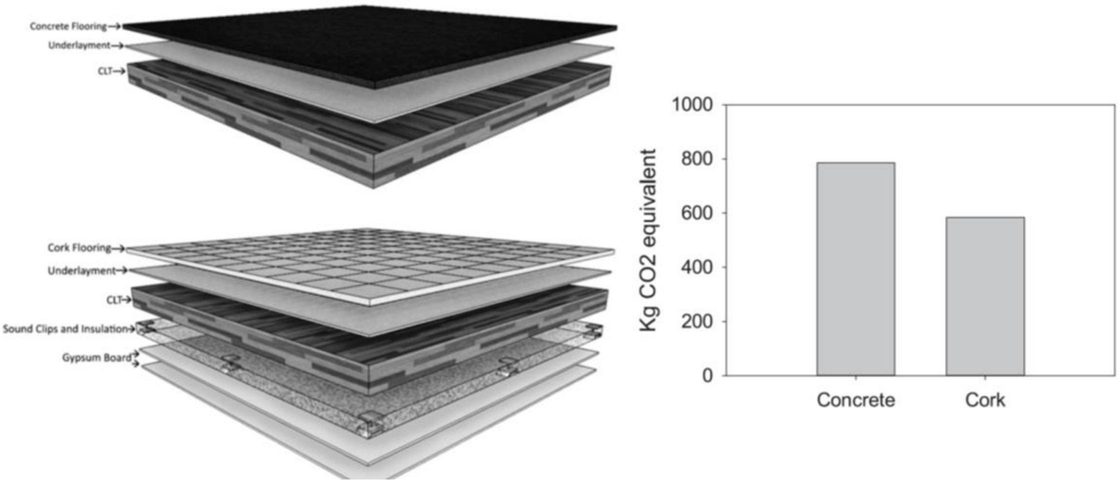

Figure 3.2: Schematic diagrams of concrete-CLT and cork tile-CLT flooring systems (left); GWP for concrete and cork-based flooring systems (right) (Lawrence et al., 2017)

3.5.2 Required concrete

Because of the lighter weight of wood, timber framed constructions have a smaller resistance against wind. With an increasing building height, this becomes more problematic. To prevent timber-framed buildings from swaying in strong winds a specific amount of reinforced concrete is added to multi-storey timber buildings. The additional concrete increases the horizontal rigidity of the building making the structure less vulnerable to high wind loads.

For example, the 14-storey timber building Treet in Norway got reinforced concrete slabs added at the 5th and 10th floor and on the roof. These reinforced concrete slabs aren't part of the loadbearing structure of the residential tower. They only add weight in order to reduce movement within the building as a result from high wind loads (Guajardo, 2016).

Despite these EWP's having opportune mechanical properties, timber construction elements still can't compete with reinforced concrete and steel on a structural level. With the Youngs modulus of reinforced concrete and steel being respectively approximately 3 and 15 times higher than CLT. When building with a timber structural frame, there'll need to be reinforced concrete (or steel) added to the loadbearing structure from a certain number of stores.

For example, the Tallwood House on the campus at the University of British Columbia in Canada is an 18-storeys high residential tower. The foundation, ground floor, second floor slab and elevator core are cast-in-place concrete. The superstructure is made up out of glulam, LVL, PSL and CLT (Teshnizi et al., 2018). A more complex hybrid-structure can be seen in the 42-storey high timber tower project of SOM where a band of reinforced concrete at the perimeter of the building and a band of reinforced concrete at the wall/floor intersections can be found. The floors, columns and shear walls between these bands are made out of CLT and glulam. This functions as a central reinforced concrete core coupled with shear walls near the edges of the building by stiff link beams (Skidmore et al., 2013).

Although timber construction elements have smaller GWP, it’s impossible that high-rise timber buildings will be realized without some amount of reinforced concrete. Appendix C shows the material quantity for multi-storey buildings for a reinforced concrete frame and a timber frame. These are the material quantities used for the LCA performed by Skullestad et al. (2016). The required concrete remains however relatively small. The applied volume of reinforced concrete varies between 2.49% (3 stores) to 9.99% (21 stores) of that of the equivalent building using reinforced concrete. Figure 2.3 shows for several WMC’s the composition of wood and reinforced concrete in the overall volume.

This means that for the GWP of timber multi-storey buildings the attribution from the production of reinforced concrete also has to be accounted within the overall GWP.

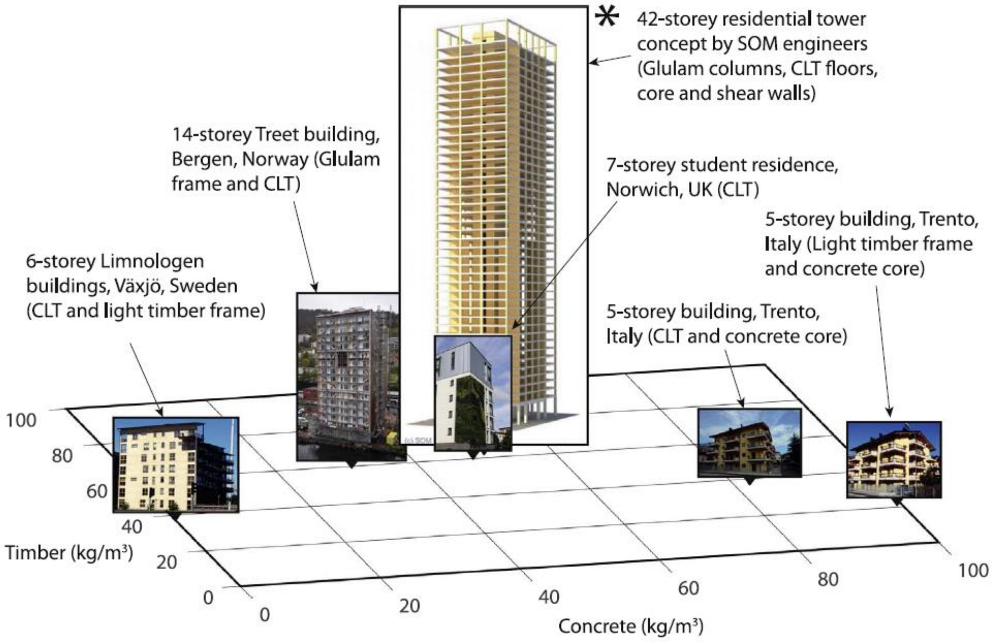

Figure 3.3: Material usage, in terms of mass, in multi-storey timber buildings (Ramage et al., 2017)

3.6 Cradle-to-gate GWP – buildings

For this part of the dissertation that focused on the cradle-to-gate phase, ten papers concerning comparative LCA’s between equivalent multi-storey buildings using different structural materials were collected. The number of stores vary from 3 to 43 stores. The results are shown in Table 3.10. In Table 3.10 a column is added that mentions rather or not the carbon sequestration during growth is included. This is an important factor to take into account when comparing these different LCA’s.

Two more papers were collected concerning comparative cradle-to-gate LCA's performed on multi-storey buildings with different structural materials. However the exact values of the results for each phase weren't given. The result is shown as bars in graphs.

The first study examined the carbon footprint of twelve multi-storey buildings with 3-8 floors. Four of these buildings had a mineral structure (reinforced concrete and bricks), six of them were built out of timber (two using CLT, four using a timber frame) and the remaining two were hybrid-structures combining timber and reinforced concrete. The information and results from this study is added in appendix D. For the A-module the A4 and A5-phase were excluded from this study. In the graph it can be clearly seen that for the cradle-to-gate phase of the buildings, the timber buildings have the lowest GWP, followed by the hybrid buildings. The mineral buildings had the biggest GWP. Four out of the six timber buildings even appeared to be carbon neutral or carbon negative within the cradle-to-gate phase. Even when the CO_2 sequestration through the growth of the timber isn't included, the timber and hybrid-buildings still have a smaller cradle-to-gate GWP than their mineral counterparts (Hafner & Schäfer, 2017).

Another study performed by Hafner and Schäfer compared the GWP of a residential 8-storey building with four different types of construction. One building using timber, the remaining three using porous reinforced concrete and perforated bricks. The results are added in appendix E. Within the cradle-to-gate phase the timber building using CLT seems to be carbon negative. Even without the CO_2 sequestrated within the wood, the timber building emits the least greenhouse gasses (Hafner & Schäfer, 2017).

Table 3.10: Cradle-to-Gate GWP for multi-storey buildings

Country	Function	Stores	Floor area [m²]	Bearing structure	A1-3 GWP [kg CO_2 eq/m²]	CO_2 sequestration	Reference
New-Zealand	School	3	1 980	Reinforced concrete	192.9	Included	(Buchanan et al, 2012)
				Steel	250.5		
				Timber	16.7		
USA	Hotel	3	2 613	Reinforced concrete	117.6	Included	(Skullestad et al, 2016)
				Timber: CLT + Glulam	33.95		
USA	Hotel	7	6 097	Reinforced concrete	109.1		
				Timber: CLT + Glulam	46.2		
USA	Hotel	12	10 542	Reinforced concrete	108.5		
				Timber: CLT + Glulam	49.7		
Norway	Hotel	21	11 823	Reinforced concrete	265.9		
				Timber (Glulam + CLT) + reinforced concrete	81		
Canada	Office	5	14 233	Reinforced concrete	420	Included	(Robertson, 2007)
				Timber (Glulam + CLT)	122		
New-Zealand	Office	6	4 247	Reinforced concrete	371 (364)	Excluded (included)	(John et al, 2008)
				Steel	380 (372)		
				Timber (LVL)	229 (29)		
Sweden	Residential	4	1 190	Reinforced concrete	122.5	Included	(Dodoo et al, 2009)
				Timber	105.5		
Australia	Not mentioned	43	30 401	Reinforced concrete	195.2	Included	(Li et al, 2019)
				Reinforced concrete + non-structural CLT elements	79.6		
				Timber (CLT-slabs)	-311.3		
China	Residential	3	5 590	Reinforced concrete	386.4 (359.7)	Excluded (included)	(Gong et al, 2012)
				Steel	133.6 (-20.8)		
				Timber	130.8 (1.1)		
Vancouver, Canada	Residential	18	12 838	Reinforced concrete	268 (259.5)	Excluded (included)	(Bowick, 2018)
			15 120	Hybrid: Timber + concrete	177.9 (146.2)		(Bowick, 2018)
UK	Residential	4	2 250	Reinforced concrete	134.2	-	(Moncaster et al, 2018)[3]
				Steel	143.1		
				Timber	59.6		
UK	Residential	3	914	Reinforced concrete	663.3	-	(Din & Brotas, 2017)
				Steel	421.8		
				Timber	266.2		
		6	1 828	Reinforced concrete	693.8		
				Steel	581.6		
				Timber	137.4		

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[3] From this LCA the average values were selected

Chapter 4 – Construction process stage

This chapter of the dissertation regards the transportation of the building materials to the construction site (A4) and the construction process of the building on site (A5). The contribution to the GWP during this phase are mostly from the combustion of fossil fuels for the transport of the required materials and the operating of the building machinery on site. The GWP and energy intensity of this stage is relatively small towards the other stages.

4.1 Transport to the construction site

The greenhouse gasses emitted in this phase (A4) originate from the combustion of fossil fuels within the transport moduli. The GWP of the A4-phase depends on three factors:

- The weight of the building elements
- The applied transport moduli
- The distance to be overpassed

Timber has a lower density compared to these other conventional structural materials (Ramage et al., 2017). This means that to transport the same volume of timber, reinforced concrete and steel over the same distance, timber requires the least energy and therefore emits the least amount of CO_2 during the A4-phase per volumetric unit.

The distance to overpass and the applied transport moduli is determined by the place of manufacturing and the construction site. This varies from site to site and from manufacturer to manufacturer. However CLT is still a relatively new product, meaning the production of CLT-products isn't as widely spread like steel and reinforced concrete are.

Because the distance the transport of the building elements need to overpass differs for every construction site, most producers don't mention the A4-phase within the EPD. However when the A4-phase is taken into account in the EPD, an average distance needs to be estimated. In order to compare the values of the EPD's, the GWP for this phase is also expressed in function of every overpassed kilometer. Because of the big influence of the overpassed distance, the A4-GWP is mostly inherent to the construction site itself rather than the material. Because of these reasons no tables have been made to compare the A4-phase of the EPD's.

Still the influence of the A4-phase can be significant. A comparative LCA was performed on a 17-storey office building in Switzerland. The GWP for the phases from A1 to A5 for a reinforced concrete and a timber structure was calculated. For the timber building three different cases for the origin of the building materials were considered. Case 1 considered the structural materials being delivered by truck over a distance of 150 km. In case 2 the structural materials were transported by train from Sweden over a distance of 2 500 km. The third case used the same Swedish producer from 2 500 km away but considered this time the structural materials being delivered by truck. Beside the distance being almost 17 times bigger, the GWP for case 1 and case 2 were respectively 176 ton CO_2 eq and 189 ton CO_2 eq.

The increased distance resulted in a 7.39% increase in the amount of released greenhouse gasses. However for case 3 the GWP resulted in 1 134 ton CO_2 eq. Meaning that a switch of transport moduli during the A4-phase resulted in a 500% increase in the emitted mass of greenhouse gasses while considering the same overpassed distance and the same transported load (Cattarinussi, 2016).

Another study determined the GWP per volumetric unit for CLT used on a construction site in Japan. This has been performed on the CLT-panels of three different producers. The first producer was from Austria, meaning the timber had to be transported to the Genoa port in Italy (700 km), thereafter it was transported oversea from the Genoa port to the Shin-Toyosu port in Japan (17 500 km). From the Shin-Toyosu port a 30 km road transportation followed to the construction site. The second producer was located 700 km from the construction site. Meaning only road transportation was carried out. The third producer was also located on the Japanese island but from a further distance. The CLT-panels were transported to the Kagoshima port to overpass a distance of 1 100 km oversea to the Shin-Toyosu port. From there a 30 km road transportation was carried out to the construction site. The results showed that for the same CLT-panels the cumulative GWP per volumetric unit from stage A1 to A4 was 34% and 40% lower for the second and third producer in comparison with the first producer (Passarelli & Koshihara, 2017). The data and results of this study are added in appendix F.

4.2 Construction process

This paragraph considers the A5-stage of an LCA. It regards the GHG's emitted during the installation of the building on the construction site. The emitting of greenhouse gasses during this phase originates from the combustion of fossil fuels by the on-site machinery (cranes, bulldozers etc.), on-site electricity use, on-site transportation, assembly and miscellaneous works (for example the combustion of acetylene during the welding process). The transportation of the construction machinery to the construction site also has to be taken into account (Hong et al., 2015).

An additional factor to the A5-GWP is the disposal of the product packaging. For this disposal an average distance had to be assumed for the product packaging. The remaining waste is relatively small for timber buildings due to the common application of prefabrication.

In Tables 4.1; 4.2 and 4.3 are the GWP' shown during the A5 phase for respectively timber, steel and reinforced concrete elements.

Buchanan (2007) noted that the energy required to construct a building is not highly dependent on the building materials. Most studies about comparing building materials assume that the construction energy is the same for all materials. In appendix G the results of a comparative LCA is shown between a timber, a steel and a reinforced concrete construction for a 3- and 6-storey apartment building. A graph is shown that illustrates the share of every LCA-stage on the overall GWP. It is shown that the A5-stage has an insignificant share on the emitted mass of greenhouse gasses for all three construction materials.

Table 4.1: GWP and energy consumption in the A5 and 'A4+A5'-phase for timber

Material	Country	Primary energy-use renewable [MJ/m³] A5	Primary energy-use non-renewable [MJ/m³] A5	A5-GWP [kg CO_2 eq/m³]	A4-5-GWP/[kg CO2 eq/m³]	Reference
CLT	Norway	1.128	0.139	21.97	56.51	(Cross Timber Systems, 2017)
	Spain	2.36	132.12	7.39	55.21	(Egoin, 2018)
	Germany	0.04	0.217	1.76	-	(Holzleimbau e.V., 2017)
	France	11.5	199	10.01	99.70	(Storaenso, 2016)
	UK	-	-	-	43.20	(PE International, 2013)
Glulam	Germany	0.153	0.845	4.52	-	(BS Holz, 2018)
	UK	0.008	0.758	5.75	-	(Schilliger Holz AG, 2018)
	Switzerland	-	-	-	37.20	(PE International, 2013)
LVL	UK	-	-	-	44.3	(PE International, 2013)

Table 4.2: GWP and energy consumption in the A5-phase for steel

Material	Country	Primary energy-use renewable [MJ/m³] A5	Primary energy-use non-renewable [MJ/m³] A5	A5-GWP [kg CO_2 eq/m³]	A5-GWP [kg CO_2 eq/metric tonne]	Reference
I, H, U, L, T and wide flats hot-rolled sections	Norway	12 324.5	1 405.15	116.18	14.8	(Conitga, 2013)

Table 4.3: GWP and energy consumption in the A5-phase for concrete

Material	Country	Primary energy-use renewable [MJ/m³] A5	Primary energy-use non-renewable [MJ/m³] A5	A5-GWP [kg CO_2 eq/m³]	A5-GWP [kg CO_2 eq/metric tonne]	Reference
Hollow core	Norway	4.36	39.4	6.93	2.77	(Contiga, 2017)
Pre-stressed beam	Norway	4.36	39.4	6.93	2.77	(Contiga, 2017)
Ready-to-mix concrete C30/37	Germany	14.14	32.78	2.59	1.08	(InformationsZentrum Beton GmbH, 2018)
Ready-to-mix concrete C35/45	Germany	14.14	32.78	2.59	1.08	(InformationsZentrum Beton GmbH, 2018)
Ready-to-mix concrete C45/55	Germany	14.14	32.78	2.59	1.08	(InformationsZentrum Beton GmbH, 2018)
Ready-to-mix concrete C50/60	Germany	14.14	32.78	2.59	1.08	(InformationsZentrum Beton GmbH, 2018)

For this reason, it is more useful to compare the different structural materials their cumulative GWP for all five A-phases of an LCA.

A 1999 study at the Environmental research group from the School of Architecture at the University of British Columbia examined the differences between the energy usage and greenhouse gas emissions during the A5-phase for reinforced concrete, steel and timber buildings. The results of this study are added in Appendix H. It can be seen that the lowest greenhouse gas emissions during the construction phase are obtained when building with steel, which ranges between 0.4 – 1.0 kg CO_2 eq/ m². The A5-GWP for timber buildings was slightly higher, with emissions ranging from 0.8 – 2.5 kg CO_2 eq/m². Concrete structural systems reached the highest emission rate with values rating from 5.0 – 20 kg CO_2 eq/m². This is mainly due to the fact that steel and timber structures have a higher rate of prefabrication than their reinforced concrete counterparts. This results in more on-site equipment use and is more labor intensive, which means that more workmen need to be transported to the construction site. For the sites that used precast concrete elements instead of cast-in-place, the GWP during the A5-phase varies between 4 – 5 kg CO_2 eq/m² (Cole, 1999). Note that in the paper of this study, no information could be found concerning the number of floors of the regarded buildings. Whether this concerns single and/or multi-storey buildings is not mentioned.

4.3 Cradle-to-site GWP – buildings

This dissertation focused until now on the cradle-to-site phases. For these thirteen papers concerning comparative LCA's between equivalent multi-storey buildings using different structural materials were collected. The number of stores vary from 3 to 17 stores. The results are shown in Table 4.4.

Table 4.4: Cradle-to-Site GWP for multi-storey buildings

Country	Function	Stores	Floor area [m^2]	Bearing structure	A1-5 GWP [kg CO_2 eq/m^2]	CO2 sequestration	Reference
Sweden	Residential	4	928	Timber frame	154.77	Excluded	(Peñaloza et al, 2013)
				Concrete frame	276		
Switserland	Office	17	41 000	Timber frame (Glulam)	116	Excluded	(Cattarinussi et al, 2016)
				Reinforced concrete	207		
Australia	Commercial	15	17 104	Reinforced concrete	523.6	Excluded	(Sandanayake et al, 2018)
UK	Residential Commercial	11	11 960	Timber	508.8		
Canada	Residential	4	1 512	Timber frame	302	-	(Padilla-Rivera et al, 2018)
				Timber frame	287		
				Reinforced concrete	442		
				Steel frame	353		
New-Zealand	School	3	1 980	Concrete	206.6	Included	(Buchanan et al, 2012)
				Steel	260.6		
				Timber	25.3		
China	Residential	4	-	Reinforced concrete	308.2	Included	(Guo et al, 2017)
				Timber (CLT)	-84		
		7	-	Reinforced concrete	292.6		
				Timber (CLT)	-85.7		
		11	-	Reinforced concrete	270		
				Timber (CLT)	-96.9		
		17	-	Reinforced concrete	265.3		
				Timber (CLT)	-97.4		
Norway	Residential	14	7 227.35	Timber	-48.8	Included	(Guajardo, 2016)
				Reinforced concrete + Steel	66.9		
Sweden	Residential	6	1 686	Reinforced concrete	433		(Tettey et al, 2019)
				Timber (CLT)	-416		
				Timber (Prefabricated modular frame)	-3		
China	Residential	3	5 590	Reinforced concrete	441 (414.3)	Excluded (included)	(Gong et al, 2012)
				Steel	197.9 (43.5)		
				Timber	172.8 (43.1)		
Canada	Office	5	14 128	Reinforced concrete	423.3	Excluded	(Chen, 2012)
				Timber (CLT + glulam)	167.8		
Canada	Residential	18	12 838	Reinforced concrete	292 (283.5)	Excluded (included)	(Bowick, 2018)
			15 120	Hybrid: Timber + concrete	200.5 (168.8)		(Bowick, 2018)
UK	Residential	3	914	Reinforced concrete	691.28	-	(Din & Brotas, 2017)
				Steel	453.32		
				Timber	299.08		
		6	1 828	Reinforced concrete	726.71		
				Steel	626.53		
				Timber	166.76		

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[4] This LCA didn't contain information about the GWP during the A5-phase

Chapter 5 – Operational phase

The fifth chapter of this dissertation regards the phase of a building between the end of its construction and the beginning of its demolition. In an LCA this is referred to as the B-phases, as can be seen in Figure 1.4. It is the operational phase that has the biggest carbon footprint of all stages in the full lifecycle of a building. This is caused by the long service life of buildings and the constant energy requirements (Peñaloza et al., 2013). For this the B-stage is the dominant stage for the outcome of a buildings LCA. From the CO_2 emitted by the global building sector, 72% would originate from the operational phase (Architecture2030, 2018).

Phases like B1 (use) and B7 (Operational water use) aren't discussed in this state-of-the-art review since the material of the loadbearing structure has no influence on the GWP and energy usage of these phases. Phases like B2, B3, B4 and B5 are also not described in this dissertation because of the limited amount of information that's available. The main affected phase by the buildings structure is the B6-phase (Operational energy use). When the differences between steel, reinforced concrete and timber buildings the energy usage due to lightning, cooking, water heating and electronic equipment use are also excluded because these factors aren't influenced by the structural material of the building. The activities that will be discussed in this chapter are space heating and space cooling, who also make up the majority of the operational energy consumption. For a comparative LCA, an existing building is hypothetically redesigned with another structural material, meaning that the data for these two parameters are often obtained from computer simulations, rather than actual on-site measurements.

This chapter focusses on the operational energy and operational carbon, in contradiction to the former two chapters where the embodied energy and embodied carbon was discussed. The operational energy and carbon refer to the energy-usage and carbon emissions during the usage of the building. Whereas the embodied energy and carbon accounts for all the energy usage and carbon releases to the atmosphere which weren't caused by the direct usage of the building. The latter is discussed in Chapter 3; 4 and 6.

When examining the GWP during the operational phase of a building, a parameter that has to be taken into account is the design lifespan. A longer lifespan results in a bigger energy-use, which increases the operational GWP of the building.

A factor during the usage phase of reinforced concrete buildings that can be taken into account is the carbonation reaction of concrete. During its lifetime, concrete elements absorb CO_2 from the atmosphere due to the carbonation reaction. However there is still little known about the specific amount of CO_2 that gets sequestrated by reinforced concrete buildings during their usage. In an LCA performed on a reinforced concrete building there can be made an assumption on the amount of absorbed carbon dioxide, this differs between the several studies. In order to make an accurate assumption, more research is needed on this matter. This factor also differs between the different cement-types. Pade and Guimaraes (2007) estimated that between 33 and 57% of the CO_2 released by calcination will be reabsorbed by carbonation. This estimation however remains uncertain. The carbonation rate is slower, if not negligible when the surface is coated (Dodoo et al., 2009).

It's also possible to take the effect of carbon sequestration of the trees into account in the operational phase. When doing so, the carbon stocked in the building material itself is neglected. The carbon uptake during the regrowth of the forest after the harvest for the material production is than calculated in the B-phase of the building.

5.1 Space heating

Timber buildings usually require less thermal insulation materials than their steel and reinforced concrete counterparts. Timber has a lower thermal conductivity than steel and reinforced concrete, this is shown in Table 5.1.

Table 5.1: Conductivity of structural materials

Material	λ [W/mK]
Timber	[5] 0.11 - 0.15
Concrete	1.93
Reinforced concrete	2.5
Brickwork	0.77
Steel	45.3

According to the author, this effect timber can have on space heating can go in two ways: 1) The same amount of insulation material is used as when the building is made up from steel or reinforced concrete, resulting in a lower U-value of the thermal envelope. A lower U-value reduces the energy-usage for space heating. 2) There is less insulation material required in the thermal envelope to obtain the same U-value as when the building is realized using reinforced concrete and/or steel. Resulting in an almost identical energy-usage for space heating. In the first case this results in a reduced operational energy and carbon, meaning a lower GWP in the B-phase. In the second case the smaller GWP is obtained through diminished embodied energy and carbon, which means that the benefit to the GWP was already obtained in the A-phase of the LCA.

In both cases, it is especially in cold climates that the small conductivity of timber can be favorable. One research was carried out on a 7-storey reinforced concrete building in Xi'an, China. The building was redesigned using CLT as the load bearing structure, and was also hypothetical relocated to Harbin, China. Xi'an and Harbin are respectively located in the cold and severe cold region of China. In this study, both the reinforced concrete and timber building had the same amount of insulation-material, making it representative for the first case. In Xi'an both buildings were provided with a 50 mm thick insulation layer, in Harbin this was 100 mm. The results of this study are shown in appendix I. The results show a significant reduction in both the operational energy and in the operational carbon for both cities.

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[5] CLT probably has a lower conductivity because it consists of multiple layers

This reduction seems to be slightly bigger in Harbin, the coldest region of the two. The reduction in GWP and energy use when building with timber can also be seen in the production phase (Liu et al., 2016).

When looking at the second case where there is a difference in insulation-material but no difference in the U-value of the thermal envelope, another comparative LCA was consulted. A 4-storey residential reinforced concrete-framed building in Växjö, Sweden was redesigned with a timber frame. For this study both the reinforced concrete and timber-framed versions were relocated in Östersund and Kiruna. These are all three cities in Sweden meaning they all know a relatively cold climate. Both buildings were designed to meet the same thermal properties for each region. This resulted in a difference in the use of insulation in the thermal envelope between the reinforced concrete and the timber building[6]. The insulation was also determined for three different standards: the original reinforced concrete building, the current Swedish building code and the passive house standard. This study solely examined the energy-usage per square meter, this for both the A, B and C-phases of the LCA. For the space heating, three different technologies were observed: bedrock heat pump, district heating and electric resistance heating. For the production phase, the energy-usage gets reduced by 21.8% - 26.6% by using timber instead of reinforced concrete for respectively the passive house standard and the reference building. During the operation phase however, no reduction could be detected. The timber building required more energy for space heating, but the difference remained insignificant. The timber building used on an annual basis 0.5% - 2.8% more final energy for space heating than its reinforced concrete counterpart. When looking at the annual primary energy use for space heating, the increase when building with timber varies from 0.9% - 2.4%. Meaning that the energy for space heating is almost identical for both buildings. The tables with the specific results of this study are added in appendix J. The energy use for air ventilation was assumed to be identical for both buildings (Dodoo et al., 2012).

In Table 5.2 are the results shown from six comparative LCA's. In these six LCA's the difference in annual energy demand for heating for WMC's was compared with reinforced concrete and/or steel equivalent buildings. Because of the relevance of the difference in U-value, an extra column was added to mention rather or not a similar U-value was assumed for the equivalent buildings.

Table 5.2: Annual heating energy for multi-storey buildings when using different structural materials (1/2)

	Country	Function	Stores	Floor area [m²]	Bearing structure	Annual heating energy use [kWh/m²]	Reference
Different U-value	Sacramento, California, USA	Residential	10	7 837	Reinforced concrete + Steel	8.44	(Khavari et al, 2016)
					Timber (CLT)	4.73	
Different U-value	Växjö, Sweden	Residential	6	1 420	Prefab-concrete frame	57	(Dodoo & Gustavsson, 2016)
			8	2 773	Massive timber-frame	36.4	
			4	1 045	Light timber-frame	79.5	

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[6] The timber building in general still used more insulation material than the reinforced concrete building. This can be explained by the fact that the ceiling and floors between the different stores were not insulated in the reinforced concrete building in contradiction to the timber building where insulation was added to the ceilings and floors. The U-value in the outer thermal envelope remained however the same.

Table 5.2: Annual heating energy for multi-storey buildings when using different structural materials (2/2)

	Country	Function	Stores	Floor area [m^2]	Bearing structure	Annual heating energy use [kWh/m^2]	Reference
Similar U-value	Växjö, Sweden	Residential	4	1 190	Concrete	68	(Dodoo et al, 2012)
					Timber	68.95	
	Östersund, Sweden				Concrete	93.65	
					Timber	94.27	
	Kiruna, Sweden				Concrete	129.43	
					Timber	130.08	
Similar U-value	New-Zealand	School	3	1 980	Reinforced concrete	35.7	(Perez et al, 2011)[7]
					Steel	34.9	
					Timber	34.3	
Similar U-value					Concrete Low	21.1	
					Steel Low	21.4	
					Timber Low	21.3	
Similar U-value	Växjö, Sweden	Residential	6	1 686	Reinforced concrete	37.2	(Tettey et al, 2019)
					Timber (CLT)	37.5	
					Timber (Modular)	37.5	
Different U-value	Harbin, China	Office	15	27 529.67	Reinforced concrete	74.16	(Dong et al, 2019)
					Timber	65.29	
	Beijing, China				Reinforced concrete	38.18	
					Timber	29.74	
	Shangia, China				Reinforced concrete	17.82	
					Timber	12.31	
	Kunming, China				Reinforced concrete	8.19	
					Timber	6.28	

5.2 Cooling and ventilation

It's within this factor of cooling and ventilation that timber buildings often have a poorer performance than their steel and reinforced concrete counterparts. Because of the light weight of timber buildings, they have a lower thermal mass, meaning it does not absorb and release heat rapidly enough to correspond to daily heating and cooling cycles (Ramage et al., 2017). Timber may have a higher specific heat capacity than reinforced concrete and steel – respectively 1 300 J/kg°C, 880 J/kg°C and 460 J/kg°C – it's because of its lower weight it has a lower thermal mass. The thermal mass of concrete and steel are respectively 3.5 and 6 times that of timber, making wooden buildings more vulnerable for overheating. This is shown in Table 5.3. The low thermal mass of EWP's can lead to overheating during the summer months, especially in hot climatic regions. Therefore timber buildings usually know a higher energy consumption for cooling and ventilation.

Table 5.3: Thermal properties of timber, concrete and steel

Material	Heat capacity [J/kgK]	Density [kg/m^3]	Thermal mass [kJ/m^{3}K]
Timber	1 300	470	611
Concrete	880	2 400	2 112
Steel	460	7 850	3 611

Timber buildings aren't solely more vulnerable for overheating because of its lower thermal mass, but also because of its lower U-value. Colder climates locations are more exposed to overheating due to radiative and conductive heat gains, while the main reason for overheating of buildings in warmer

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[7] The buildings labeled with 'low' their thermal envelope has been redesigned with increased insulation values to reduce the impact of heat losses when looking at the influence of thermal mass provided by the structural systems.

climatic regions are convective heat gains. Therefore, higher U-values in cooling season perform better in warmer locations and lower U-values in cooler (Pajek et al., 2017).

For one study the 7-storey reinforced concrete building located in Xi'an and its redesigned timber variant mentioned in 4.1 at page 31 were hypothetically relocated in 31 Chinese cities, spread over the five different climatic regions within the Chinese mainland (Severe Cold, Cold, Hot Summer - Cold Winter, Hot Summer - Warm Winter and Temperate). For all the 31 cities the difference in operational energy consumption and GHG-emissions between the reinforced concrete and timber-frame are determined. For this research only energy used for heating, cooling and cooling appliances are simulated. The results of this study show that for all 31 cities (and thus for all the five climates) the timber building has a smaller energy consumption and lower GHG-emissions than its reinforced concrete-framed counterpart. The annual operational energy consumption for the reinforced concrete building ranged from 30.7 – 324.7 MJ/m² with an average of 162.8 MJ/m². For the CLT-building these values varied between 18.3 – 241.9 MJ/m² with an average of 116.4 MJ/m². The relative reduction in operational energy consumption for CLT-buildings in comparison with reinforced concrete buildings ranges between 25 – 35% with an average of 29.4%. When looking at the operational GHG-emissions, the reinforced concrete building emits between 3.4 – 34.4 kg CO_2 eq/m² every year with the weighted average value of 19.4 kg CO_2 eq/m². For the CLT-building this was 2.5 – 27 kg CO_2 eq/m² every annum, with the average value being 14.8 kg CO_2 eq/m². The relative reduction in operational carbon for timber buildings in comparison with reinforced concrete ranges from 20 – 30%, with the average being 24.6%. The results of this research are added in appendix K. Although the paper of this research also states that overheating may occur in the CLT-building in most cities, resulting in a higher energy usage for cooling in the timber-framed building, the percentages of energy saving and carbon reduction seems to show little correlation with the climatic zone. This could be declared by the fact that electricity is used for cooling and raw coal for heating, resulting in a larger carbon footprint for energy consumption for heating. Despite when the energy saving between the CLT and reinforced concrete building is expressed in function of the used volume of CLT, there can be a linear relationship observed between the climate and the energy savings. With the biggest energy savings in the coldest region, and the smallest in the warmest region. Taking the total amount of energy consumption into consideration, the buildings in the cold regions require much more energy than those in other regions for heating. For this reason it would be more favorable for the climate to give projects concerning timber multi-storey buildings precedence in the cold regions[8] (Guo et al., 2017).

The influence of WMC's on the operational energy demand for heating and cooling under different climates was further examined. For this research a 15-storey reinforced concrete office building in Harbin was redesigned with a CLT structure. Again the building was hypothetical relocated in four other cities (Beijing, Shanghai, Shenzhen, Kunming) making all five climatic regions of the Chinese mainland represented in this paper. The overall operational energy consumption was determined through

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[8] In the case of China this is not necessarily true because in the North (in the colder climates) coal is mainly used as an energy source.

simulation, and in specific the ones for heating and cooling. For Shenzhen which is located in ‘Hot Summer Warm Winter’-region only cooling energy was determined since there’s no heating demand. The results of this study are shown in appendix L. The results show that for all the climatic regions in China the CLT building requires less energy for spacial heating. The CLT-buildings consumed 11.97% - 30.94% less energy for heating than the reinforced concrete benchmark. Remarkable was that the smallest relative reduction for space heating was found in the severe cold region, and the biggest in the ‘Hot Summer Cold Winter’-region. On the contrary, for all five cities, the CLT-building used more energy for space cooling. The increase in energy demand for cooling varied between 0.63% - 10.97%. The smallest raise was observed in the ‘Hot Summer Warm Winter’-region, the biggest in the temperate climate. For the overall operational phase, the reinforced concrete benchmark required 2 – 4% more energy than the CLT counterpart for the Severe Cold region, the Cold region and the ‘Hot Summer Cold Winter’-region. For the Temperate region and the ‘Hot Summer Warm Winter’-region the operational energy demand seemed to be similar. From this study it was concluded that the CLT-building was more efficient in the cold regions in terms of energy savings (Dong et al., 2019).

Khavari et al. (2016) also concluded that CLT buildings will be much more efficient for regions where heating energy takes a larger portion of the overall consumption. In their study a CLT-envelope resulted in 40% energy savings for heating when compared with reinforced concrete. However CLT envelope will trap the internal heat and be slightly less effective in cooling.

In Table 5.4 are the results shown from four comparative LCA’s. These papers examined the difference in annual energy consumption for space cooling between timber multi-storey buildings and their steel and/or reinforced concrete equivalent counterparts.

Table 5.4: Annual cooling and ventilation energy for multi-storey buildings when using different structural materials

Country	**Function**	**Stores**	**Floor area [m^2]**	**Bearing structure**	**Annual cooling & ventilation energy use [kWh/m^2]**	**Reference**
Sacramento, California, USA	Residential	10	7 837	Reinforced concrete + Steel	8.8	(Khavari et al, 2016)
				Timber (CLT)	9.4	
Växjö, Sweden	Residential	6	1 420	Prefab-concrete frame	3	(Dodoo & Gustavsson, 2016)[9]
		8	2 773	Massive timber-frame	4.9	
		4	1 045	Light timber-frame	2.3	
New-Zealand	School	3	1 980	Reinforced concrete	0.3	(Perez et al, 2011)
				Steel	0.3	
				Timber	0.35	
				Concrete Low	0.45	
				Steel Low	0.45	
				Timber Low	0.45	
Harbin, China	Office	15	27 529.67	Reinforced concrete	31.81	(Dong et al, 2019)
				Timber	32.86	
Beijing, China				Reinforced concrete	44.07	
				Timber	45.38	
Shangia, China				Reinforced concrete	43.66	
				Timber	44.64	
Shenzhen, China				Reinforced concrete	83.63	
				Timber	84.16	
Kunming, China				Reinforced concrete	31.24	
				Timber	34.67	

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[9] The 3 buildings in Växjö are not completely equivalent because of a difference in glazing area.

5.3 Total operational carbon footprint

To determine the difference in overall operational energy and carbon, fourteen comparative LCA's were collected. Their results are given in Table 5.5. Only six of these fourteen papers provided data of the GWP during the operational phase, thirteen contained information about the operational energy demand. Since the GHG-emissions during the usage of the buildings are proportionate with operational energy consumption, the latter is also shown in Table 5.5.

Some LCA's only include the operational energy-use for HVAC because this is directly affected by the structural material of the building. Other LCA's also include the energy consumption from lighting, water heating, and electrical appliances. Since the latter is not affected by the choice of structural material the LCA's who include these processes will result in smaller differences in both GWP and operational energy consumption. Therefore there need to be made a distinction between the LCA's who only include HVAC for the B6-phase and those who include other energy consuming processes.

Table 5.4: Operational GWP and energy consumption of multi-storey buildings when constructed with different structural materials (1/2)

	Country	Function	Stores	Floor area [m²]	Lifespan [years]	Bearing structure	B GWP [kg CO₂ eq/m²]	Operational energy use [kWh/m²]	Anual energy use [kWh/m²year]	Included in the operational energy	Reference
Similar U-value	China (Harbin, cold region)	Residential	4	-	50	Reinforced concrete	6 916.7	9 531.7	190.63	Heating; Cooling; Appliances	(Guo et al, 2017)
						Timber (CLT)	6 314.1	8 737.5	174.75		
			7	-		Reinforced concrete	6 698.7	9 255.7	185.11		
						Timber (CLT)	6 121.8	8 506.1	170.12		
			11	-		Reinforced concrete	6 596.2	9 122.1	182.44		
						Timber (CLT)	6 025.6	8 377.8	167.56		
			17	-		Reinforced concrete	6 532.1	9 038.5	180.77		
						Timber (CLT)	5 967.9	8 301.3	166.03		
Similar U-value	New-Zealand	School	3	1 980	60	Reinforced concrete	1 238.9	2 330.4 (3 203.4)	38.84 (53.39)	HVAC (+Appliances; Lighting; Water heating)	(Buchanan et al, 2012) (Perez et al, 2011)
						Steel	1 260.1	2 290.8 (3 163.8)	38.18 (52.73)		
						Timber	1 223.7	2 254.8 (3 127.8)	37.58 (52.13)		
						Concrete Low	969.2	1 466.4 (2 335.8)	24.44 (38.93)		
						Steel Low	-	1 485 (2 354.4)	24.75 (39.24)		
						Timber Low	-	1 479 (2 348.4)	24.65 (39.14)		
U-value slightly different	New-Zealand, Christchurch	Office	6	4 247	60	Reinforced concrete	1 156.1	5 083.3	84.72	Heating, cooling, Water heating, lighting, room electricity and miscellaneous systems	(John et al, 2008)
						Steel	1 177.3	5 138.9	85.65		
						Timber	1 215.2	5 277.8	87.96		
						Timber with timber non-structural elements	1 186.2	5 166.7	86.11		
Similar U-value	Växjö, Sweden	Residential	4	1 190	50	Reinforced concrete	-	3 415	68.30	Heating	(Dodoo et al, 2012)
						Timber	-	3 446	68.92		
	Östersund, Sweden					Reinforced concrete	-	4 682.5	93.65		
						Timber	-	4 713.5	94.27		
	Kiruna, Sweden					Reinforced concrete	-	6 471.5	129.43		
						Timber	-	6 504	130.08		
Different U-value	Sacramento, California, USA	Residential	10	7 837	-	Reinforced concrete + Steel	-	-	17.2 (144.96)	Heating; Cooling (+Electricity; Water	(Khavari et al, 2016)
						Timber (CLT)	-	-	14.1 (137.62)		
Different U-value	Växjö, Sweden	Residential	6	1 420	-	Prefab-concrete frame	-	-	60	Heating; Cooling	(Dodoo & Gustavsson, 2016)
			8	2 773		Massive timber-frame	-	-	41.3		
			4	1 045		Light timber-frame	-	-	81.8		
Different U-value	Xi'an, China	Residential	7	2799.3	50	Reinforced concrete	-	2 509	50.18	Heating; Cooling; Lighting	(Liu et al, 2016)[10]
						Timber (CLT)	-	1 520	30.4		
	Harbin, China					Reinforced concrete	-	3 756	75.11		
						Timber (CLT)	-	2 569	51.38		
	Helsinki, Finland	Residential	3	259.6	50	Timber (CLT)	-	5 110 - 5 725	108.35	Heating; cooling; Water heating; Lighting; Appliances	(Pal et al, 2017)
						Reinforced concrete	-	5 265 - 5 900	111.65		
						Steel	-	5 500 - 6 060	115.6		
Similar U-value	Vancouver, Canada	Office	3	4 620	50	Timber	-	17 600	352	Heating, Cooling, Lighting	(Cole & Kernan, 1996)
						Steel	-	17 827.8	356.56		
						Reinforced concrete	-	17 705.6	354.11		
	Toronto, Canada					Timber	-	27 475	549.5		
						Steel	-	27 702.8	554.06		
						Reinforced concrete	-	27 580.6	551.61		

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[10] For the operational energy 80% of the full life-cycle energy was taken since it was mentioned in the paper that " the operation stage is the major period of energy consumption of the buildings, accounting for at least 80% in four scenarios.".

Table 5.5: Operational GWP and energy consumption of multi-storey buildings when constructed with different structural materials (2/2)

	Country	Function	Stores	Floor area [m^2]	Lifespan [years]	Bearing structure	B GWP [kg CO_2 eq/m^2]	Operational energy use [kWh/m^2]	Anual energy use [kWh/m^2year]	Included in the operational energy	Reference
Different U-value	Harbin, China	Office	15	27 529.67	-	Reinforced concrete	-	-	105.98 (201.59)	HVAC (+Lighting; Water heating; Appliances)	(Dong et al, 2019)
						Timber	-	-	98.15 (194.73)		
	Beijing, China					Reinforced concrete	-	-	82.26 (156)		
						Timber	-	-	75.12 (149.67)		
	Shangia, China					Reinforced concrete	-	-	61.48 (124.15)		
						Timber	-	-	56.94 (121.13)		
	Shenzhen, China					Reinforced concrete	-	-	83.63 (134.07)		
						Timber	-	-	84.16 (134.72)		
	Kunming, China					Reinforced concrete	-	-	39.43 (97.8)		
						Timber	-	-	40.95 (99.82)		
Similar U-value	Beijing, China	Residential	3	5 590	50	Reinforced concrete	348.84	3 548	70.96	Total energy consumption	(Gong et al, 2012)
						Steel	352.42	3 791.5	75.83		
						Timber	347.05	3 294.6	65.89		
	Vancouver, Canada	Office	5	14 128	30	Reinforced concrete	-	3700.6	123.35	Heating; Cooling; Lighting; Water heating; Appliances	(Chen, 2012)
						Timber (CLT + Glulam)	-	3653.9	121.80		
Different U-value	Vancouver, Canada	Residential	18	12 838	100	Reinforced concrete	1 542.3	22 413.9	224.14	HVAC; Lighting; Water Heating; Appliances	(Bowick, 2018)
				15 120		Hybrid: Timber + concrete	1 617.1	20 504.5	205.05		(Bowick, 2018)
Similar U-value	UK	Residential	3	914	60	Reinforced concrete	948.4	-	-	HVAC; Water Heating; Appliances	(Din & Brotas, 2017)[11]
						Timber	992.4	-	-		
			6	1 828		Reinforced concrete	965.5	-	-		
						Timber	1 009.5	-	-		
			3	914	100	Reinforced concrete	1 224.4	-	-		
						Timber	1 264.9	-	-		
			6	1 828		Reinforced concrete	1 250	-	-		
						Timber	1 290.5	-	-		
			3	914	125	Reinforced concrete	1 299.3	-	-		
						Timber	1 338.6	-	-		
			6	1 828		Reinforced concrete	1 329.1	-	-		
						Timber	1 368.4	-	-		

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[11] The comparison between timber and steel was left out because the operational GWP was assumed to be identical for the timber and steel variant.

Chapter 6 – End of life phase

In the sixth chapter, this state-of-the-art review compares the end of life scenarios for the WMC's with the steel and reinforced concrete benchmarks. These are the four C-phases and the D-phase of an LCA. These will both be discussed on a product and a building-level. Just as in chapter 3 and 4 the comparison on the product scale will be made by using EPD's. For the buildings this will be realized by collecting LCA's.

The GWP of this phase are smaller than the previous discussed phases.

6.1 Demolition

The C1-phase concerns the demolition of the building. The GWP of the C1-phase origins from the on-site machinery use for the demolition and material gathering.

There is relatively little information available about the energy consumption and the amount of emissions during this stage. The GWP from the C1-phase have been assumed to be identical to the one at the A5-phase. This is also found to be a common approach used in several EPD's (Fufa et al., 2018). Another study mentioned an investigation that showed that the demolition of a building in China requires approximately 90% of the energy consumption for the erection of the building (Liu et al., 2016). In 4.2 at page 28 a study has already been discussed that showed how the construction of reinforced concrete multi-storey buildings required more energy than their steel and timber counterparts. A small difference between steel and timber was observed with steel consuming the least energy.

One comparative LCA of a 4-storey residential building estimated that the required energy for the demolition activities is estimated to have an average of less than 10 kWh/m² per usable area. This corresponds with an GWP of 3 kg CO_2 eq/m². This paper was a comparative LCA between three different timber buildings, no comparison was made with a steel or reinforced concrete benchmark (Dodoo et al., 2014).

Only nine EPD's contained data about the GWP and energy consumption during the demolition phase. Because of the lack of data and the small contribution the C1-phase has, this stage will not be discussed any further.

In EPD's like the reinforced concrete beam of Contiga, the assumption of the A5-GWP and C1-GWP being equal was found back.

Table 6.1: GWP and energy consumption in the C1-phase for timber

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m³] C1	Primary energy-use non-renewable [MJ/m³] C1	C1-GWP [kg CO_2 eq/m³]	C1-GWP [kg CO_2 eq/metric tonne]
CLT	2017	Egoin	Spain	0.43	77.46	4.99	9.50
	2017	Stora Enso	France	0.28	48.4	3.31	7.04
	2016	Cross timber systems	Norway	1.129	0.138	0.01	0.02

Table 6.2: GWP and energy consumption in the C1-phase for steel

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ]	Primary energy-use non-renewable [MJ]	C1-GWP [kg CO_2 eq/m^3]	C1-GWP [kg CO_2 eq/metric tonne]
Hot-rolled sections	2013	Contiga	Norway	6 170	696	58.25	7.42

Table 6.3: GWP and energy consumption in the C1-phase for concrete

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m^3]	Primary energy-use non-renewable [MJ/m^3]	C1-GWP [kg CO_2 eq/m^3]	C1-GWP [kg CO_2 eq/metric tonne]
Concrete beam	2016	Contiga	Norway	10.46	94.56	6.65	[12] 2.77
Unreinforced concrete C30/37	2018	InformationsZentrum Beton GmbH	Germany	2.8	41.9	3.1	1.29
Unreinforced concrete C35/45	2018	InformationsZentrum Beton GmbH	Germany	2.8	41.9	3.1	1.29
Unreinforced concrete C45/55	2018	InformationsZentrum Beton GmbH	Germany	2.8	41.9	3.1	1.29
Unreinforced concrete C50/60	2018	InformationsZentrum Beton GmbH	Germany	2.8	41.9	3.1	1.29

6.2 Transport

The C2-stage of the LCA concerns the transport of the material waste from the demolition site to its place of disposal. The greenhouse gasses emitted in this phase originate from the combustion of fossil fuels within the transport moduli. The GWP of the C2-phase depends on three factors:

- The weight of the waste
- The applied transport moduli
- The distance to be overpassed

One study declared that the cumulative energy use for stage C1 and C2 might be less than 3% of the energy content of the demolition waste (Börjesson & Gustavsson, 2000). Because of their small contribution to the GWP, the lack of data and info and the fact that the GWP and energy consumption is more dependent on the location of the demolition site than the material itself, this phase won’t be discussed further.

6.3 Waste processing

After the demolition and transport of the construction waste, it can either be processed or disposed. The latter will be discussed in subchapter 6.4. The GWP of the C3-hase can vary a lot between different buildings and producers of construction materials because of the different possible scenarios. Several options are available for the end-of-life use of the construction waste.

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[12] The specific weight wasn’t mentioned in the EPD and was therefore estimated to be 2.400 kg/m^3

The European Parliament has established a cascade use principle for wood, which suggests wood be used in the following order of priority: wood-based products, re-use (D), recycling (D), bioenergy (C3), and disposal (C4) (Ramage et al., 2017).

For this subchapter it should be noticed that the end-of-life scenarios discussed here are the currently ones available. Multi-storey buildings constructed nowadays can have a designed lifespan reaching 50 – 125 years. By their time of demolition it's likely more effective and climate-friendly options have been established for the construction waste.

6.3.1 Timber

Waste processing of construction timber mainly consists in using the wood as an energy-source. Up to now, the bioenergy scenario for timber consists of incineration and energy-recovery (Hafner et al., 2014). This scenario results however in emitting the carbon that was sequestrated by the trees during their growth in the A1-stage. This would make wooden building materials in their full life-cycle carbon neutral instead of carbon negative. Still climatic benefits from this process can be obtained in the D-stage if the energy-recovery from the wood substitutes energy production from fossil fuels.

Wood products can be used to produce energy through direct combustion or by conversion to liquid or gaseous fuel before burning. However wood containing adhesives like formaldehyde (like EWP's do) can't be deported to a regular power station to be burned. Timber containing harmful substances such as formaldehyde can only be used for energy generation in special stations equipped with appropriate combustion facilities (Ramage et al., 2017). Contaminated wood is fired in municipal solid waste combustion facilities or combustion plants for hazardous waste (Jungmeier et al., 2001). The firing of the wood waste makes the embodied carbon getting back emitted in the atmosphere as CO_2.

The use of wood as a renewable energy source and a mitigation for climate change is a heavily discussed topic. One study by Leturcq investigated the climatic beneficial potential of using timber waste as a substitutional energy source for fossil fuels. The study found that the replacement of fossil fuels by wood fuel does not reduce short term carbon emissions. This can be explained by the fact that wood has a higher emission factor than that of other fuels in common use. This paper however also discusses the fact that the carbon storage within timber is only temporary. Under influence of biogenic agents, the wood decomposes releasing the sequestrated carbon back into the atmosphere. So in the long term, if fossil fuels are used instead of timber waste this carbon released by decomposing gets added to the CO_2 emitted during the combustion of these fossil fuels. Leturcq examined all sort of applications for wooden materials and claimed within this paper that this view of carbon being eventually released into the atmosphere by combustion is not justified. "The chemical composition and the physical characteristics of ligneous matter, excepting mechanical properties, are the same as those of timber wood" (Leturcq, 2013). But it's the possible decline in mechanical properties that can make constructive timber unusable after usage.

Another paper discusses the statement that forest wood as biomass would be carbon neutral. A written advice of almost 800 scientists said that the policy of EU - where cutting down trees to burn them qualifies as low-carbon and renewable energy - would accelerate climate change in the next decades. It states that the renewability of trees and their potential as biomass to reduce their GWP can only be achieved over long periods. This way the rate of tree harvesting can't exceed the forest's incremental growth such the emitted CO_2 by burning the timber waste can be reabsorbed by the forest (Searchinger et al., 2018).

For the author of the dissertation, in order for wood fuel to be low-carbon, a long period of carbon storage is required. A solution that can be provided by building with timber since buildings are designed for a long lifespan. The LCA's collected for chapter 7 of this dissertation showed that WMC's can be designed with a lifespan of 50 – 125 years. However this tought applies to the timber structures that are constructed today cause by the time the building get demolished the newly planted trees already got the time to take up the carbon that the incineration of the wood waste will release again. This way no carbon will have been added in the future in comparison with the present atmospheric carbon concentration.

In Table 6.4 are the GWP's shown of eleven EPD's from seven countries. Here it can be seen that the value of the GWP is very similar to the one of the A1-phase shown in Table 3.1, only this time being positive. It should be noted that the C3-GWP for timber is determined by the incineration of the wood. The reduction in GWP by replacing fossil fuels for energy generation by wood waste is accounted within the D-stage.

Table 6.4: GWP and energy consumption in the C3-phase for timber

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m^3] C3	Primary energy-use non-renewable [MJ/m^3] C3	GWP [kg CO_2 eq/m^3] C3	GWP [kg CO_2 eq/metric tonne] C3
CLT	2017	Egoin	Spain	0	0	859.38	1637
	2016	Cross timber systems	Norway	4.18	56.19	701.9	1671
	2016	BSP Holz	Germany	4.7	87.8	793	1 612.9
	2018	BSP Holz	Germany	-7 900	-40.5	758	1 613
	2018	Rubner	Italy	-7 950	-86.8	759	1 646
	2017	Storaenso	France	0.62	105	7.17	15.26
Glulam	2018	BS Holz	Germany	-8 110	-45.8	778	1 610.1
	2013	BS Holz	Germany	4.7	87.8	818.8	1 610.9
	2018	Rubner	Italy	-7 670	-130	767	1 723.6
	2018	Schiliger Holz	Switserland	-7 150	-4.71	686	1 633.3
	2017	WoodSolutions	Australia	-10 200	82.1	1 020	1 642.5

6.3.2 Steel

The only processing the steel scrap goes through is sorting, preparation and shredding. The only purpose of this waste process is to make the steel ready for recycling. Emissions during the C3-phase for steel are due to the energy-usage of the machinery performing the sorting, preparation and shredding. For steel the C3-GWP shows to be relatively small.

In Table 6.5 are the GWP and energy consumption of eight EPD's for steel products shown.

Table 6.5: GWP and energy consumption in the C3-phase for steel

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m^3] C3	Primary energy-use non-renewable [MJ/m^3] C3	C3-GWP [kg CO$_2$ eq/m^3]	C3-GWP [kg CO$_2$ eq/metric tonne]
Hot rolled uncoated steelplates	2018	NMLK DanSteel	Denmark	94.2	319.5	19.47	2.48
Structural steel S235 -S960	2018	Bauforumstahl	Germany	85.57	252.77	14.44	1.84
Hot rolled structural and merchant bar products	2016	OneSteel	Australia	27.48	368.95	19.63	2.5
Steel sections	2017	Arcelor Mittal	Luxembourg	68.77	267.69	15.94	2.03
Structural steel sections and merchant bars	2018	Arcelor Mittal	Luxembourg	85.57	252.77	14.44	1.84
Double-sized hot dip galvanized coated steel	2017	Arcelor Mittal	Luxembourg	81.64	276.32	16.56	2.11
Welded Beams and Columns	2015	Bluescope	Australia	14.44	2747.5	186.05	23.7

6.3.3 Reinforced concrete

The processing of the reinforced concrete waste consists of pre-screening, metal separation and crushing of the concrete. The contribution to the GWP during this phase is due to the energy consumption of the machinery performing these activities.

In Table 6.6 are the GWP's and energy usage during the C3-phase presented from five EPD's. The precast element of MPA includes the reinforcement steel.

Table 6.6: GWP and energy consumption in the C3-phase for concrete

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m^3] C3	Primary energy-use non-renewable [MJ/m^3] C3	C3-GWP [kg CO$_2$ eq/m^3]	C3-GWP [kg CO$_2$ eq/metric tonne]
Precast Concrete Ground Beam	2017	MPA	UK	9.28	110	-34.3[13]	14.3
Unreinforced concrete C30/37	2018	InformationsZentrum Beton GmbH	Germany	20.7	78.7	6	2.5
Unreinforced concrete C35/45	2018	InformationsZentrum Beton GmbH	Germany	20.7	78.7	6	2.5
Unreinforced concrete C45/55	2018	InformationsZentrum Beton GmbH	Germany	20.7	78.7	6	0.25
Unreinforced concrete C50/60	2018	InformationsZentrum Beton GmbH	Germany	20.7	78.7	6	2.5

6.4 Disposal

The share of the waste that doesn't get processed for re-use, recycling or energy generation will be disposed. The effect of the disposal of the construction waste is calculated in the C4-phase of an LCA.

6.4.1 Timber

EWP's have been treated with poisonous chemicals, to reduce the risk of mold or to impregnate it against insects. This fact decreases the possibility of reuse and even recycling of reclaimed wood

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[13] The GWP of MPA seems to be negative which isn't normally the case for the C3-stage of reinforced concrete. The cause of this wasn't mentioned in the EPD. Possibly the increased carbonation after the crushing of the concrete, that takes place at a landfill has been taken into account in the C3-stage, which actually should be included in the C4-stage.

(Hafner et al., 2014). Disposal of EWP's only takes place if all other end-of-life scenarios can't be executed. Disposal of timber waste can take place in combustion without energy use or as landfill where it naturally decomposes.

Landfilling of wood waste seems to be the least favorable option. Many governments have already banned the landfill of wood waste. Among them are Sweden, Austria and Germany. Others have discouraged landfilling through taxation. On the landfills biodegradation of the timber takes place, most of the cellulose and hemicellulose in wood are biodegradable and quickly decompose to small components. This process of biodegradation makes 0 – 3% of the carbon in wood gets emitted as landfill gas. The composition of such LFG (Landfill Gas) is 56% methane, 31% CO_2, 10% nitrogen, 1% oxygen, 1% trace species and 1% moisture. A large portion of remaining carbon is permanently sequestered in the soil. Most of the modern landfill sites are required to flare or use this LFG as energy to prevent the emission of methane into the atmosphere (Ramage et al., 2017). The rest of the carbon remains in the landfill indefinitely (Micales & Skog, 1997). This contradicts with what was stated in the paper of Leturcq mentioned in paragraph 6.3.1, that preferring fossil fuels over wood fuel would be unfavorable because of the eventual decay of the complete amount of carbon in the timber waste. Meaning that the carbon of wood would eventually be emitted in the atmosphere either way.

To estimate the GWP from landfilling, most European countries use the default values of the IPCC 2006 Guidelines for National GHG Inventories. The IPCC allows the use of country-specific DOC_f (Degradable Organic Content that decomposes) values. However, investigations into country and product specific decomposition are both timely and costly and thus unlikely to be undertaken without significant evidence of disparity. The IPCC provides a DOC_f factor of 50% for wood products in landfilled waste, which is very likely to be a gross overestimation. One study investigated the DOC_f of 16 hardwood species and 10 softwood species. The carbon loss on the landfill for hardwoods ranged from 0 to 23.2% with an average of 10.5%. For the softwood species the results varied between 0 – 8% with an average of 2.9%. The lower carbon decay of softwood can be explained by the greater amount of lignin which reduces carbohydrate bioavailability. The founded results of this study show that the GWP calculated with the default value of the IPCC is a high overestimation. Most of the sequestrated carbon during the tree's growth would stay stored within the wood. In this research the authors also state that there remains a knowledge gap when it comes to the carbon decay of EWP's (O'Dwyer et al., 2018).

Ximenes et al. (2018) examined the carbon loss of EWP's on landfills. For this research 130 EWP's decomposing at 4 different landfills in Australia were chemically analyzed. They found that for these EWP's the carbon loss ranged from 0.6 – 9%. This seemed a lot lower than the assumed value of 50% by the IPCC. However the authors mention to be caution with these results seeming that it's possible decay took place prior to disposal in the landfill. In this paper it was not mentioned whether CLT, glulam or LVL were included in these 130 EWP's.

Wang et al. (2011) researched the carbon decay of four types of EWP's with a landfill simulation via a bioreactor. This allowed the experiment to run until no more CH_4 was produced, or until >95% of potential CH_4 was produced. This timeframe ranged from between approximately 200–1 400 days. Still the carbon loss for panel board and Plywood was 1.1%; 1.4% for Medium Density Fibreboard and 19.9% for OSB-panels form hardwood but no carbon loss for OSB-panels made out of softwood (O'Dwyer et al., 2018).

To examine the carbon decay over a longer period of time, the timber waste of two Australian buried landfills was dug up and analyzed chemically, physically and microscopically. These wood samples were recovered after 16 – 44 years buried in the landfill. The analyses were focused on solid wood products rather than composite wood products. From the first landfill in Sydney, seven wood species were analyzed. For four species no carbon loss was found. For the three other species the carbon loss ranged from 0.6% - 7.9%. This was after 44 years of being buried underground. In the second landfill the rate of carbon decay was higher, ranging from 0 to 37.1%. The second landfill contained rainforest species who showed a significantly higher carbon decay. The two landfills had two tree species in common, the Agathis and the Pinus Radiata. The Agathis showed on both landfills no signs of carbon decay, the Pinus Radiata lost in the two landfills 4.4% and 7.9% of its carbon mass. In paragraph '3.1.1 Timber' it was mentioned that Radiata Pine is a tree species used for construction applications. This research also mentions that moisture is a factor influencing decay rates in landfills. The minimum wood moisture content for degradation is about 25%, and the optimal moisture content is between 40-70% (Ximenes et al., 2015). In subchapter '3.3.1 Timber' it was already mentioned that constructive timber is dried during its production to a moisture content of 8-12%.

Also fungal decay of wood requires oxygen. So the biological degradation of wood when buried in anaerobic landfills is caused by bacterial activity instead of fungal. The bacterial decay of timber proceeds at a much slower when compared with fungi (Ximenes et al., 2008).

It should be noted that it is difficult to determine the specific amount of carbon that gets released into the atmosphere during the decomposition of wood. This is due to the slow decomposition speed of timber at the landfill. It's possible that delayed emissions are not collected during the post-closure period of the measurements which reduces the lifetime collection efficiency. In any case using active LFG collection and power generation can significantly reduce the GWP from the landfill of wood. One study showed a reduction of 28% when catching the LFG to generate energy. However the authors of this study noted that this value of 28% should not be used as representative for other landfills (Lee et al., 2017).

The IPCC also provides a ratio of 1:1 for the composition of CH_4/CO_2 in landfill gas. If 50% of the carbon in landfilled wood gets decomposed, this means that 25% of the carbon in timber gets converted to CH_4. Milke et al. (2010) estimate that only 5% of the wood carbon is converted into methane. The sensitivity of methane-producing micro-organisms to many trace organics and metals would support the assumption that chemically-treated wood is very difficult to degrade anaerobically.

The several studies mention here above state that the calculation of carbon decay of wood by using the IPCC default factor of 0.5 turns out to be a gross overestimation. Meaning that LCA's who applied this value of 50% will make a big overestimation of the GWP of the C4-phase. However, determining the accurate amount of GHG gasses that gets emitted during the landfill of timber waste remains a hard task. No papers determining the carbon decay at landfilling of constructive EWP’s like CLT, glulam and LVL could be obtained.

A possible explanation for the absence of studies investigating the carbon decay of these structural EWP’s is that these are relatively new products. CLT for example was invented in the beginning of the 1990’s and has only been commercially available since the mid 1990’s. This means that most buildings using CLT haven’t been demolished yet, not to mention that long term landfilling of CLT hasn’t occurred yet. Also the illegalization and discouraging of landfilling timber by government makes the possibility to examine the long-term emissions of landfilling CLT, glulam and LVL even harder.

Only three EPD’s gave a specific value for the GWP during the C4-stage. This could partly be explained because of the fact that not all producers consider landfilling because it’s the last option of the cascade system. And also because there’s little certainty about determining the accurate GWP for landfilling. In Table 6.7 are the data from these three EPD’s shown.

Table 6.7: GWP and energy consumption in the C4-phase for timber

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m^3] C4	Primary energy-use non-renewable [MJ/m^3] C4	GWP [kg CO_2 eq/m^3] C4	GWP [kg CO_2 eq/metric tonne] C4
CLT	2016	Cross timber systems	Norway	0.014	0.59	0.02	0.040
	2017	Storaenso	France	-4 420	44.6	665	1414.89
Glulam (softwood)	2017	WoodSolutions	Australia	53	857	61.8	99.5[14]
				53	857	435	700.5[15]
Glulam (hardwood)				53.1	859	58.2	86.4[14]
				53.1	859	426	632[15]

6.4.2 Steel

Because of its high potential for reuse and recycling, steel is rarely disposed. Only three EPD’s gave up a GWP value for the C4 phase, which are shown in Table 6.8. Several EPD’s let the C4-phase account for the presumed 1% loss of material during the end-of-life stages. Further information concerning disposal of constructive steel couldn’t be obtained.

Table 6.8: GWP and energy consumption in the C4-phase for steel elements

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m^3] C4	Primary energy-use non-renewable [MJ/m^3] C4	C4-GWP [kg CO_2 eq/m^3]	C4-GWP [kg CO_2 eq/metric tonne]
Structural hollow sections	2017	Tata Steel	UK Netherlands	1.98	16.96	1.26	0.16
Hot rolled structural and merchant bar products	2016	OneSteel	Australia	5.4	80	42.4	5.4
Welded Beams and Columns	2015	Bluescope	Australia	6.14	130.31	8.79	1.12

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[14] A landfill scenario was assumed with a DOCf of 0,1% for softwoods and 0,0% for hardwoods. These two values are based on bioreactor laboratory research.

[15] A conservative landfill scenario was assumed with an NGA-value of 10%.

6.4.3 Reinforced concrete

Landfilling of concrete can have a CO_2-sequestrating effect. This is because of the carbonation reaction taking place in concrete, which isn’t finished at the time of demolition. It can take centuries before the carbonization of a concrete construction or demolished concrete is complete (Sjunnesson, 2005).

Before the landfilling of concrete, the material needs to be crushed. The volume of carbonated concrete increases exponentially when concrete is demolished, since carbonation is directly related to the exposed surface. Pade & Guimaraes (2007) calculated the carbonation rate of concrete in a 100-year lifespan of which 70 years are during the usage of the building and 30 years after demolition. They calculated this for three countries. In Iceland where the concrete is sent to the landfill without being crushed, the carbonation at the end of its usage is 31%. After 30 years at the landfill the carbonation increased to 37%. In Denmark where the concrete is being scrambled, these percentages were 37% at the end of the operational phase and 86% after 100 years. For Norway these values were respectively 33% and 59%.

The carbonation reaction has a faster rate in crushed concrete rather than in reinforced concrete walls and beams. On average it takes 200 years to reach 100% carbonation of the concrete used in buildings. Börjesson & Gustavsson (2000) investigated the difference in GWP between the Wällüdden (a 4-storey residential building in Växjö, Sweden) and its reinforced concrete equivalent. When the carbonation of concrete is excluded and a landfill without LFG capture is assumed as the end-of-life scenario for the timber building, the net GWP for the timber building is about 1.5 - 2 times smaller when expressed in CO_2 eq. However when the carbonation of concrete is included in the calculation, the differences in net GWP are much smaller. However when the carbonation of concrete is included and the produced biogas from landfilling timber is assumed, the net GWP will be much lower for the timber building than for its reinforced concrete counterpart (Börjesson & Gustavsson, 2000). It should be noted that this study assumed an average carbon decay rate of 20%. The studies mentioned in paragraph ‘6.4.1 Timber’ showed a smaller carbon decay.

Despite concrete being a material which is frequently landfilled, little information could be obtained concerning the effect disposed concrete has on climate change. This could be partly explained by the fact that a lot of the landfill of concrete happens illegal. According to the Brazilian Association for the Recycling of Construction Waste (Abrecon) only 1% of Brazil’s concrete waste is recycled, about half of Brazilian municipalities send their demolition waste directly to landfills. Most of this happens illegal. In Shenzhen, China 84% of the construction waste is dumped. Almost half of this waste is disposed in unlicensed landfills (Guardian, 2019). In countries like the Netherlands the landfilling of concrete has been banned (Knoeri et al., 2013). This illegal landfilling limits the possibility to perform research about the GWP of landfilled concrete.

Only one EPD concerning reinforced concrete contained data about the GWP of the C4-phase. This is shown in Table 6.9.

Table 6.9: GWP and energy consumption in the C4-phase for concrete

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m³]	Primary energy-use non-renewable [MJ/m³]	C4-GWP [kg CO_2 eq/m³]	C4-GWP [kg CO_2 eq/metric tonne]
Precast Concrete Ground Beam	2017	MPA	UK	5.89	51.9	0.71	0.3

6.5 Reuse, recovery and recycle

This subchapter discusses the differences in the D-phase of the LCA. It concerns the climatic effects the re-use of the demolition waste as material or energy source can have. This option of recycling is priority for wood products, it is the first choice in the cascade system for waste.

Often will these recycled materials be applied for products of lower value and quality. This type of recycling is referred to as ‘downcycling’.

The GWP during the D-phase of the LCA can be the result of the avoided GHG emissions by not having to extract and produce ‘virgin’ material or the avoided GHG emissions by using the construction waste as a substitute of fossil fuels.

6.5.1 Timber

The reduction of mechanical properties after the operational phase and therefore the possibility of these EWP’s to be re-used as the loadbearing material of multi-storey buildings is at the moment still unclear. When recycled they’re likely to be downcycled, for example to be used in particleboard. The recycling of timber allows a longer storage of the carbon within the wood.

These wood products can be reprocessed as fibrous material for making new wood-based products such as furniture, flooring, packaging, pulp and joinery (Ramage et al., 2017).

No studies concerning the recycling potential of CLT, glulam or LVL could be obtained, neither about the decrease of their mechanical properties after usage. One study however researched the potential to make CLT using wood waste, the so called CLST (Cross-Laminated Secondary Timber). These CLST-panels were made out of mixed-species softwood boards collected from construction and demolition sites. These CLST-panels were compared with a reference CLT-panel. Both materials were similar in compression stiffness but the bending strength of the CLST was only 60% of that of the CLT-board. The paper concluded that for structural applications CLST has to be combined with CLT. The authors of this study also stated that more testing is needed to build upon this concept (Rose et al., 2018).

An example of how recycling timber can result in avoided GHG emissions is applying the waste wood in the production of particleboard. The kiln-drying of the wood is the largest energy consuming process in the production of particleboard. Timber which is used in construction has already been kiln-dried during its own production meaning that no – or reduced – drying is required when using wood waste from the demolition site. One study calculated the GWP of the production of particleboard using recovered wood and virgin wood. The effect of the use of forestland was taken into account. The scenario where harvested timber was used in the production of particleboard and the recovered wood was used as biofuel to substitute coal has 5.97% more GHG savings than when the recovered wood was used in the particleboard and the harvested wood was applied as biofuel (Sathre & Gustavsson, 2006). Similar comparisons were made in this study for other scenarios, this is added in appendix M. Hossain & Poon (2018) found a reduction of 6% in GWP when using recycled wood in particleboard instead of virgin wood.

Another study examined the effect on the GWP of the whole cascading system. Where wood waste was first recycled as particleboard and later incinerated in a power plant. In comparison with using primary wood the cascading system reduced the GWP by 10.8% (Höglmeier et al., 2014).

Consequently, when comparing a recycling system such as the cascading of waste wood to an already rather environmentally friendly system such as products from primary wood, no outstanding amounts of savings can be expected (Höglmeier et al., 2014).

For timber it is also common to calculate the avoided GHG emissions by incineration of wood waste with energy recovery within the D-phase. The emissions due to the incineration itself are accounted within the C3-phase. The same methodology applies to the re-use as a material. The shredding of the timber to wood chips is assigned to the C3-phase, but the reduction in GWP by avoided production of virgin wood by recycling the used wood is assigned to the D-phase.

The potential benefit of substituting fossil fuels by wood waste is highly dependent on the assumed timeframe. Because of wood's carbon bonds, water content and lower burning temperature, wood waste that replaces coal or natural gas in a power plant emits per kWh respectively 1.5 or 3 times the amount of CO_2. Initially it's assumed that allowing trees to regrow can reabsorb the carbon, however a forest that regrows typically absorbs less carbon than if the forest were left unharvested. It also takes many years of forest regrowth to achieve substantial reductions in the GWP. Overall, replacing fossil fuels by wood waste would result in 2-3 times more carbon in the atmosphere in 2050 per GJ of final energy. Increasing the atmospheric carbon concentration for decades, even if it's only temporarily, can still cause permanent damages to the climate (Searchinger et al., 2018). Carbon neutral does not necessarily mean climate change neutral. If the release of biogenic CO_2 occurs before the same amount is again sequestered by replanted trees, the related harvest will have caused a temporary increased radiative forcing in the atmosphere. Temporarily adding CO_2 to the atmosphere will increase the rate of carbon uptake by the oceans and terrestrial biosphere, in order to obtain a new equilibrium (Skullestad et al., 2016).

In Table 6.10 are the GWP's presented from the D-phase of fifteen different EPD's. These values are negative because the D-phase represents the benefits gained from the end-of-life scenario of the waste. For the case of energy generation this value represents the avoided GHG emissions by replacing the use of fossil fuels. In the case of recycling this D-GWP represents the avoided energy during production when using second hand materials instead of virgin materials.

Table 6.10: GWP and energy consumption in the D-phase for Timber[16] [17]

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m^3] D	Primary energy-use non-renewable [MJ/m^3] D	D-GWP [kg CO_2 eq/m^3]	D-GWP [kg CO_2 eq/metric tonne]
CLT	2016	Cross timber systems	Norway	-2 528	-487	-32.51	-77.4
	2017	Storaenso	France	-123	-2 490	-29	-61.7
	2016	Storaenso	France	-	-	-414	-880.85
	2018	Egoin	Spain	-12 803.84	-869.47	-56.52	-107.66
	2016	BSP Holz	Germany	-328	-7 390	-360	-732.23
	2018	BSP Holz	Germany	-1 330	-6 110	-404	-859.57
	2018	Rubner	Italy	-1 700	-7 380	-410	-889.37
	2013	UK National Industry	UK	-3.51	-121	-8.39 (a)	-17.19
				-388	-9 690	-591 (b)	-1211.07
				-73	-1 280	-78.9 (c)	-161.68
Glulam	2018	BZ Holz	Germany	-1 360	-6 280	-415	-858.84
	2013	BZ Holz	Germany	-338.8	-7 617	-372.4	-732.54
	2013	UK National Industry	UK	-3.52	-121	-8.41	-17.16
				-389	-9 720	-593 (a)	-1210.20
				-73.1	-1 280	-79.1 (b)	-161.43
	2018	Rubner	Italy	-1 710	-7 420	-412 (c)	-925.84
	2018	Schiliger Holz	Switzerland	-819	-6 810	-196	-466.67
	2017	WoodSolutions (Softwood)	Australia	-1.88	-11 300	-641 (a)	-1032.21
				-2 510	-1 740	-142 (b)	-228.66
				-13 800	-4 980	612 (c)	985.51
		WoodSolutions (Hardwood)		-2.07	-12 400	-706 (a)	-1047.48
				-2 410	-424	-44.3 (b)	-65.73
				-12 700	-6 160	408 (c)	605.34
LVL	2013	UK National Industry	UK	-3.49	-121	-8.35 (a)	-17.11
				-388	-9 700	-592 (b)	-1213.11
				-72.6	-1 270	-78.6 (c)	-78.60

6.5.2 Steel

Steel is a highly recyclable material. In section '3.1.2 Steel' it was already mentioned that scrap metal is one of the raw materials of steel. Recovered steel is crushed and re-melted. As a result of this method steel is 100% recyclable and can be used infinitely (World Steel, 2019). Global steel recovery rates estimate that about 85 % of all scrap from construction steel was recycled on a global scale. However, since recycled steel is desired for steel production, the current availability of steel scrap is not high enough to meet the demand, meaning that iron ore still has to be extracted for steel production (Skullestad et al., 2016).

The recycling of steel results in reductions in both energy and coking coal used. Manufacturing steel from scrap requires one third of the energy compared with the energy needed to produce it from iron ore (World Steel, 2018). Within the EPD from Bluescope it is mentioned that an improvement in the recycling rate of 11% (from 89% to 100%) results in a reduction in the GWP of 12%. When looking solely at the production process, an increase in secondary steel by 5% results in a 3% decrease in the GWP. For the EPD's collected for this dissertation a recycling rate of 85 – 92% was assumed.

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[16] The EPD from UK National Industry calculated three different end-of-life scenarios for both CLT glulam and LVL: (a) 100% recycling (b) 100% Energy Recovery (c) 100% Landfill

[17] The EPD from WoodSolutions calculated three different end-of-life scenarios for both glulam made from softwood and glulam made from hardwood: (a) Energy Recovery (b) Reuse (c) Recycling

One study examined the overall effect of the use of scrap in steel manufacturing on the materials GWP. The reduction in GWP as a result of avoided virgin steel ranged from 560 to 2 360 kg CO_2 eq per metric tonne produced steel (Damgaard et al., 2009). These values seem in line with the values of the A1-GWP for steel given in Table 3.1 at paragraph '3.1.2 Steel' of this dissertation.

Gan et al. (2017) calculated the effect of steel recycling on the embodied carbon of a 60-storey composite core-outrigger building in Hong Kong. Structural steel and rebar account for 80% of the embodied carbon of this core-outrigger building. When manufacturing steel with a traditional blast furnace, it only accepts 30% steel scrap. When using an EAF, the products can be realized for the full 100% out of recycled steel. They calculated that when redesigning the building with steel from the blast furnace - being made up out of 30% recycled steel - the embodied carbon decreased by 15%. In case of steel manufactured with an EAF consisting for 100% out of recycled steel, the embodied GWP was reduced by 60% (Gan et al., 2017).

Steel is capable of remaining its strength for longer periods of time. For this reason prefabricated steel structures can be re-used. Several EPD's assume a reuse rate of 7-11%. In Table 6.11 the benefits in GWP of recycling and reusing steel are shown for eleven EPD's.

Table 6.11: GWP and energy consumption in the D-phase for steel

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m^3]	Primary energy-use non-renewable [MJ/m^3]	D-GWP [kg CO_2 eq/m^3]	D-GWP [kg CO_2 eq/metric tonne]
Structural Steel Sections	2017	Arcelor Mittal	Luxembourgh	-1 271.70	2 245.10	685.31	87.3
Structural Steel Sections and merchant bars	2018	Arcelor Mittal	Luxembourgh	21	-3 540	-2 794.60	-356
Hot dip galvanized steel	2017	Arcelor Mittal	Luxembourgh	6 810.40	-108 026.4	-11 976.8	-1 530
I, H, U, L, T and wide flats hot-rolled sections	2013	Contiga	Norway	-6 075.9	-2 849.6	-1 774.1	-226
Hot rolled uncoated steel plates	2018	DanSteel	Denmark	10 990	-113 040	-15 150.50	-1 930
Structural Steel: Sections and Plates	2018	Bauforumstahl	Germany	155.4	-31 164.5	-3 242.10	-413
Hot rolled structural and merchant bar products	2016	OneSteel	Australia	5 181	-86 350	-9 420	-1 200
Hot-rolled steel plates, sheets and coils, and cold-formed tubes and sections	2014	Ruukki	Finland	5 887.5	-95 613	-10 205	-1 300
Cold-formed steel studs	2016	SCSglobal	USA Canada	0	-49 977.60	-5 934.80	-760
Structural hollow sections	2017	Tata Steel	UK Netherlands	6 570.40	-112 255	-12 010.50	-1 530
Welded Beams and Columns	2015	Bluescope	Australia	5 196.70	-100 480	-9 577	-1 220

6.5.3 Reinforced concrete

Demolished concrete, if not landfilled, is usually crushed into recycled aggregate. Later it can be used in road construction, as filling in drainage works or recycled as aggregate in the production of new reinforced concrete. Recycled aggregate is usually stored for 2-16 weeks at the crushing plant before it is used. During this period, the rate of carbonation is substantially higher than during the lifetime of the building because of an increased surface being exposed to the atmosphere (Skullestad et al., 2016).

A frequent scenario for the recycling of concrete waste is the application as a road sub-base layer. This allows the carbonation reaction of the concrete to continue resulting in absorbing CO_2 from the atmosphere. Yang et al. (2017) calculated which share of the emitted CO_2 during the production of the concrete is absorbed again by the concrete during both its usage as a load-bearing material and as a sub-layer in road construction. This was calculated for an 11-floor apartment building and a 10-floor office building. Both with a life expectancy of 40 years and a recycle span of 60 years. For the apartment and office building, respectively 5.6% (40.9 kg/m^3) and 5.5% (105.6 kg/m^3) of the emissions during production were reabsorbed during the 40 years of operational phase. During the following 60 years where the concrete was recycled in the road construction these values were 10.2% (73.75 kg/m^3) and 11.5% (219.54 kg/m^3). When looking at it per year, the recycled use as sub-layer in road construction resulted in an increase in absorbed carbon per year of 20.21% for the apartment building and 38.6% for the office building.

Another recycling option for crushed concrete is to be used as aggregate in new reinforced concrete products. However, because of the larger surface of the coarse when using recycled aggregates a higher amount of cement is required, with cement being the dominant contributor to the GWP of the reinforced concrete production. Knoeri et al. (2017) investigated the difference in GWP for a recycled concrete mixture and a conventional reinforced concrete product. They found similar GWP's for recycled and conventional reinforced concrete. The avoided carbon emissions by not needing to extract virgin aggregates seemed to be outbalanced by the additional amount of cement needed.

Similar results were found by Braunschweig et al. (n.d.). They performed a comparative LCA on high quality reinforced concrete using virgin and recycled aggregates. Both energy- and emission-wise, the studies found little differences for virgin or recycled construction concrete (Braunschweig et al., n.d.).

Marinkovic et al. (2010) calculated the difference in cradle-to-gate GWP for reinforced concrete with virgin aggregates and recycled aggregates. The first scenario showed an increase of 3.91% in GWP when using recycled aggregates (307.6 – 319.6 kg CO_2 eq/m^3). The second scenario assumed identical transport distances for both kind of aggregates. This scenario had a GWP increase of 11.41% for reinforced concrete consisting of recycled aggregates (307.6 – 342.7 kg CO_2 eq/m^3) (Marinkovic et al., 2010).

In Table 6.12 are the GWP's and energy-usage shown during the D-phase for four different EPD's.

Table 6.12: GWP and energy consumption in the D-phase for concrete

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m³]	Primary energy-use non-renewable [MJ/m³]	D-GWP [kg CO_2 eq/m³]	D-GWP [kg CO_2 eq/metric tonne]
Unreinforced concrete C30/37	2018	InformationsZentrum Beton GmbH	Germany	-94.1	-279	-21.4	-8.92
Unreinforced concrete C35/45	2018	InformationsZentrum Beton GmbH	Germany	-94.1	-279	-21.4	-8.92
Unreinforced concrete C40/50	2018	InformationsZentrum Beton GmbH	Germany	-94.1	-279	-21.4	-8.92
Unreinforced concrete C50/60	2018	InformationsZentrum Beton GmbH	Germany	-94.1	-279	-21.4	-8.92

6.6 Complete end-of-life GWP

In Tables 6.13; 6.14 and 6.15 are the GWP's and energy-usage during the end-of-life phases presented for respectively timber, steel and reinforced concrete.

Table 6.13: GWP and energy consumption in the End-of-Life for timber

Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m³] (C+D)	Primary energy-use non-renewable [MJ/m³] (C+D)	End-of-Life GWP [kg CO₂ eq/m³] (C+D)	End of Life GWP [kg CO₂ eq/metric tonne] (C+D)	End-of-Life scenario
2016	Cross timber systems	Norway	-2 521.7	-353.4	674.1	1 605	Incineration for energy recovery
2017	Storaenso	France	-4 541.2	-2 226.4	650.6	1 384.3	57,2% recycled; 25,5% used for energy recovery; 17,3% is buried
2016	Storaenso	France	115.5	-7 245	339	721.3	Incineration for energy recovery
2018	Egoin	Spain	-12 802.9	-752.9	810.2	1 543.3	Recycled
2016	BSP Holz	Germany	-323.3	-7 295.9	443.5	902.1	Incineration for energy recovery
2018	BSP Holz	Germany	-9 230	-6 144	354.5	754.2	77% recycling, 23% used for energy production
2018	Rubner	Italy	-9 290	-7 466.8	349	757	100% recycled
2013	UK National Industry	UK	-8 233.5	155	808.6	1 656.97	100% recycling
			-382.9	-9 381	252	516.39	100% energy recovery
			-50.5	-573	853.1	1 748.16	100% landfill
2018	BZ Holz	Germany	-9 471	-6 318.9	363.5	752.2	100% energy recovery
2013	BZ Holz	Germany	-334.1	-7 522.7	446.9	879.1	100% energy recovery
2013	UK National Industry	UK	-8 253.5	156	810.6	1 654.29	100% recycling
			-382.8	-9 410	253	516.33	100% energy recovery
			-50.6	-571	854.9	1 744.69	100% landfill
2018	Rubner	Italy	-9 380	-7 550	355	765.1	Incineration for energy recovery
2018	Schiliger Holz	Switzerland	-7 969	-6 796	491.4	1 158.9	Incineration for energy recovery
2013	UK National Industry	UK	-8 193.5	156	805.7	1 651.02	100% recycling
			-382.7	-9 389	253	518.44	100% energy recovery
			-50.2	-564	849.4	1 740.57	100% landfill

Table 6.14: GWP and energy consumption in the End-of-Life for steel

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m³] (C+D)	Primary energy-use non-renewable [MJ/m³] (C+D)	End-of-Life GWP [kg CO₂ eq/m³] (C+D)	End of Life GWP [kg CO₂ eq/metric tonne] (C+D)	End-of-Life scenario
Structural Steel Sections	2017	Arcelor Mittal	Luxembourgh	-1 202.9	2 512.8	701.24	89.33	88% recycled; 11% reused; 1% landfill
Structural Steel Sections and merchant bars	2018	Arcelor Mittal	Luxembourgh	250.4	-27 536.2	-2 780.2	-354.2	88% recycled; 11% reused; 1% landfill
Hot dip galvanized steel	2017	Arcelor Mittal	Luxembourgh	6 891.8	-107 750.9	-11 960.3	-1 527.9	98% recycled; 2% landfill
I, H, U, L, T and wide flats hot-rolled sections	2013	Contiga	Norway	106.9	-1 829.1	-1 692.5	-215.6	Recycling
Hot rolled uncoated steel plates	2010	DanSteel	Denmark	11 084.2	-112 720.5	-15 131	-1 927.5	95% recycled
Structural Steel: Sections and Plates S235 - S960	2018	Bauforumstahl	Germany	-628	-60 445	-6 908	-880	88% recycled; 11% reused; 1% landfill
Hot rolled structural and merchant bar products	2016	OneSteel	Australia	5 266.6	-85 353.1	-9 358	-1 192.1	89% recycling; 11% landfill
Hot-rolled steel plates, sheets and coils, and cold-formed tubes and sections	2014	Ruukki	Finland	5 887.5	-95 613	-10 205	-1 300	90% recycled
Cold-formed steel studs	2016	SCSglobal	USA Canada	0	-49 977.6	-5 934.8	-760	Recycling
Structural hollow sections	2017	Tata Steel	UK Netherlands	6 643.5	-110 730.8	-11 900.9	-1 516	92% recycled; 7% reused; 1% landfill
Welded Beams and Columns	2015	Bluescope	Australia	5 217.3	-97 602.2	-9 382.2	-1 195.2	89% recycled
Structural Steel: Sections and Plates S235 - S960	2018	Bauforumstahl	Germany	241	-3 937.8	-3 227.6	-411.2	88% recycled; 11% reused; 1% landfill

Table 6.15: GWP and energy consumption in the End-of-Life for concrete

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m³]	Primary energy-use non-renewable [MJ/m³]	C+D-GWP [kg CO₂ eq/m³]	C+D-GWP [kg CO₂ eq/metric tonne]	End-of-Life scenario
Unreinforced concrete C30/37	2018	InformationsZentrum Beton GmbH	Germany	-34.4	4.6	-0.29	-0.12	Recycled in road construction
Unreinforced concrete C35/45	2018	InformationsZentrum Beton GmbH	Germany	-34.4	4.6	-0.29	-0.12	Recycled in road construction
Unreinforced concrete C40/50	2018	InformationsZentrum Beton GmbH	Germany	-34.4	4.6	-0.29	-0.12	Recycled in road construction
Unreinforced concrete C50/60	2018	InformationsZentrum Beton GmbH	Germany	-34.4	4.6	-0.29	-0.12	Recycled in road construction
Precast Concrete Ground Beams	2017	British precast	UK	16.51	276.9	-26.7	-11.1	90% recycled; 10% landfilled

In Table 6.16 are the BF's given of the multi-storey buildings during their C and D-phase of eight comparative LCA's. Because of the strong influence the choice of end-of-life scenario has on the GWP, there was a column added with the assumed end-of-life scenario.

Table 6.16: End-of-Life GWP of multi-storey buildings when constructed with different structural materials (1/2)

Country	Function	Stores	Floor area [m^2]	Bearing structure	C+D GWP [kg CO$_2$ eq/m^2]	End of Life scenario	Reference
Sweden	Residential	6	1 686	Reinforced concrete	-157 (-132)	4 months exposure to atmosphere + reuse as below-ground filling	[18] (Tettey et al, 2019)
				Timber (CLT)	-336 (-212)	Combustion for energy	
				Timber (Modular)	-198 (-127)		
China	Residential	3	5 590	Reinforced concrete	0.169	Only demolition is considered	(Gong et al, 2012)
				Steel	0.037		
				Timber	0.04		
New-Zealand	School	3	1 980	Reinforced concrete	16.7	100% of the concrete is sent to clean landfills, 85% of the reinforcing steel is recycled	(Buchanan et al, 2012)
				Steel	-64.6	85% is recycled	
				Timber	89.9	82% is landfilled, 18% is decomposed. 43% of the formed CH4 during decomposition is burned for energy recovery replacing fossil fuels	
China	Residential	4	-	Reinforced concrete	18	Concrete building: All the concrete and all the reinforcement steel is landfilled Timber building: 50% is recycled, 50% is used for biomass energy	(Guo et al, 2017)
				Timber (CLT)	45.6		
		7	-	Reinforced concrete	18		
				Timber (CLT)	46.5		
		11	-	Reinforced concrete	18		
				Timber (CLT)	52		
		17	-	Reinforced concrete	18		
				Timber (CLT)	52.3		
New-Zealand	Office	6	4 247	Reinforced concrete	39.6	[19] All materials are completely landfilled	(John et al, 2008)
				Steel	22.4		
				Timber	124.6		
				Reinforced concrete	31.8	Concrete and steel are completely recycled Timber is used boiler fuel to provide energy	
				Steel	-56.7		
				Timber	2.6		
Sweden	Residential	4	1 190	Reinforced concrete	-9	90% of the concrete is landfilled and is crushed and exposed to air for 4 months, 10% is lost. 90% of the rebar steel gets recycled	(Dodoo et al, 2009)
				Timber	-4	90% is recovered for energy, the remaining 10% is oxidized naturally without energy recovery	

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[18] The value between brackets is when electricity generation and energy substitution are gas based, otherwise it's coal based.

[19] A carbon decay of 18% is assumed

Table 6.16: End-of-Life GWP of multi-storey buildings when constructed with different structural materials (2/2)

Country	Function	Stores	Floor area [m²]	Bearing structure	C+D GWP [kg CO_2 eq/m²]	End of Life scenario	Reference
Canada	Residential	18	12 838	Reinforced concrete	16.7	Landfilling	(Bowick, 2018)
			15 120	Hybrid: Timber + concrete	13	Landfilling + incineration for energy use	(Bowick, 2018)
UK	Residential	3 (60 years lifespan)	914	Reinforced concrete	-30.9	Recycling + landfill	(Din & Brotas, 2017)
				Steel	-288.8		
				Timber	65.3		
		6 (60 years lifespan	1 828	Reinforced concrete	-54.4		
				Steel	-313.4		
				Timber	56.1		
		3 (100 years lifespan)	914	Reinforced concrete	-75.3		
				Steel	-372.5		
				Timber	98.6		
		6 (100 years lifespan)	1 828	Reinforced concrete	-89.1		
				Steel	-387.7		
				Timber	98.8		
		3 (125 years lifespan)	914	Reinforced concrete	-95.7		
				Steel	-343.2		
				Timber	109.5		
		6 (125 years lifespan)	1 828	Reinforced concrete	-107		
				Steel	-361.7		
				Timber	105.9		

Chapter 7 – Complete lifecycle GWP

This chapter shows the GWP for the full lifecycle of the materials and the buildings. In Table 7.1; 7.2 and 7.3 are the cumulative GWP and energy usage shown for respectively timber, steel and reinforced concrete products used in multi-storey buildings for their entire life-cycle. For this 34 EPD's were collected.

Table 7.1: GWP and energy consumption in the complete life-cycle for timber

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m^3]	Primary energy-use non-renewable [MJ/m^3]	GWP [kg CO$_2$ eq/m^3]	GWP [kg CO$_2$ eq/metric tonne]	End-of-Life scenario
CLT	2017	Egoin	Spain	13 873.9	3 519.7	179.9	342.67	Recycled
	2017	Stora Enso	France	4 065.7	707.6	75.4	160.43	57,2% recycled; 25,5% used for energy recovery; 17,3% is buried
	2016	Stora Enso	Austria	9 215.5	-6 281	-332	-706.38	Incineration for energy recovery
	2016	Cross timber systems	Norway	6 118.4	2 421.8	163.6	389.52	Incineration for energy recovery
	2018	Rubner	Italy	1 110	-6 016.8	-315	-683.30	100% recycled
	2016	BSP Holz	Germany	10 487.1	-3 902.9	-168.3	-342.3	Incineration for energy recovery
	2018	BSP Holz	Germany	466.1	-3 868.6	-238.2	-506.9	77% recycling, 23% used for energy production
	2013	UK National Industry	UK	2 386.1	5 317	357.8	733.20	100% recycling
				10 236.7	-4 219	-198.8	-407.38	100% energy recovery
				10 569.1	4 589	402.3	824.4	100% landfill
Glulam	2013	BS Holz	Germany	10 760.6	-4 610.4	-198.9	-391.25	100% energy recovery
	2018	BS Holz	Germany	1 444.9	-3 926.7	-246.7	-510.54	100% energy recovery
	2018	Rubner	Italy	1 920	-6 050	-291	-653.93	Incineration for energy recovery
	2018	Schilliger Holz	Switzerland	831.2	-4 799.4	-113.8	-268.40	Incineration for energy recovery
	2017	WoodSolutions (softwood)	Australia	-10 200	0	1020	1 643	Recycling
				3 601.9	-6 237.9	-233	-375	Incineration for energy recovery
				13 852.7	5 834	-550.5	-886	Landfill
	2017	WoodSolutions (hardwood)	Australia	1 908	0	-408	-605.34	Recycling
				1 497.9	-6 150.9	6	8.9	Incineration for energy recovery
				12 753.1	5 837	-349.8	-519	Landfill
	2013	UK National Industry	UK	2 161.9	5 421	359.8	734.29	100% recycling
				10 031.6	-4 145	-197.8	-403.67	100% energy recovery
				10 364.8	4 694	404.1	824.7	100% landfill
LVL	2013	UK National Industry	UK	2 417.6	5 936	313	641.4	100% recycling
				10 228.4	-3 609	-239.7	-491.2	100% energy recovery
				10 560.9	5 216	356.7	730.9	100% landfill

Table 7.2: GWP and energy consumption in the complete life-cycle for steel

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m^3]	Primary energy-use non-renewable [MJ/m^3]	GWP [kg CO$_2$ eq/m^3]	GWP [kg CO$_2$ eq/metric tonne]	End-of-Life scenario
Trusses and beams from hot-rolled plates, coils and sheet	2014	Ruukki	Finland	22 843.5	139 023.5	11 068.5	1 410	90% recycled
Trusses and beams from cold formed structural tubes	2014	Ruukki	Finland	10 597.5	141 378.5	11 225.5	1 430	90% recycled
Cold-Formed Steel Studs and Track	2016	SCSglobal	USA/Canada	8 807.7	178 744.5	11 932	1 520	Recycling
HISTAR steel sections	2017	Arcelor Mittal	Luxemburg	5 265.8	74 497.3	4 814.6	613.3	88% recycled; 11% reused; 1% landfill
Hot rolled structural steel sections and merchant bars	2018	Arcelor Mittal	Luxemburg	9 356.4	70 588.8	6 168.8	785.8	88% recycled; 11% reused; 1% landfill
Hot dip galvanised steel with Magnelis coating	2017	Arcelor Mittal	Luxemburg	15 267.7	74 641.5	8 079.40	1 032.1	98% recycled; 2% landfill
Structural steel (S235 - S960)	2010	Bauforumstahl	Germany	4 474.5	92 473	6 280	800	88% recycled; 11% reused; 1% landfill
Structural steel (sections and plates	2018	Bauforumstahl	Germany	12 173	59 363.3	5 642.9	718.8	88% recycled; 11% reused; 1% landfill
Hot-rolled sections	2013	Contiga	Norway	59 947.5	129 344.5	8 973.3	1 143.1	Recycling
Uncoated steel plate	2018	DanSteel	Denmark	25 999.2	109 434.5	9 361	1 192.5	95% recycled
Structural sections	2016	OneSteel	Australia	6 977.9	156 427	19 129.7	2 436.9	89% recycling; 11% landfill
Structural hollow sections	2017	Tata Steel	UK	10 921.7	11 394.2	7 724.1	984	92% recycled; 7% reused; 1% landfill
Welded beams and columns	2015	Bluescope	Australia	8 059	19 066.6	12 990.3	1 654.8	89% recycled

Table 7.3: GWP and energy consumption in the complete life-cycle for steel

Material	Year	Producer/EPD-publisher	Country	Primary energy-use renewable [MJ/m³]	Primary energy-use non-renewable [MJ/m³]	GWP [kg CO_2 eq/m³]	GWP [kg CO_2 eq/metric tonne]	End-of-Life scenario
Unreinforced concrete C30/37	2018	InformationsZentrum Beton GmbH	Germany	154.4	1 178.9	224.3	93.5	Recycled in road construction
Unreinforced concrete C35/45	2018	InformationsZentrum Beton GmbH	Germany	183.6	2 694.9	253.9	105.8	Recycled in road construction
Unreinforced concrete C45/55	2018	InformationsZentrum Beton GmbH	Germany	254.8	1 914.1	315.89	131.6	Recycled in road construction
Unreinforced concrete C50/60	2018	InformationsZentrum Beton GmbH	Germany	264.5	1 919.7	329.6	137.3	Recycled in road construction
Precast Concrete Ground Beam	2017	MPA British Precast	UK	494.9	4 137.9	450.14	187.6	90% recycled; 10% landfilled

In Table 7.4 are the BF's shown from thirteen comparative LCA's that calculated the full lifecycle. All the relevant factors and assumptions (difference in U-value, lifespan, end-of-life scenario and included operational activities) that have an influence on the outcome of the LCA have been added in this table.

Table 7.4: GWP of multi-storey buildings when constructed with different structural materials (1/2)

	Country	Function	Stores	Floor area [m²]	Bearing structure	Lifespan [years]	End of Life scenario	GWP [kg CO_2 eq/m²]	Included in the operational energy	Included life-stages	Reference
	Sweden	Residential	4	1 190	Reinforced concrete	100	90% of the concrete is landfilled and is crushed and exposed to air for 4 months, 10% is lost. 90% of the rebar steel gets recycled	30.8		A1; A2; A3; A4; A5; B1; C1; C2; C3; C4; D	(Dodoo et al, 2009)[20]
					Timber		90% is recovered for energy, the remaining 10% is oxidized naturally without energy recovery	-20.6			
U-value slightly different	New-Zealand, Christchurch	Office	6	4 247	Reinforced concrete	60	All materials are completely landfilled	1 599.7	Heating, cooling, Water heating, lighting, room electricity and miscellaneous systems	A1; A2; A3; A4; B2; B6; B7; C2; C3; C4; D	(John et al, 2008)
					Steel			1 620.7			
					Timber			1 408.5			
					Reinforced concrete		Concrete and steel are completely recycled Timber is used as boiler fuel to provide energy	1 596.9			
					Steel			1 546.3			
					Timber			1 415.1			
Similar U-value	New-Zealand	School	3	1 980	Reinforced concrete	60	100% of the concrete is sent to clean landfills, 85% of the reinforcing steel is recycled	1 462.1	Heating; Cooling; Appliances; Lighting; Water heating	A1; A2; A3; A4; B2; B6; C3; C4; D	(Buchanan et al, 2012)
					Steel		85% is recycled	1 456.6			
					Timber		82% is landfilled, 18% is decomposed. 43% of the formed CH_4 during decomposition is burned for energy recovery replacing fossil fuels	1 338.9			
Similar U-value	Beijing, China	Residential	3	5 590	Reinforced concrete	50	Only demolition is considered	788.9	Total energy consumption	A1; A2; A3; A4; A5; B6; C1	(Gong et al, 2012)[21]
					Steel			549.2			
					Timber			520.6			
Identical U-vlaue	Växjö, Sweden	Residential	6	1 686	Reinforced concrete	80	4 months exposure to atmosphere + reuse as below-ground filling	472 (378)	HVAC; Water heating	A1; A2; A3; A4; A5; B6; B7; C1; C2; C3; C4; D	(Tettey et al, 2019)[22]
					Timber (CLT)		Combustion for energy	-566 (-311)			
					Timber (Modular)			-15 (33)			
	Vancouver, Canada	Residential	18	12 838	Reinforced concrete	100	Landfilling	1 968	HVAC; Lighting; Water Heating; Appliances	A1; A2; A3; A4; A5; B2; B3; B4; B6; B7; C1; C2; C3; C4; D	(Bowick, 2018)
				15 120	Hybrid: Timber + concrete		Landfilling + incineration for energy use	1 944.4			(Bowick, 2018)
	Australia	-	3	9 750	Steel	-	-	348.7		Cradle-to-grave, not further specified	(Townsend & Wagner, n.d.)
					Timber		-	112.8			
							Thermal utilisation of wood waste	-153.8			
Similar U-value	China (Harbin, cold region)	Residential	4	-	Reinforced concrete	50	Concrete building: All the concrete and all the reinforcement steel is landfilled Timber building: 50% is recycled, 50% is used for biomass energy	7 242.90	Heating; Cooling; Appliances	A1; A2; A3; A4; A5; B6; C1; C2; C3; C4; D	(Guo et al, 2017)
					Timber (CLT)			6 275.70			
			7	-	Reinforced concrete			7 009.30			
					Timber (CLT)			6 082.60			
			11	-	Reinforced concrete			6 884.20			
					Timber (CLT)			5 980.70			
			17	-	Reinforced concrete			6 815.40			
					Timber (CLT)			5 922.80			
Different U-value	China (Harbin, severe cold region)	Residential	7	2 799.3	Reinforced concrete	50	Landfilled	1 870	Heating; Cooling; Lighting	A1; A2; A3; A4; A5; B6; C1; C3; C4; D	(Liu et al, 2016)
					Timber		55% recycled, 45% biomass energy	1 070			
							90% recycled	990			
	Xi'an, China (cold region)				Reinforced concrete		Landfilled	1 350			
					Timber		55% recycled, 45% biomass energy	820			
							90% recycled	730			
	Brisbane, Australia	Residential	4	603	Reinforced concrete	60	Landfilled, 85% of steel rebars is recycled	260.4	-	A1; A2; A3; A4; A5; B2; C1; C2; C3; C4	(Lu et al, 2017)
					Steel		100% recycled	189.1			
					Timber: LVL mid-rotation hardwood		Incineration with energy recovery	47.1			
					Timber: LVL hardwood			75.8			
					Timber: LVL softwood			61.7			

Table 7.4: GWP of multi-storey buildings when constructed with different structural materials (2/2)

	Country	Function	Stores	Floor area [m²]	Bearing structure	Lifespan [years]	End of Life scenario	GWP [kg CO_2 eq/m²]	Included in the operational energy	Included life-stages	Reference
	USA	Residential	3	2 613	Reinforced concrete	60	Concrete: 90% is 4 months landfilled and later recycled Timber: Incineration with energy recovery	127.9		A1; A2; A3; D	(Skullestad et al, 2016)
					Timber: CLT + Glulam			-140.3			
			7	6 097	Reinforced concrete			117			
					Timber: CLT + Glulam			-144.7			
			12	10 542	Reinforced concrete			117.3			
					Timber: CLT + Glulam			-169.1			
	Norway	Hotel	21	11 823	Reinforced concrete			355.2			
					Timber: CLT + Glulam			-230.8			
	Sweden	Residential	4	-	Timber	-	-	30		Cradle-to-grave, B-phase excluded	(Eriksson, 2004)
					Reinforced concrete			400			
Similar U-value	UK	Residential	3	914	Reinforced concrete	60	Recycling + landfill	1 762.3	HVAC; Water Heating; Appliances	A1; A2; A3; A4; A5; B4; B6; C1; C2; C3; C4	(Din & Brotas, 2017)
					Steel			1 506.9			
					Timber			1 488.8			
			6	1 828	Reinforced concrete			1 785.8			
					Steel			1 662.3			
					Timber			1361			
			3	914	Reinforced concrete	100		2 117.5			
					Steel			1 921.7			
					Timber			1 894.8			
			6	1 828	Reinforced concrete			2 152.1			
					Steel			2 083.3			
					Timber			1 773.2			
			3	914	Reinforced concrete	125		2 341.9			
					Steel			2 131.3			
					Timber			2 055.2			
			6	1 828	Reinforced concrete			2 377.8			
					Steel			2 286.2			
					Timber			1 925.5			

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[20] It was nowhere in the paper literally mentioned that B6 was the only operational phase taken into consideration. Out of the description in this paper it was assumed only B6 was the solely considered operational phase.

[21] The value between brackets is when electricity generation and energy substitution are gas based, otherwise it's coal based.

Chapter 8 – Assessment and discussion of the results

8.1 During the different life stages

8.1.1 Production phase

To make the comparison on a material scale, 60 EPD's were collected. Their Cradle-to-Gate GWP's are plotted in boxplots for timber, steel and (reinforced) concrete. This is shown in Figures 8.1 and 8.2. Figure 8.1 shows the timber boxplot when the sequestration of CO_2 during its growth are included. Figure 8.2 shows this when the effect of sequestration is excluded.

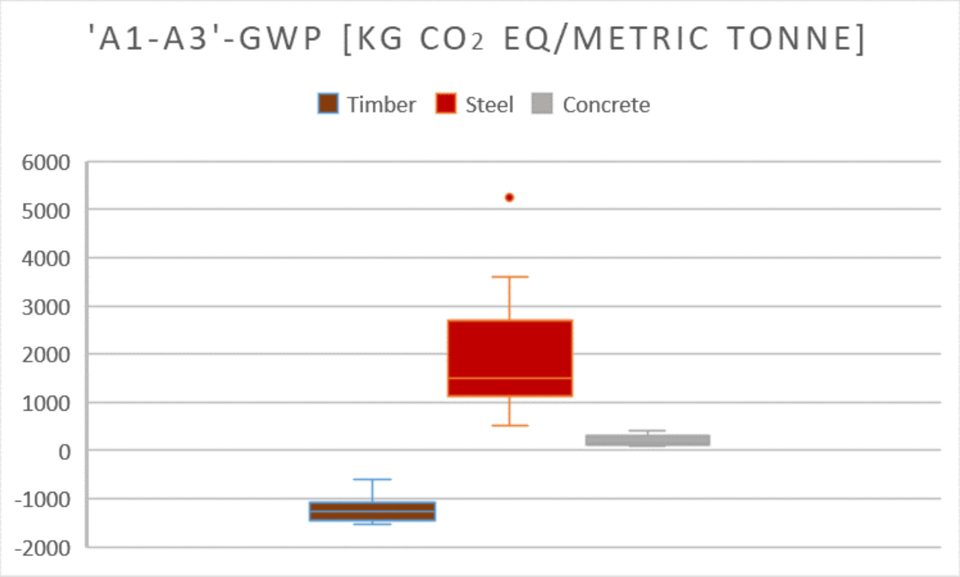

Figure 8.1: Cradle-to-Gate GWP of structural elements made out of concrete, timber or steel when carbon sequestration by timber is taken into account

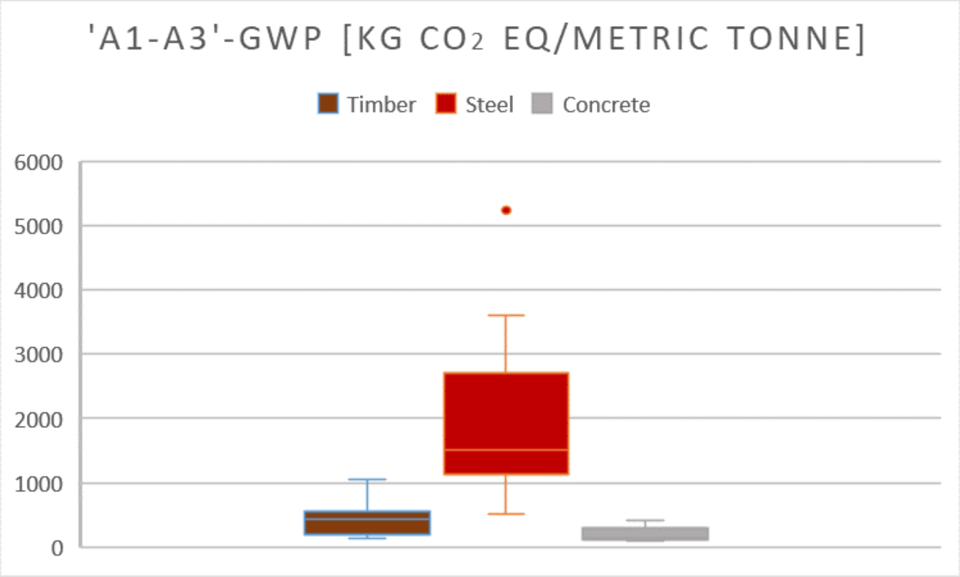

Figure 8.2: Cradle-to-Site GWP of structural elements made out of concrete, timber or steel when carbon sequestration by timber is excluded

As can be seen, timber has a lower GWP than both steel and reinforced concrete. However when excluding the sequestrated carbon in the timber, reinforced concrete seems to have a lower GWP per mass unit. The LCA's show that in the cradle-to-gate phase the timber variant always has a smaller GWP. This can be explained by the fact that the density of reinforced concrete is approximately five times higher than timber. In Figure 8.3 both materials were plotted in a boxplot again, only this time their GWP was expressed in volume unit instead of mass unit. This shows that reinforced concrete elements have a bigger GWP than the timber elements.

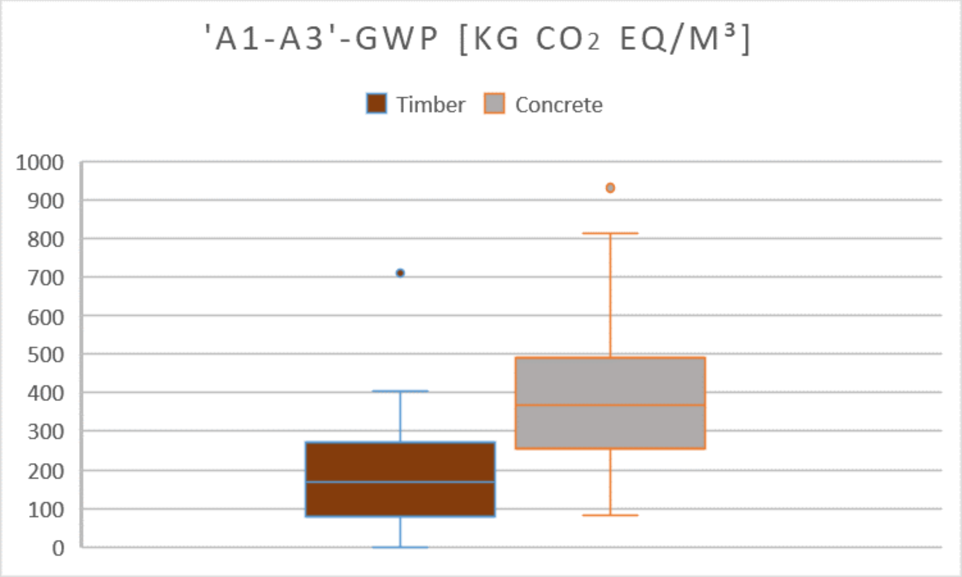

Figure 8.3: Cradle-to-Gate GWP per volumetric unit of structural elements made out of concrete or timber when carbon sequestration by timber is excluded

From this it can be concluded that planting trees for future construction projects results in a reduction of carbon emissions once the building is constructed. But also in the timeframe from the point of harvesting till finishing the construction works timber causes the least carbon emissions. So currently planned projects can achieve a smaller carbon footprint at the moment of finishing the construction works if they choose for sustainably harvested timber as the loadbearing structure.

From the collected ten comparative LCA's who focus on the cradle-to-gate phase of the building, eight were selected discussing eleven cases. They were selected because they took the sequestrated carbon into account when calculating the GWP. Their results are presented in Figure 8.4.

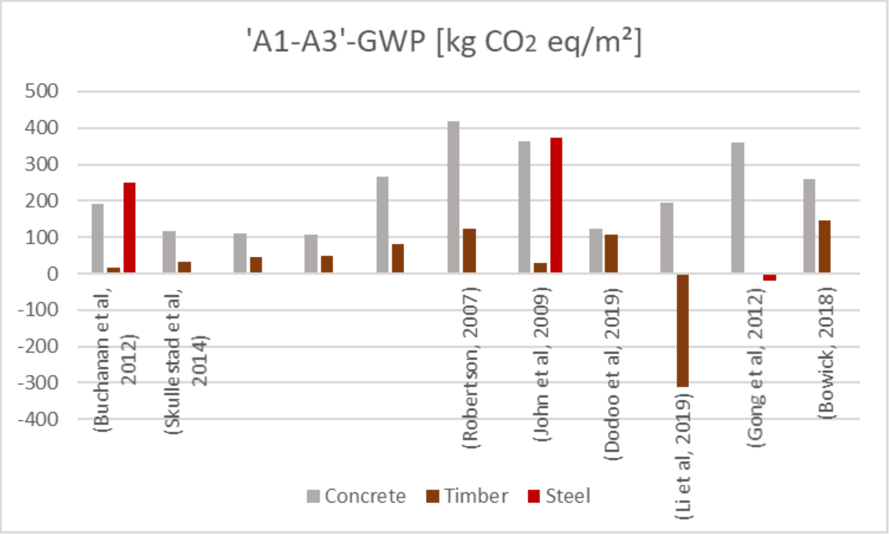

Figure 8.4: Cradle-to-Gate GWP of multi-storey buildings made out of concrete, timber or steel when carbon sequestration by timber is taken into account

All eleven cases show a lower GWP for the timber variant when compared with its reinforced concrete counterpart. The reduction in GWP when building with timber ranges from 13.88% to 259.48%. From the three cases that made the comparison with steel as well, two showed a reduction in GWP for timber of 92.2% and 93.33%. Gong et al. (2012) even had a negative GWP for the steel building. Because the steel variant in the research of Gong et al. (2012) still contained a big amount of wooden materials and the timber structure still used reinforced concrete construction elements, the steel version of the building achieved a smaller carbon footprint.

When comparing the cradle-to-gate GWP's when the carbon sequestration benefit of timber is not taken into account, the timber variant still seems to outperform the steel and reinforced concrete version in the frame of climate change. This is shown in Figure 8.5. Three comparative LCA's show a reduction in GWP of 33.62; 38.27 and 66.15% when building with timber instead of reinforced concrete. Between timber and steel the reductions are 2.10% and 39.74%.

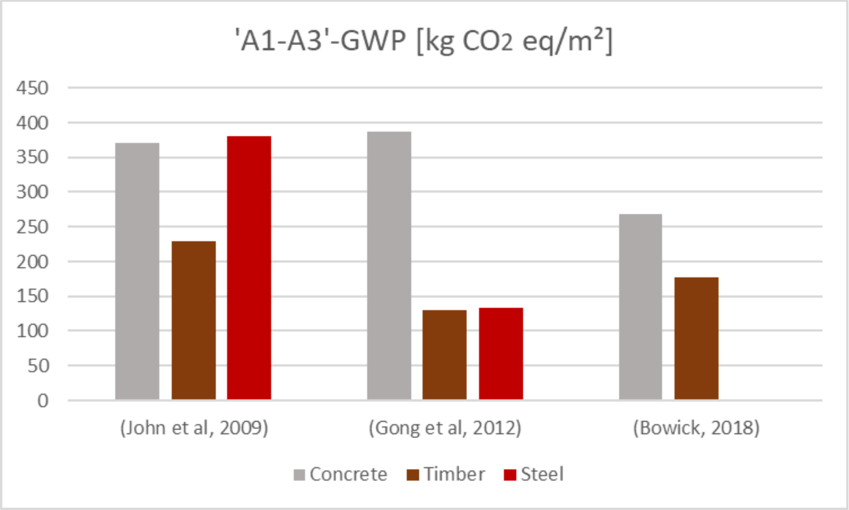

Figure 8.5: Cradle-to-Gate GWP of multi-storey buildings made out of concrete, timber or steel when carbon sequestration by timber is excluded

Two remaining LCA's concerning the cradle-to-gate phases didn't mention rather or not the carbon sequestration during the timber growth was included. In both LCA's the timber variant had the lowest GWP.

Two more papers both by Hafner & Schäfer (2017) performed a comparative LCA on multi-storey buildings using different structural materials. Their results have been added in appendix D and E. For the two papers, both when carbon sequestration of timber is included and excluded, the timber building seemed to have the lowest BF in the cradle-to-gate stage.

When looking at the LCA's who determined the GWP for the full cradle-to-site stage, five papers concerning eight cases were found that included the carbon sequestration during wood growth. In all cases the timber variant had the lowest GWP. This is presented in Figure 8.6. The reduction in GWP between the timber and reinforced concrete variant of the multi-storey building ranged from 40.46% to 172.94%. For the two cases that compared steel with timber, the reductions were 0.92% and 90.29%.

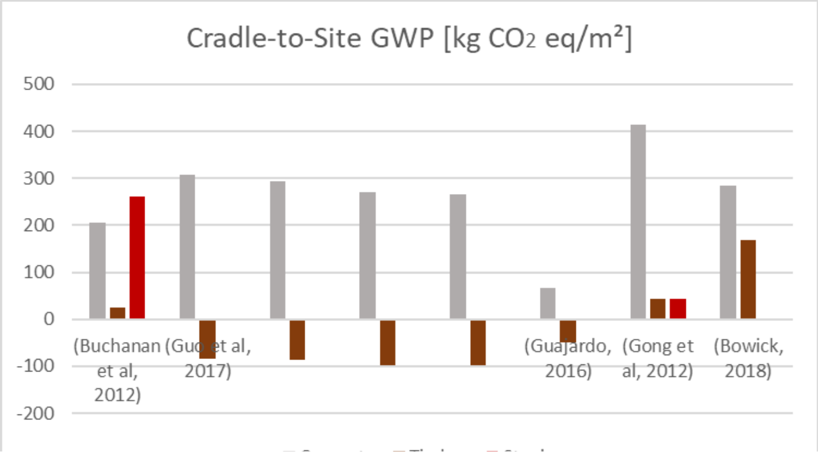

Figure 8.6: Cradle-to-Site GWP of multi-storey buildings made out of reinforced concrete, timber or steel when carbon sequestration by timber is taken into account

Six LCA's excluded the benefit of carbon sequestration when determining the cradle-to-site GWP. Their results are presented in Figure 8.7. Again in all six papers the multi-storey building resulted in the lowest GWP. The GWP reductions when reinforced concrete is switched for timber range from 2.83% - 60.82%. Remarkable is that Gong et al. (2012) calculated a GWP reduction of 0.92% between timber and steel when including carbon sequestration but found a reduction of 12.86% when the effect of the carbon uptake is not considered. This is due to the high amount of wooden materials in the steel variant of the building.

Three remaining comparative LCA's that focused on the A1-A5 phases were collected but didn't mentioned rather the carbon uptake from the atmosphere was taken into account. In all three papers timber achieved the smallest carbon footprint.

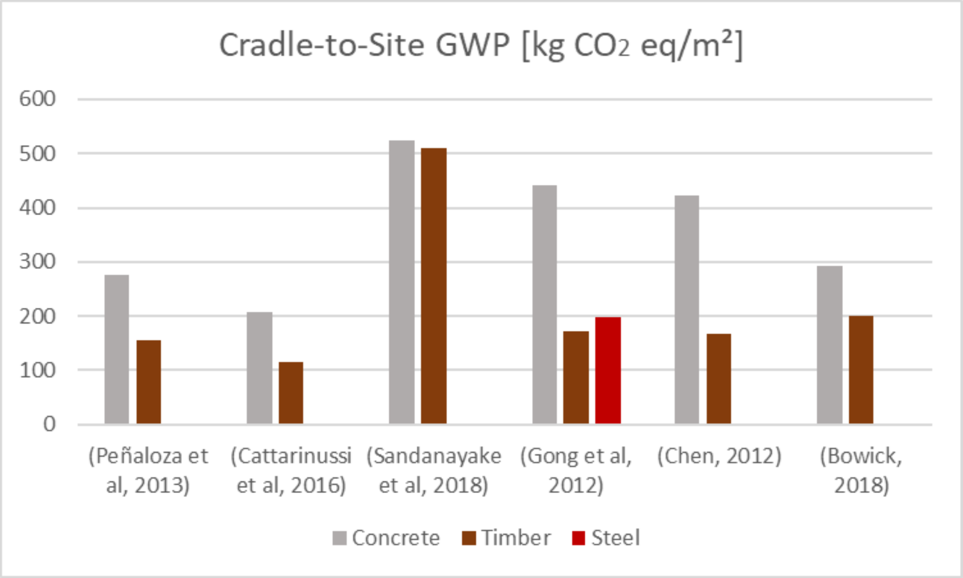

Figure 8.7: Cradle-to-Site GWP of multi-storey buildings made out of concrete, timber or steel when carbon sequestration by timber is excluded

8.1.2 Operational phase

As mentioned before, the operational phase is the dominant phase for both the energy consumption and GWP within the full life-cycle of the building. When WMC are compared to reinforced concrete and steel equivalent, little differences were found for this phase.

For the comparative LCA's discussing the B-phase, six LCA's gave the GWP for fourteen cases. It was suspected that timber buildings would obtain a smaller operational GWP in colder climates and a bigger GWP in hotter climates. This is because timber has a positive effect on the energy consumption for space heating and a negative effect on energy consumption for space cooling. In Figure 8.8 is shown that three out of six LCA's (6 out of 14 cases) showed a smaller B-GWP for the timber building. In the other three the wooden building had a bigger GWP in the usage phase. Still these differences remain rather small. With the differences between timber and reinforced concrete multi-storey buildings varying between -5.11% and 8.71%, and when comparing timber and steel these values are respectively -3.22% and 2.89%.

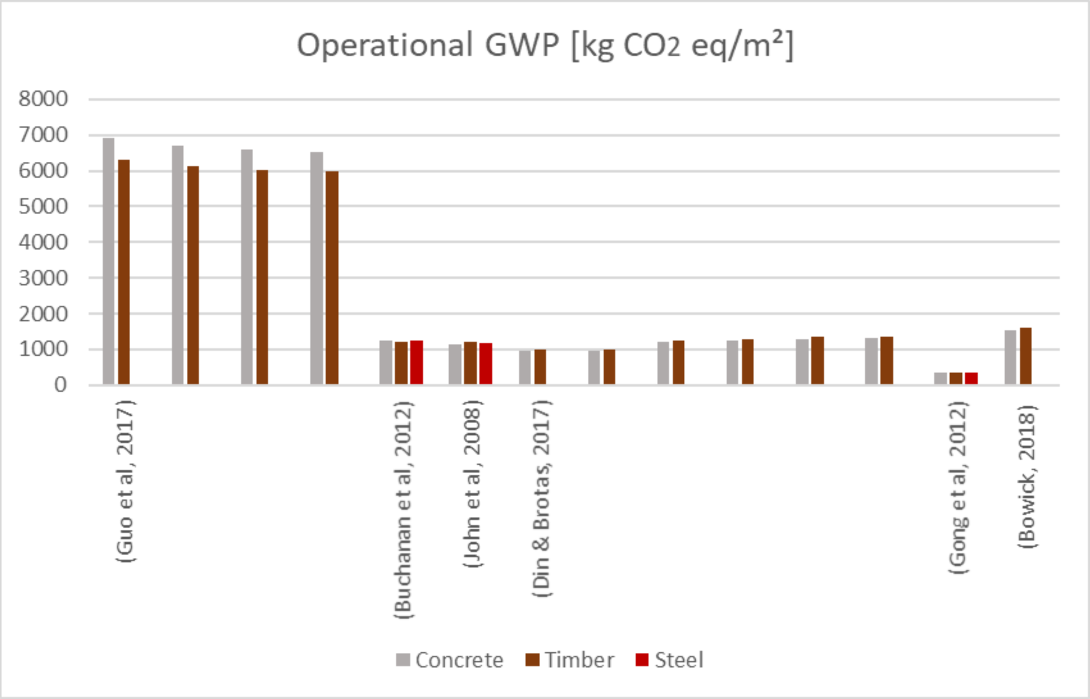

Figure 8.8: Operational GWP of multi-storey buildings made out of concrete, timber or steel

The majority of the collected comparative LCA's focused on the energy usage rather than the associated emissions. The different annual energy consumptions are presented in Figure 8.9. Thirteen comparative LCA's were collected calculating 33 cases. From these 33 cases, 22 of the timber variant of the multi-storey building had a smaller energy consumption than the reinforced concrete and/or steel equivalent. The energy savings when using timber instead of reinforced concrete vary between 39.42% and -6.86%. For the comparison between steel and timber these values are 6.27% and -15.09%. All the relative differences are added in appendix N.

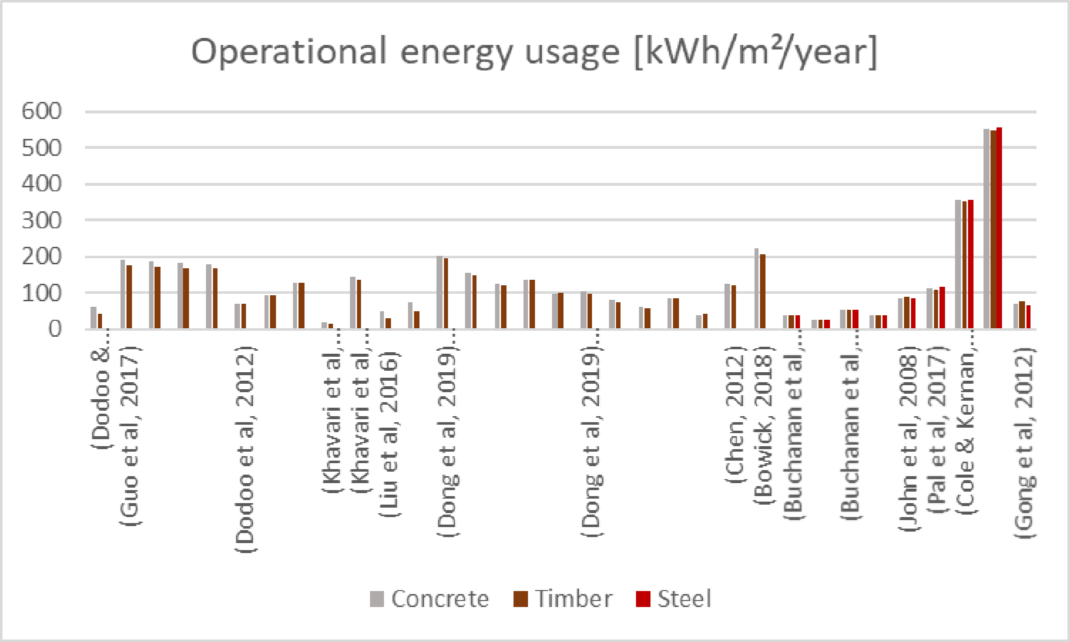

Figure 8.9: Annual operational energy consumption of multi-storey buildings made out of concrete, timber or steel

To examine the effect of the local climate on the operational energy consumption, the relative differences between the energy usage of the timber multi-storey buildings and the reinforced concrete and steel versions have been ranged from coldest to warmest climatic zone. This has only been done to the LCA's that included all the energy consuming processes from the operational phase, being HVAC, lighting, water heating and miscellaneous systems. The activities whose energy demand is not affected by the structural material of the building are suspected to be identical and therefore will lead to an overall decrease in the relative differences. Not enough comparative LCA's who only included HVAC were available to spot a trend when ranged from cold to warm climates.

Figure 8.10 shows the graph of the relative differences. For this graph eight comparative LCA's were collected discussing fourteen cases. A positive value means the timber building consumed less energy than the steel or reinforced concrete variant of the building. A negative value represents an increase in operational energy usage for the timber variant of the building. The specific values are added in appendix O, and the math to obtain these values is shown in appendix N. The LCA's selected all considered similar U-values.

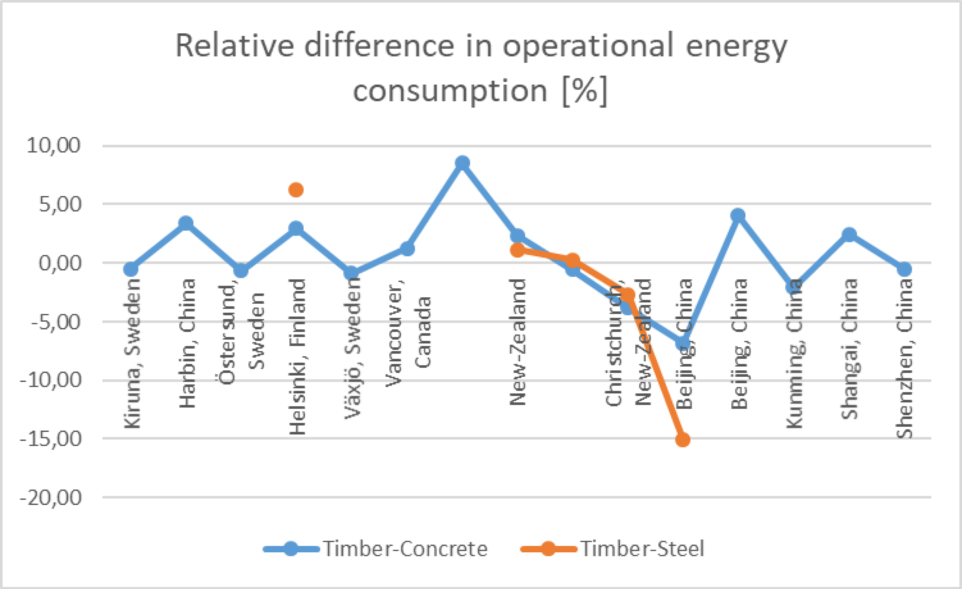

Figure 8.10: Relative difference in operational energy consumption between timber multi-storey buildings and its concrete or steel equivalent, ranged from cold to hot climates

No trend could be spotted through the different climatic zones for the differences between the reinforced concrete and timber variant. When ranging the energy consumption difference between steel and timber from cold to warm climates, a strict declining graph is obtained However the latter was plotted only using five cases which correspond with a declining line in the Timber/Concrete graph.

The annual energy consumption for heating from several comparative LCA's is shown in Figure 8.11. The same was done for the energy usage for cooling in Figure 8.12. Because the other life-cycles are in no way related to the local climate and the savings in the B6-phase show no relationship with the climate, the effect of the local climate on the overall GWP won't be examined in this dissertation. For the energy use for heating in Figure 8.11, a distinction was made between the LCA's that assumed a different U-value for the equivalent buildings and the ones that assumed an identical U-value.

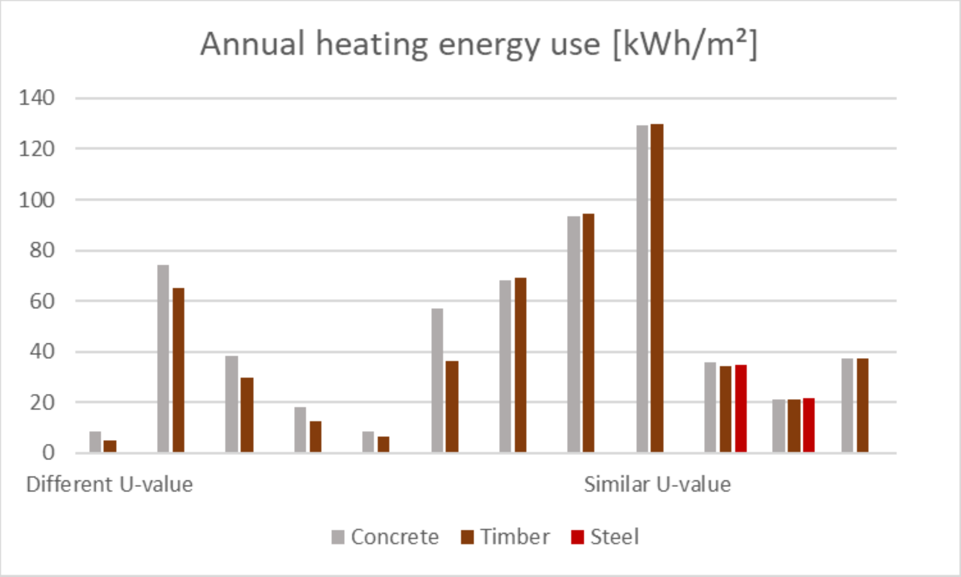

Figure 8.11: Annual energy consumption for heating in multi-storey buildings made out of reinforced concrete, timber or steel

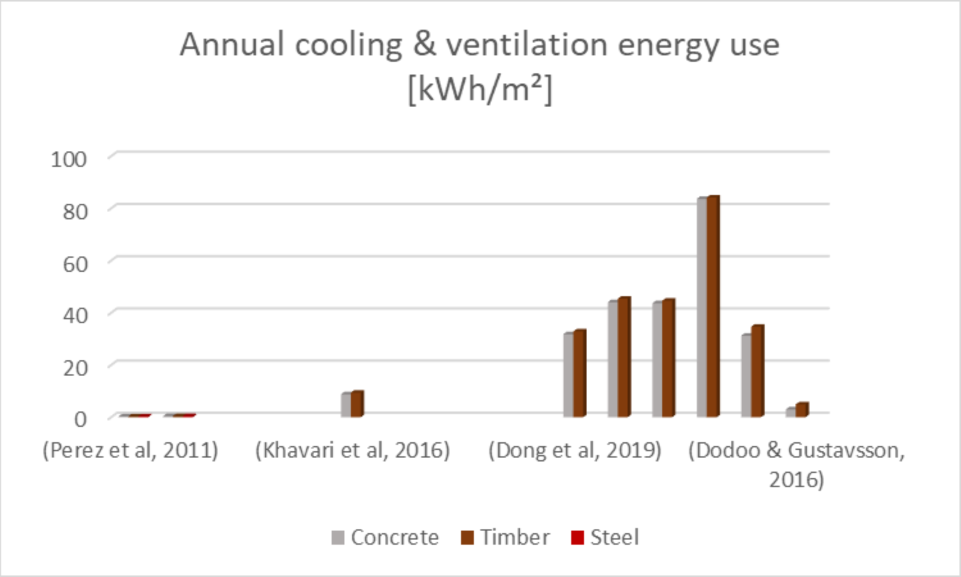

Figure 8.12: Annual energy consumption for cooling & ventilation in multi-storey buildings made out of reinforced concrete, timber or steel

From the twelve cases in Figure 8.11, seven timber variants consumed less energy for heating than the reinforced concrete or steel benchmark. Six from these seven cases had a higher U-value than the reinforced concrete benchmark. From the nine cases that compared the energy consumption for cooling and ventilation, the timber building always required more energy than the steel or reinforced concrete version of the building.

From this it was concluded that today there's a lack of sufficient evidence that the timber variant of multi-storey buildings obtains greater reductions in energy usage when build in colder climates.

8.1.3 End-of-Life

The end-of-life stage shows the biggest variation in results. This is due to the different possible scenarios.

In Figure 8.13 are the GWP per metric of the construction materials plotted in boxplots. In the end-of-life stage, the timber materials seem to have the highest GWP. Due to its high recycling rate, almost all the steel materials have a negative GWP for the C- and D-stage. The five EPD’s collected for reinforced concrete seems to be have a GWP of almost 0. This is because all the five EPD’s presume a recycling scenario for the reinforced concrete waste. The avoided GHG emissions from extracting and transporting new aggregates is outbalanced by the increased amount of cement when using recycled aggregates.

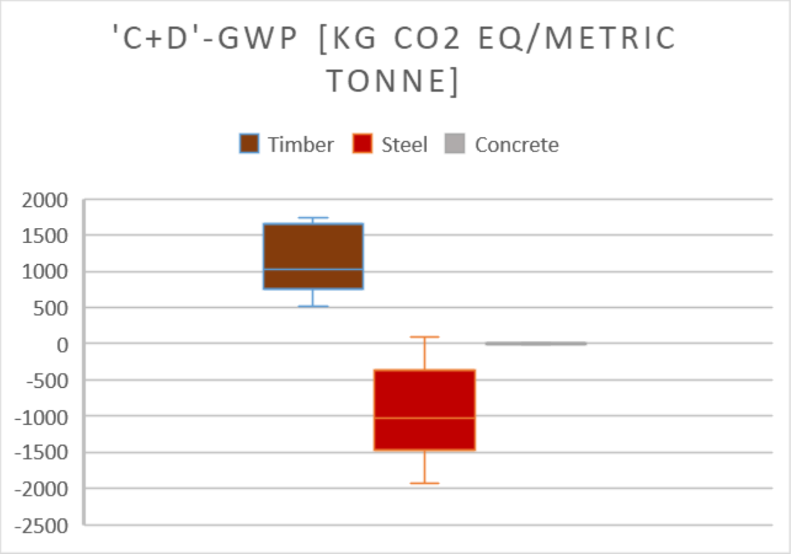

Figure 8.13: End-of-Life GWP of structural elements made out of concrete, timber or steel

The GWP during the end-of-life highly depends on the chosen scenario. That is why the timber boxplot was split up according to its end-of-life scenario. This is shown in Figure 8.14.

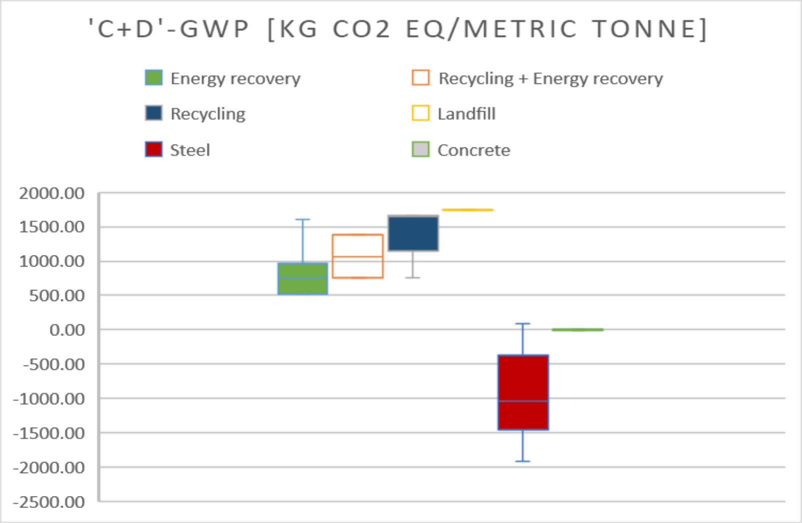

Figure 8.14: End-of-Life GWP of structural elements made out of reinforced concrete and steel. The four left boxplots represent the GWP of structural timber waste according to their end-of-life scenario

In Figure 8.15 it can be seen that the usage of the timber waste for energy production seems to have to smallest GWP, followed by recycling and with landfilling being the least favorable option. Still all four scenarios show a bigger GWP than reinforced concrete and steel.

This matter is highly uncertain to draw a conclusion cause as mentioned in ‘6.4.1 Timber’ there is still a lot of uncertainty about the carbon emissions from landfilling wood waste. The two LCA’s that assumed landfill as an end-of-life scenario both assumed a carbon decay of 18%, of which 50% forms CO_2 and 50% forms CH_4. It has already been mentioned in this dissertation that this is likely to be an overestimation.

For this subchapter seven comparative LCA’s were collected with nineteen different cases. This is shown in Figure 8.15. All nineteen cases compare timber with reinforced concrete, and nine cases from three LCA’s compared timber with steel. For all three cases steel performed much better than timber. This is due to the high recycling rate of steel. When comparing reinforced concrete to timber, in five out of nineteen cases the timber waste had a smaller GWP. Because the outcome of the GWP of the C and D-stage highly depends on the chosen scenario, both the absolute GWP and the relative differences between timber and reinforced concrete and between timber and steel were ranged in a graph according to the end-of-life scenario. This can be seen in Figures 8.15 and 8.16. In Figure 8.16 a positive value means a reduction in GWP for the timber building in comparison with its reinforced concrete or steel equivalent. A negative value represents an increase. The values of these relative savings and the math to obtain them are given in appendix P.

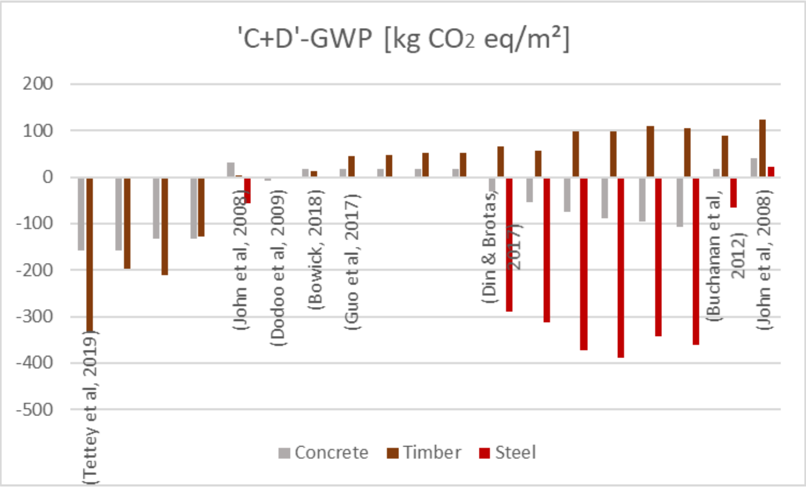

Figure 8.15: End-of-Life GWP of multi-storey buildings made out of reinforced concrete, timber and steel

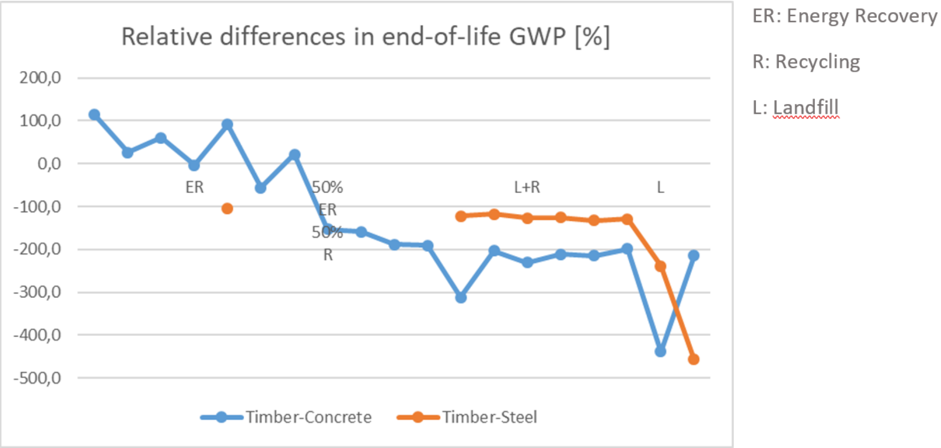

Figure 8.16: Difference in End-of-Life GWP of multi-storey buildings made out of reinforced concrete, timber and steel, ranged according to the different end-of-life scenarios

In the graph of Figure 8.16 a trend can be spotted. It shows that for timber waste the scenario of energy recovery has the smallest GWP. Of the seven cases that assume energy recovery for the timber waste, five had a better climatic performance than reinforced concrete. For both ‘50% recovery and 50% recycling’ and the landfill-scenario, reinforced concrete always seems to be more beneficial to the climate than timber. The combination of landfilling and recycling caused timber to have a bigger GWP than reinforced concrete and steel. 100% landfill seems to be emits more CO_2 and CH_4 than replacing fossil fuels with wood fuel. The end-of-life scenario for steel and reinforced concrete always seems to be the same with steel being recycled and concrete being landfilled and afterwards reused as sublayer in road construction.

8.2 Full Life-cycle

8.2.1 Material

In Figure 8.17 three boxplots were plotted showing the GWP’s of 33 EPD’s. It shows that for a full life cycle timber has greater carbon benefits than steel. However between concrete and timber no clear conclusion could be drawn. Analogous with paragraph 8.1.1 the boxplots for both timber and concrete were plotted again, but now expressing the carbon emissions in function of their volumetric unit in Figure 8.18.

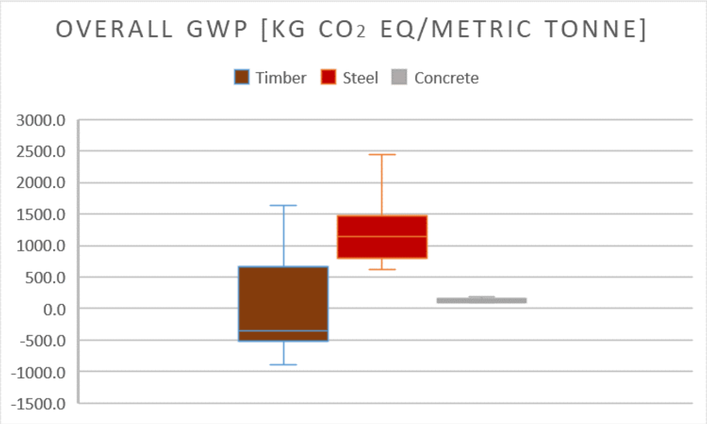

Figure 8.17: Overall GWP of structural elements made out of concrete, timber or steel

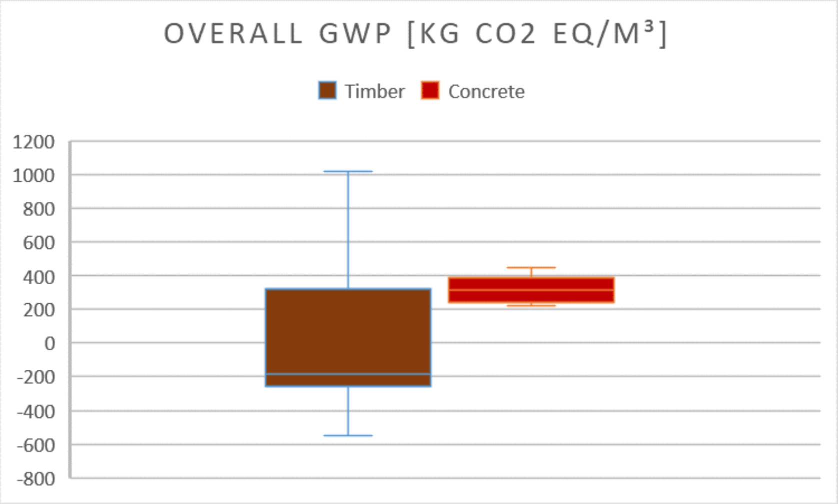

Figure 8.18: Overall GWP per volumetric unit of structural elements made out of concrete or timber

The boxplots shows a smaller GWP for the timber materials than for the steel and concrete elements.

8.2.2 Buildings

Of the collected LCA's that cover the full life-cycle, nine were selected because they take all four the life-stages into account (A, B, C and D) when calculating the overall GWP. These nine LCA's calculate the GWP for 27 cases. The results were for all 27 cases of the nine LCA's unanimous, being that the timber variant of the multi-storey building had the smallest carbon footprint. This is shown in the graph in Figure 8.19.

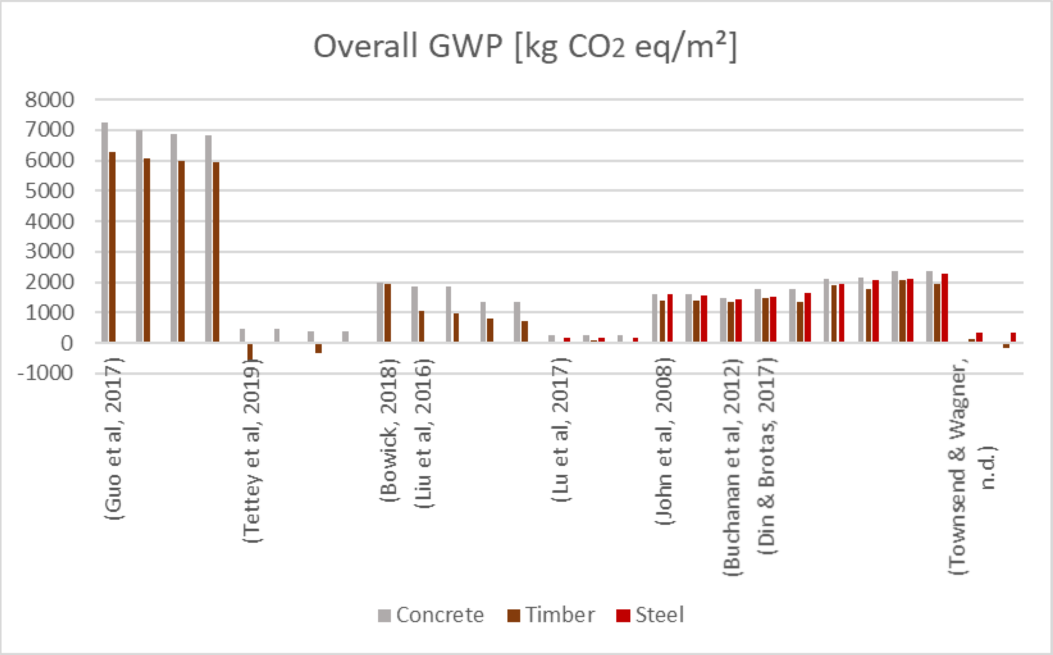

Figure 8.19: Overall GWP of multi-storey buildings made out of reinforced concrete, timber and steel

When comparing the timber variant of the multi-storey construction with reinforced concrete, the reduction in GWP varies between 1.22% and 219.92%. For steel the minimum and maximum relative savings in GWP when building with timber instead of steel are respectively 1.20% and 144.11%. This is shown in a graph in Figure 8.20. The reason for this big range in relative savings is due to different assumptions for factors such as end-of-life scenario and the included operational activities. The specific values for these relative savings are added in appendix Q.

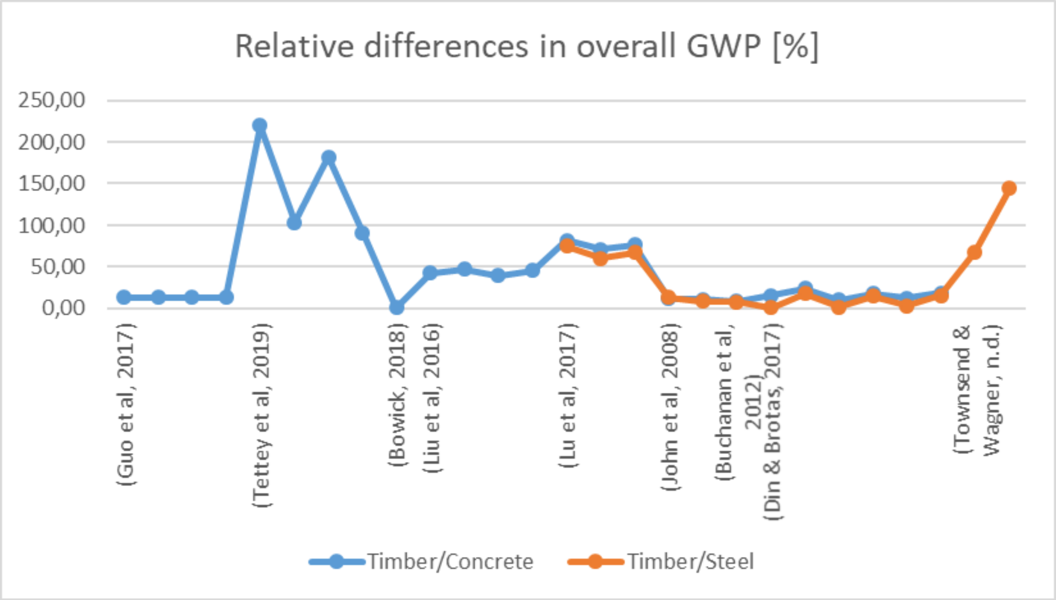

Figure 8.20: Relative difference in overall GWP between timber multi-storey buildings and its reinforced concrete or steel equivalent

One trend that can be noticed when looking at the upper graph is that the reductions in GWP when constructing with timber are bigger for reinforced concrete than for steel.

Three extra comparative LCA's were found who left out the B-phase because it was assumed to be identical. Their results are shown in Figure 8.21. For all three of these LCA's, the timber variant of the multi-storey building seems to have the smallest GWP.

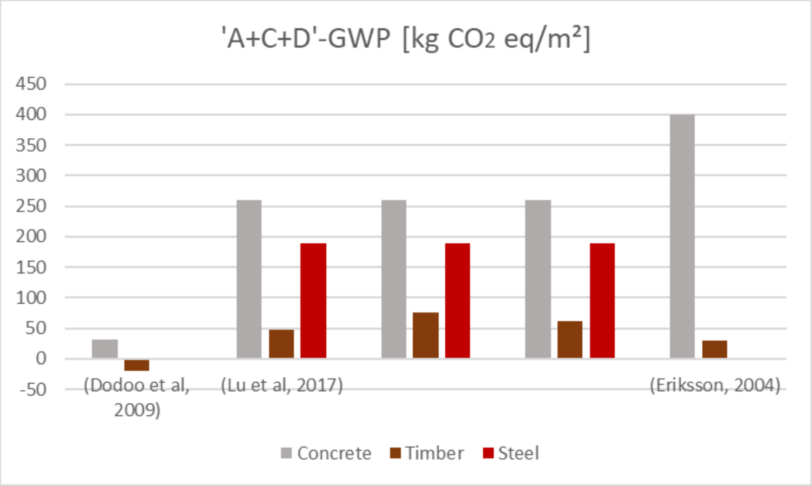

Figure 8.21: 'A+C+D'-GWP of multi-storey buildings made out of reinforced concrete, timber and steel

The outcome is unanimously that in all cases the timber variant has the smallest GWP when comparing it to its steel and reinforced concrete counterparts. From this it can be concluded that multi-storey buildings have a lower carbon footprint when realized with timber.

8.2.3 Effect of the End-of-Life scenario

Because it has already been shown that the assumed end-of-life scenario can have a big influence on the overall GWP, the relative difference in overall GWP have been ranged according to their end-of-life scenario. This is shown in the graph of Figure 8.22. Seven LCA's were selected discussing seventeen cases. The values of these relative differences have been added to appendix R.

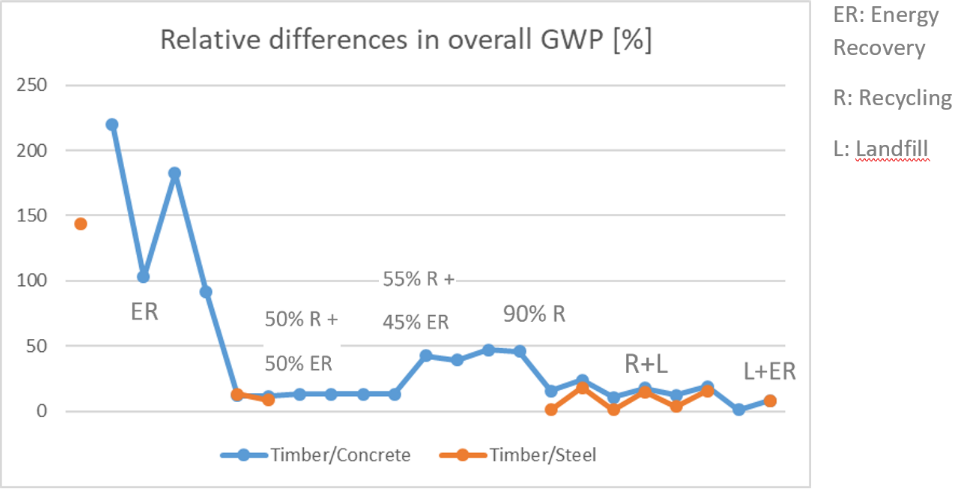

Figure 8.22: Difference in GWP of multi-storey buildings made out of reinforced concrete, timber and steel, ranged according to the different end-of-life scenarios

Analogous with the results from paragraph 8.1.3 energy recovery seems to be the most favorable end-of-life scenario for timber waste while landfilling is the least favorable. Recycling seems to be positioned between these two scenarios. In the graph there can be a trend spotted where an increased recycling rate results in an increased reduction in the GWP.

The four comparative LCA's that left out the B-phase all assume incineration with energy recovery as the end-of-life scenario. For that reason their relative reduction in GWP won't be compared in this paragraph.

In Figure 8.23 the GWP's of the timber materials are split up according to their end-of-life scenario. It can be seen that using the timber waste for energy recovery (combined or not with recycling) causes a smaller GWP than concrete. Recycling or landfilling of timber waste doesn't necessarily results in a reduction or increase in GWP when compared with concrete.

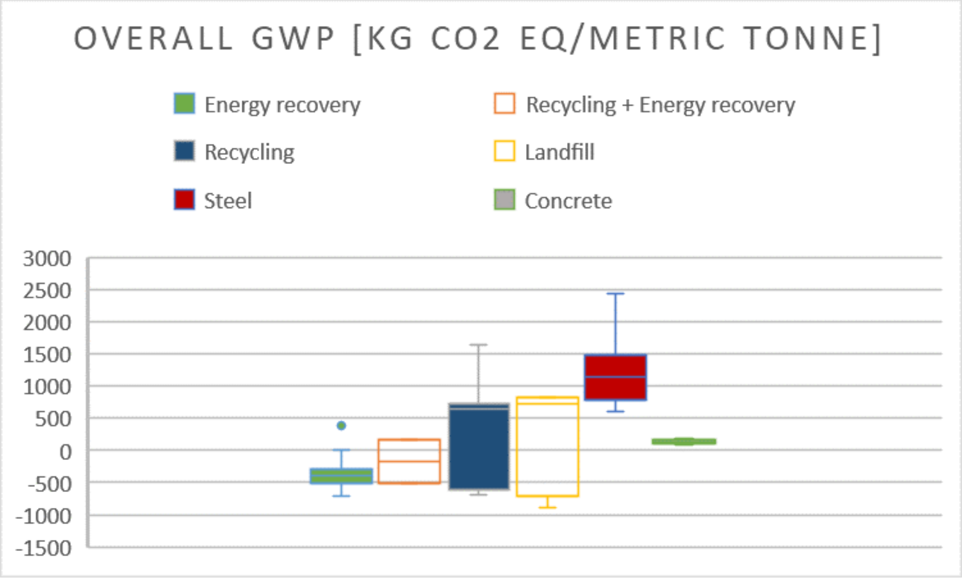

Figure 8.23: Overall GWP of structural elements made out of concrete and steel. The four left boxplots represent the GWP of structural timber waste according to chosen end-of-life scenario

The results of the gathered data for both materials and buildings show that the energy recovery for timber waste is the most beneficial towards GWP reductions, landfilling is the least favorable and recycling is in between these two options. However the collected literature for this dissertation shows that there is little to no information about the GHG emissions during the landfilling or recycling of CLT, glulam or LVL.

Also as discussed in paragraph '6.3.1 Timber' the climatic benefits of burning wood as a substitution for the use of fossil fuels are a highly controversial point. First of all the potential carbon reduction by using wood fuel instead of fossil fuels depends on the considered timeframe. The collected EPD's don't take the period of use of the product into account (design lifespan of the building). Secondly, burning wood instead of fossil fuels can cause temporarily increases in atmospheric carbon concentrations which can lead to permanent climate damage.

The conclusion taken from this part of the dissertation is that current data shows that the greatest reduction in GWP is achieved when the construction wood is combusted for energy use after its usage. But further research concerning the consequences of energy usage and GWP from recycling or landfilling of CLT, glulam and LVL is required. Both about the influence of the timeframe, the possible temporarily increase of atmospheric carbon concentrations and sustainable holistic system on timber production and timber waste management.

8.2.4 Effect of design lifespan

As mentioned the operational phase is the dominant stage within the lifecycle for both GWP and energy consumption while little differences are observed in the B-phase between timber, reinforced concrete and steel constructions. Because of this it could be expected that an increasing designed lifespan would reduce the savings in GWP between timber and reinforced concrete or steel buildings.

Din & Brotas (2017) calculated the GWP for a 3- and 6-storey building for three different lifespans, being 60; 100 and 125 years. The results of that research are shown in Figure 8.24. This graph shows no trend in a decrease in GWP with an increasing building lifespan.

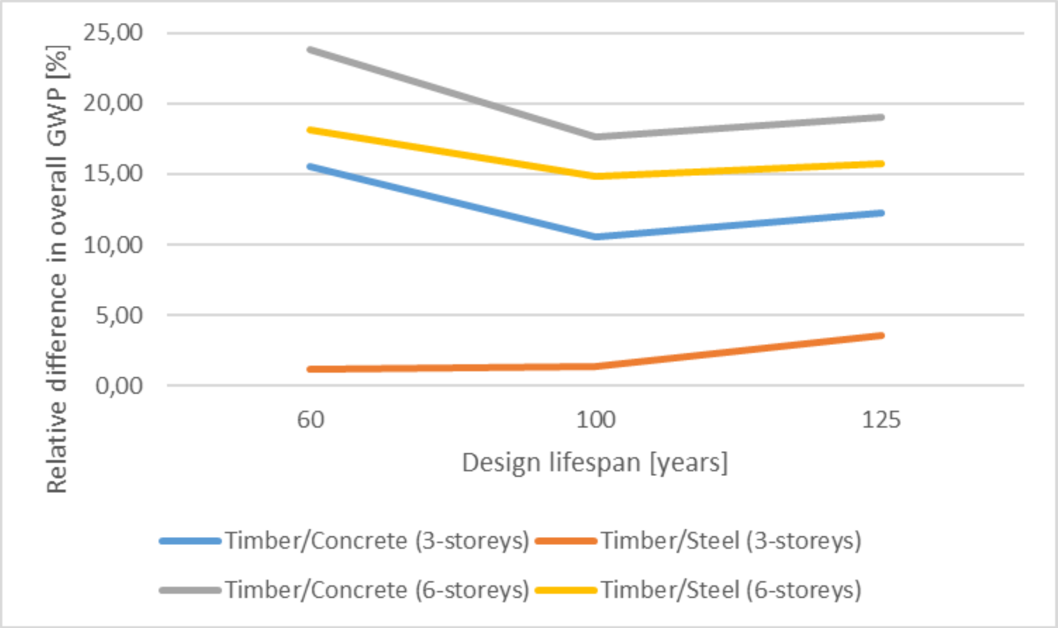

Figure 8.24: Relative difference in overall GWP when building with timber, ranged according to an increasing lifespan

No graph from the data from the comparative LCA's could be made because of the diversity in assumptions related to included operational activities and end-of-life scenarios.

From this, it was concluded that with today's available research no decrease in the difference in GWP between timber multi-storey buildings and its reinforced concrete and steel counterparts could be observed with an increasing designed lifespan.

Chapter 9 – Conclusion

This dissertation made a meta-analysis of the existing research concerning the potential GWP reductions of multi-storey buildings when constructed with timber. This was made both at the level of the buildings and at the level of the construction material. For this EPD’s, comparative LCA’s and existing academic literature were collected. The main outcomes of this research are the following:

- At the level of the building material it is shown that a reduction in GWP is achieved by switching from steel and reinforced concrete to timber.

  At the building level, for the production phase, the timber variant of the multi-storey building seems to have the lowest carbon emissions when compared with steel and reinforced concrete, even if the benefit of carbon sequestration during growth is excluded. This is both true for the cradle-to-gate phase and for the cradle-to-site phase. Only in one case the steel building had a lower carbon footprint than the timber one, but this was also due to a high amount of timber used in the steel variant. The minimum and maximum relative differences are shown in Table 9.1. So planting trees for future construction projects results in a reduction of carbon emissions once the building is constructed. But also in the time period that extends from the point of harvesting to finishing the construction works, timber causes the least carbon emissions. So currently planned projects can achieve a smaller carbon footprint at the moment of finishing the construction works if they choose sustainably harvested timber as the loadbearing structure.

Table 9.1: The minimum and maximum relative differences between the timber variant of the multi-storey building and its reinforced concrete or steel counterpart for different phases and assumptions of carbon sequestration

Materials	Phase	Carbon sequestration	Relative difference [%]	
			Minimum	Maximum
Timber/concrete	Cradle-to-Gate	Included	13,88	259,48
		Excluded	33,62	66,15
	Cradle-to-Site	Included	40,46	172,94
		Excluded	2,83	60,82
Timber/steel	Cradle-to-Gate	Included	-105,29	93,33
		Excluded	2,1	39,74
	Cradle-to-Site	Included	0,92	90,29
		Excluded	12,86	

- It was found that multi-storey buildings won’t necessarily consume less energy during operation when made out of wood. Little differences are found in the operational energy consumption between the different structural materials. No sufficient evidence was found that the switch to timber for multi-storey buildings would have greater climatic benefits in colder climates. It was found however that timber buildings require more energy for cooling and ventilation, and when constructed with the same thickness of insulation less energy is required to heat the timber building.
- On a material level, timber can’t seem to achieve less carbon emissions per mass unit.

After the usage of the building, the GWP highly depends on the chosen scenario for the construction waste. When the waste is used for energy recovery the timber building can outperform reinforced concrete and steel in the end-of-life stage as well. This is not the case when the waste is recycled or landfilled.

- At a material level timber seems to achieve a smaller overall GWP. Also for the overall GWP of the building the outcome is unanimous: timber always resulted in a smaller GWP. The reductions between timber and steel ranged from 1.20% to 144.11%, when comparing reinforced concrete and timber these values were 1.22% and 219.92%.
- For the overall GWP, the greatest reductions when using timber can be seen when the waste is reused for energy recovery. The smallest ones in the case of landfilling. The scenario of recycling is situated in between.
- So far it couldn't be pointed out that an increased design lifespan would result in a decreased reduction when building multi-storey constructions with timber.

Through the making of this state-of-the art review, three main shortages in the existing research were found. For that it's recommended that more research would be carried out to the following topics:

1) Carbonation of concrete during the usage phase.
   It's still unclear which share of the emitted carbon during the cement production gets reabsorbed during the operational phase of the reinforced concrete elements. This can have a decreasing effect on the GWP of reinforced concrete buildings

2) Carbon decay of EWP's.
   There is no existing information about the long-term effects of landfilling CLT, glulam or LVL. It's unclear which amount of GHG's gets emitted at a landfill. The collected literature for this dissertation focused on the carbon decay of regular wooden products and EWP's such as particleboard or OSB in landfills. They all show that the CH_4 production at landfills is likely to be overestimated, causing the end-of-life scenario of landfilling to have a bigger GWP than in reality.

3) Incineration of structural EWP's with energy recovery.
   Combustion of wood for energy generation, even if sustainable harvest is assumed and the produced energy replaces fossil fuels, can cause temporarily increases in CO_2 concentrations in the atmosphere. The firing of wood would cause more carbon emissions per produced kWh than coal or natural gas. Still this was shown to be the most favorable end-of-life scenario for timber waste. More research is required to both the short term and long-term effects of burning structural EWP's for energy generation.

Another suggestion for further research is to investigate the potential reduction in GWP for low energy multi-storey buildings when constructed with timber. It was shown through this research that the operational phase is the dominant stage for the GWP, but at the same time the stage that is affected the least by the structural material. Low energy buildings are designed to consume less energy during the operational phase. Constructing them with wood could possibly reduce the GWP during the production and end-of-life phase. For this further research is required.

To examine the influence of the local climate and the designed lifespan, more comparative LCA’s are required. In order to be able to spot a clear trend, these LCA’s have to be performed following to the same standard.

Also the effect on the GWP of the used adhesives in the structural EWP’s needs to be investigated further.

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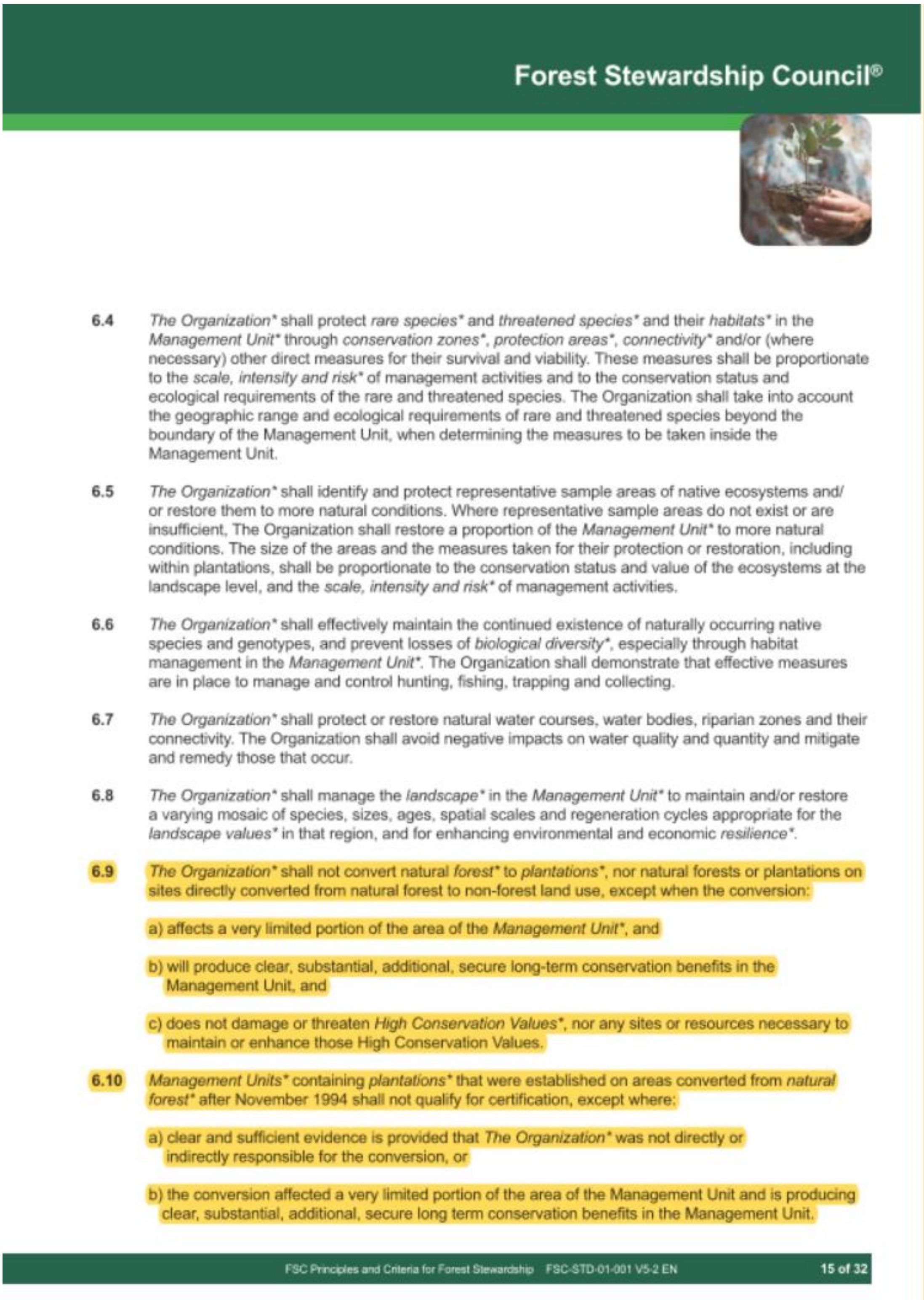
Appendix A: Page 15 of the FSC international standard



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6.4 *The Organization** shall protect *rare species** and *threatened species** and their *habitats** in the *Management Unit** through *conservation zones**, *protection areas**, *connectivity** and/or (where necessary) other direct measures for their survival and viability. These measures shall be proportionate to the *scale, intensity and risk** of management activities and to the conservation status and ecological requirements of the rare and threatened species. The Organization shall take into account the geographic range and ecological requirements of rare and threatened species beyond the boundary of the Management Unit, when determining the measures to be taken inside the Management Unit.

6.5 *The Organization** shall identify and protect representative sample areas of native ecosystems and/or restore them to more natural conditions. Where representative sample areas do not exist or are insufficient, The Organization shall restore a proportion of the *Management Unit** to more natural conditions. The size of the areas and the measures taken for their protection or restoration, including within plantations, shall be proportionate to the conservation status and value of the ecosystems at the landscape level, and the *scale, intensity and risk** of management activities.

6.6 *The Organization** shall effectively maintain the continued existence of naturally occurring native species and genotypes, and prevent losses of *biological diversity**, especially through habitat management in the *Management Unit**. The Organization shall demonstrate that effective measures are in place to manage and control hunting, fishing, trapping and collecting.

6.7 *The Organization** shall protect or restore natural water courses, water bodies, riparian zones and their connectivity. The Organization shall avoid negative impacts on water quality and quantity and mitigate and remedy those that occur.

6.8 *The Organization** shall manage the *landscape** in the *Management Unit** to maintain and/or restore a varying mosaic of species, sizes, ages, spatial scales and regeneration cycles appropriate for the *landscape values** in that region, and for enhancing environmental and economic *resilience**.

6.9 *The Organization** shall not convert natural *forest** to *plantations**, nor natural forests or plantations on sites directly converted from natural forest to non-forest land use, except when the conversion:

a) affects a very limited portion of the area of the *Management Unit**, and

b) will produce clear, substantial, additional, secure long-term conservation benefits in the Management Unit, and

c) does not damage or threaten *High Conservation Values**, nor any sites or resources necessary to maintain or enhance those High Conservation Values.

6.10 *Management Units** containing *plantations** that were established on areas converted from *natural forest** after November 1994 shall not qualify for certification, except where:

a) clear and sufficient evidence is provided that *The Organization** was not directly or indirectly responsible for the conversion, or

b) the conversion affected a very limited portion of the area of the Management Unit and is producing clear, substantial, additional, secure long term conservation benefits in the Management Unit.

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Appendix B: Results from the LCI on wood production in the Pacific Northwest and the Southeast in the USA performed by Puettmann and Wilson

TABLE 4. *Cradle-to-gate, cumulative energy*[1] *(MJ/m^3) allocated to one cubic meter of structural wood products manufactured in the Pacific Northwest (PNW) and Southeast (SE) regions. Electricity production is included.*

	PNW					SE				
	Glulam	Lumber, KD	Lumber, green	LVL	Plywood	Glulam	Lumber, KD	LVL	Plywood	OSB
	MJ/m^3					MJ/m^3				
Harvesting	147	143	139	148	148	213	203	189	206	217
Product manufacturing	4,650	3,415	295	3,670	2,700	5,056	3,175	4,700	4,227	7,412
Resin production	409	0	0	755	699	584	0	1,048	1,021	3,126
Transportation[2]	161	147	113	112	90	391	114	219	196	390
TOTAL	5,367	3,705	548	4,684	3,638	6,244	3,492	6,156	5,649	11,145

[1] Energy values were determined for the fuel using their higher heating values (HHV) in units of MJ/kg as follows: coal 26.2, diesel 44.0, liquid petroleum gas 54.0, natural gas 54.4, crude oil 45.5, oven dry wood 20.9, and gasoline 48.4. Energy from uranium was determined as 381,000 MJ/kg and electricity at 3.6 MJ/kWh.

[2] Transportation of logs and other materials to production facilities.

TABLE 5. *Cradle-to-gate cumulative energy*[1] *requirements by fuel source (MJ/m^3) allocated to one cubic meter of structural wood products produced in the Pacific Northwest (PNW) and Southeast (SE) regions. Fuels for electricity production are included.*

	PNW					SE				
	Glulam	Lumber, KD	Lumber, green	LVL	Plywood	Glulam	Lumber, KD	LVL	Plywood	OSB
	MJ/m^3					MJ/m^3				
Coal	210	92	49	198	132	854	356	857	676	1,270
Crude oil	534	361	274	706	486	916	337	812	756	1,883
Natural gas	1,957	1,447	108	1,559	898	2,013	279	2,156	1,536	3,809
Uranium	30	7	4	15	10	84	35	63	50	114
Biomass	2,258	1,595	0	1,741	1,800	2,344	2,473	2,205	2,573	3,951
Hydropower	376	200	111	459	308	21	4	45	43	98
Electricity other	2	3	2	7	5	11	8	18	15	20
TOTAL	5,367	3,705	548	4,684	3,638	6,244	3,492	6,156	5,649	11,145

[1] Energy values were determined for the fuel using their higher heating values (HHV) in units of MJ/kg as follows: coal 26.2, natural gas 54.4, crude oil 45.5, and oven-dry wood (biomass) 20.9. Energy from uranium was determined at 381,000 MJ/kg and electricity at 3.6 MJ/kWh.

TABLE 6. *Cradle-to-gate cumulative emissions to air allocated to one cubic meter of structural wood products produced in the Pacific Northwest (PNW) and Southeast (SE) production regions; includes all life-cycle processes from forest regeneration through wood products production. Emissions resulting from transportation between life-cycle stages and with raw materials, fuels and electricity production are included.*

	PNW					SE				
	Glulam	Lumber, KD	Lumber, green	LVL	Plywood	Glulam	Lumber	LVL	Plywood	OSB
	kg/m^3					kg/m^3				
CO	2.00	1.43	0.22	1.29	1.24	2.07	1.83	1.78	1.90	1.79
CO_2 (biomass)	230	160	0.01	141	146	231	248	196	229	378
CO_2 (fossil)	126	92	27.13	87	56	199	62	170	128	294
HAPS	0.20	0.01	0.00	0.13	0.11	0.01	0.01	0.11	0.22	0.41
Methane	0.28	0.19	0.02	0.22	0.13	0.40	0.10	0.41	0.30	0.70
NO_2	0.92	0.67	0.31	0.69	0.57	1.26	0.64	1.11	0.95	1.52
Particulates	0.57	0.05	0.03	0.34	0.33	0.19	0.05	0.60	0.41	0.37
Particulates (unspecified)	0.04	0.01	0.01	0.02	0.01	0.09	0.04	0.09	0.07	0.12
SO_2	1.36	1.03	0.12	1.14	0.67	1.78	0.43	1.90	1.41	3.09
VOC's	0.31	0.08	0.03	0.32	0.34	1.14	0.49	0.04	0.16	1.06
Total	361.68	255.47	27.88	232.15	205.40	436.94	313.59	372.04	362.42	681.06

Tabel 1 GWP of the different GHG gasses (Duurzame Woningbouw – Vlaamse maatstaf voor duurzaam wonen en bouwen, 2011)

Greenhouse gas	GWP
Carbon dioxide CO_2	1
Methane CH_4	23
Nitrogen oxides NO_x	310
Hydrofluorcarbons HFCs	140 -11700
Perfluorcarbons PFKs	6500 - 9200
Sulfur hexafluoride SF_6	23 900

	Glulam		LVL	
	PNW	**SE**	**PNW**	**SE**
CO_2 emitted [kg/m³]	356	430	228	366
CH_4 emitted [kg/m³]	0,28	0,4	0,22	0,41
NO_2 emitted [kg/m³]	0,92	1,26	0,69	1,11
GWP [kg CO_2 eq/m³]	647,64	829,8	446,96	719,53
Total air-emissions [kg/m³]	361,68	436,94	232,15	372,04
Energy for product manufacturing [MJ/m³]	5.367	6.244	4.684	6.156
CO_2 eq emitted [kg/MJ]	0,1207	0,1329	0,0954	0,1169
Total air-emissions [kg/MJ]	0,0674	0,0700	0,0496	0,0604
Reduction in CO_2-emissions for 1 MJ used during manufacturing [%]	9,20	-	18,36	-
Reduction in air-emissions for 1 MJ used during manufacturing [%]	3,70	-	17,99	-

Appendix C: The material quantity data from the LCA performed on a multi-storey hotel for 3, 7, 12 and 21 stores by Skullestad J.L., Bohne R.A. , & Lohne J.

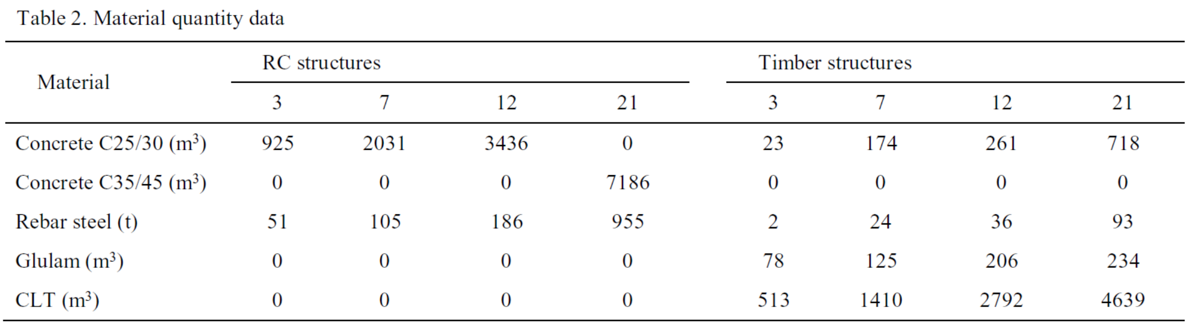


Table 2. Material quantity data

Material	RC structures				Timber structures			
	3	7	12	21	3	7	12	21
Concrete C25/30 (m³)	925	2031	3436	0	23	174	261	718
Concrete C35/45 (m³)	0	0	0	7186	0	0	0	0
Rebar steel (t)	51	105	186	955	2	24	36	93
Glulam (m³)	0	0	0	0	78	125	206	234
CLT (m³)	0	0	0	0	513	1410	2792	4639

Storeys		3	7	12	21
Concrete volume [m³]	Reinforced concrete	925	2031	3436	7186
	Timber	23	174	261	718
Percentage [%]		2,49	8,57	7,60	9,99

Appendix D: Comparative LCA between timber, mineral and hybrids multi-storey buildings performed by Hafner & Schäfer

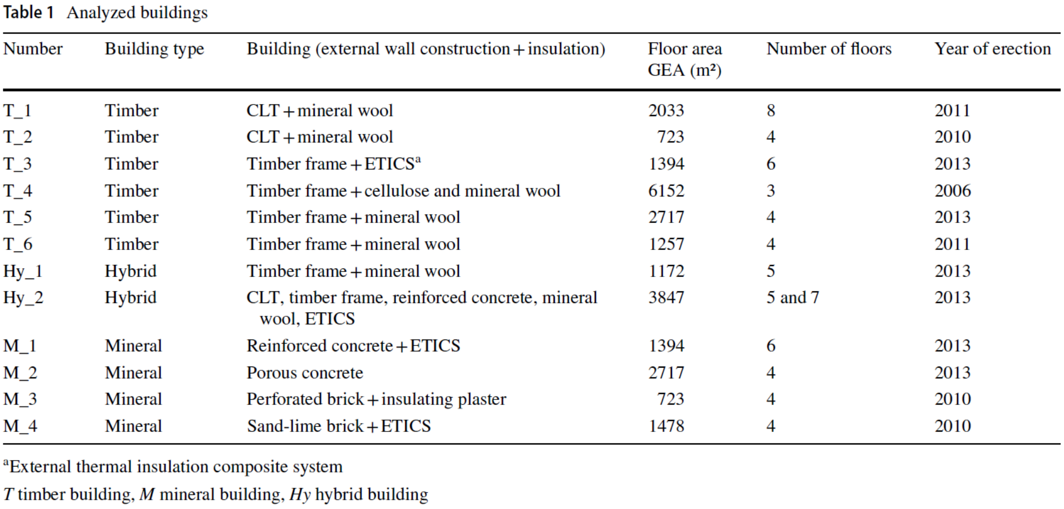
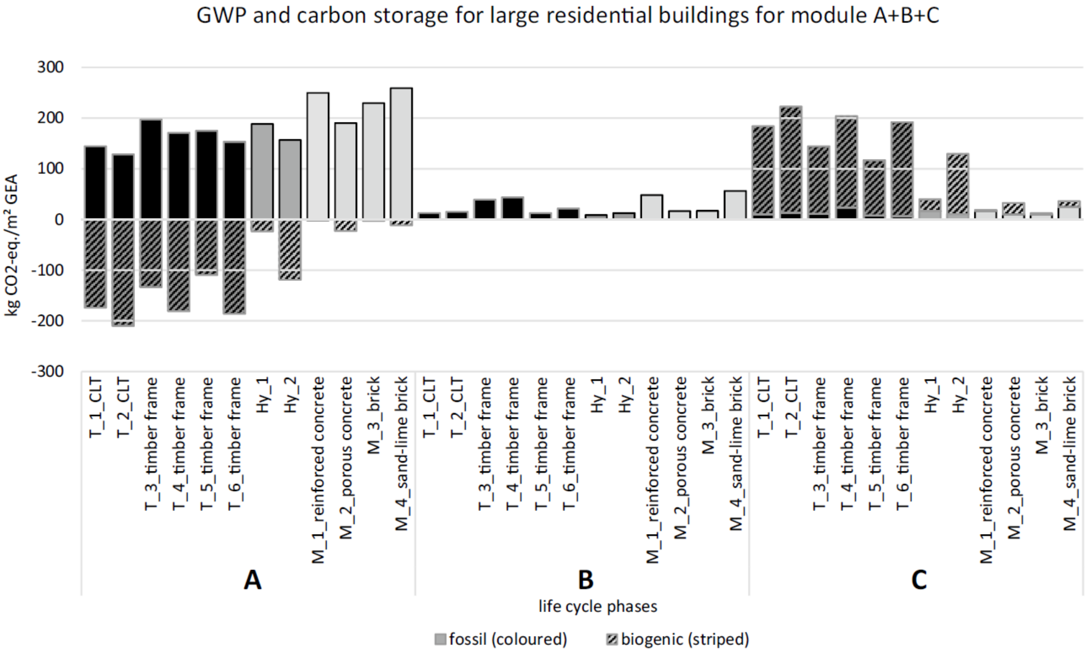


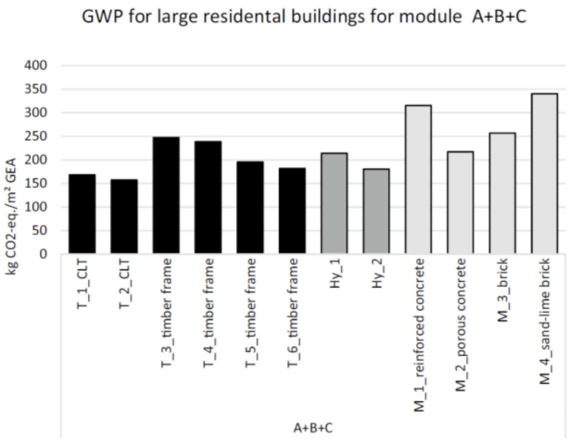
Table 1 Analyzed buildings

Number	Building type	Building (external wall construction + insulation)	Floor area GEA (m²)	Number of floors	Year of erection
T_1	Timber	CLT + mineral wool	2033	8	2011
T_2	Timber	CLT + mineral wool	723	4	2010
T_3	Timber	Timber frame + ETICS[a]	1394	6	2013
T_4	Timber	Timber frame + cellulose and mineral wool	6152	3	2006
T_5	Timber	Timber frame + mineral wool	2717	4	2013
T_6	Timber	Timber frame + mineral wool	1257	4	2011
Hy_1	Hybrid	Timber frame + mineral wool	1172	5	2013
Hy_2	Hybrid	CLT, timber frame, reinforced concrete, mineral wool, ETICS	3847	5 and 7	2013
M_1	Mineral	Reinforced concrete + ETICS	1394	6	2013
M_2	Mineral	Porous concrete	2717	4	2013
M_3	Mineral	Perforated brick + insulating plaster	723	4	2010
M_4	Mineral	Sand-lime brick + ETICS	1478	4	2010

[a] External thermal insulation composite system

T timber building, *M* mineral building, *Hy* hybrid building





Appendix E: Comparative LCA between timber and mineral multi-storey buildings performed by Hafner & Schäfer

A. Hafner, S. Schäfer / Journal of Cleaner Production 167 (2017) 630–642 635

Table 3
Analysed buildings: "Original" timber buildings and mineral counterparts. Buildings with first number 1 are single/two family houses; buildings starting with number 2 are multi-story residential buildings.

Number	Name	Year of construction	Construction + insulation	GEA [m^2]	floors	primary energy demand, [kwh/m^{2}a], rounded
2.2_T	Original	2013	Timber frame + ETICS	1394	(multi-residential building) G+5	39
2.2_M	Counterpart		Reinforced concrete + ETICS			
2.5_T	Original	2006	Timber frame + cellulose and mineral wool	6152	(multi-residential building) G+2	17
2.5_M	Counterpart		Perforated brick + ETICS			
2.6_T	Original	2013	Timber frame + mineral wool	2717	(multi-residential building) G+3	14
2.6_M	Counterpart		Porous concrete			
2.7_T	Original	2011	CLT + mineral wool	2033	(multi-residential building) G+7	10
2.7_M1	Counterpart		Porous concrete			
2.7_M2	Counterpart		Perforated brick + insulating plaster			
2.7_M3	Counterpart		Perforated brick + mineral wool (+facing brick*)			
2.9_T	Original	2011	Timber frame + mineral wool	1257	(multi-residential building) G+3	19
2.9_M	Counterpart		Sand-lime brick + ETICS			
2.10_T	Original	2010	CLT + mineral wool	723	(multi-residential building) G+3	20
2.10_M1	Counterpart		Porous concrete			
2.10_M2	Counterpart		Perforated brick + insulating plaster			
2.10_M3	Counterpart		Perforated brick + mineral wool (+facing brick*)			

*facing brick is part of the façade cladding (finishing element).

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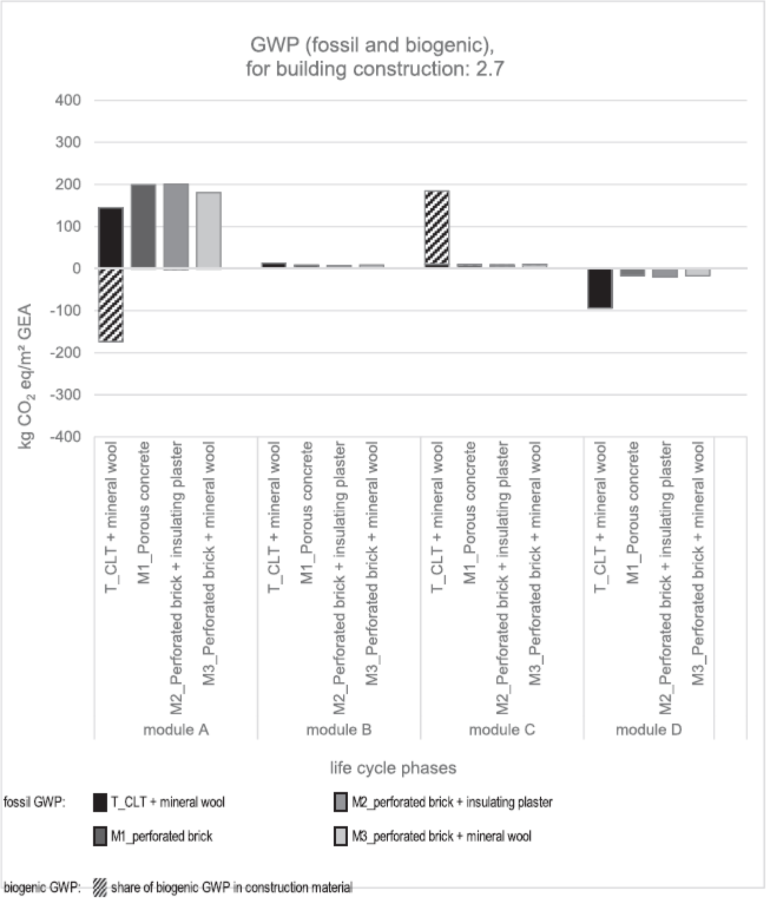


Fig. 3. LCA results (indicator GWP) for building construction 2.7 (multi-story residential building) divided in different lifecycle stages A, B, C and D. GWP is completely coloured and biogenic GWP is shaded.

Appendix F: Comparative LCA between three CLT-producers performed by Passarelli & Koshihara

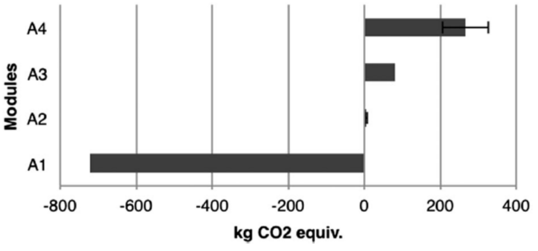


Figure 3. GWP of Company 1 for assessed modules A1–A3 (Production stage) and A4 Transport from factory to site (Construction stage).

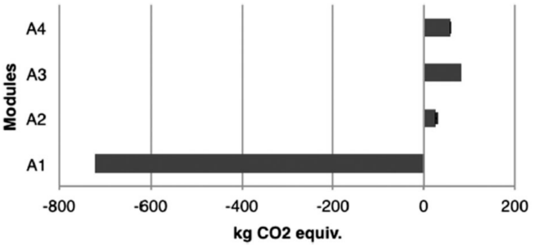


Figure 4. GWP of Company 2 for assessed modules A1–A3 (Production stage) and A4 Transport from factory to site (Construction stage).

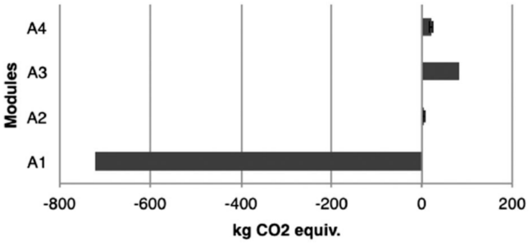


Figure 5. GWP of Company 3 for assessed modules A1–A3 (Production stage) and A4 Transport from factory to site (Construction stage).

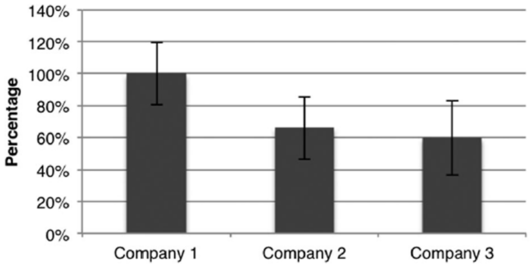
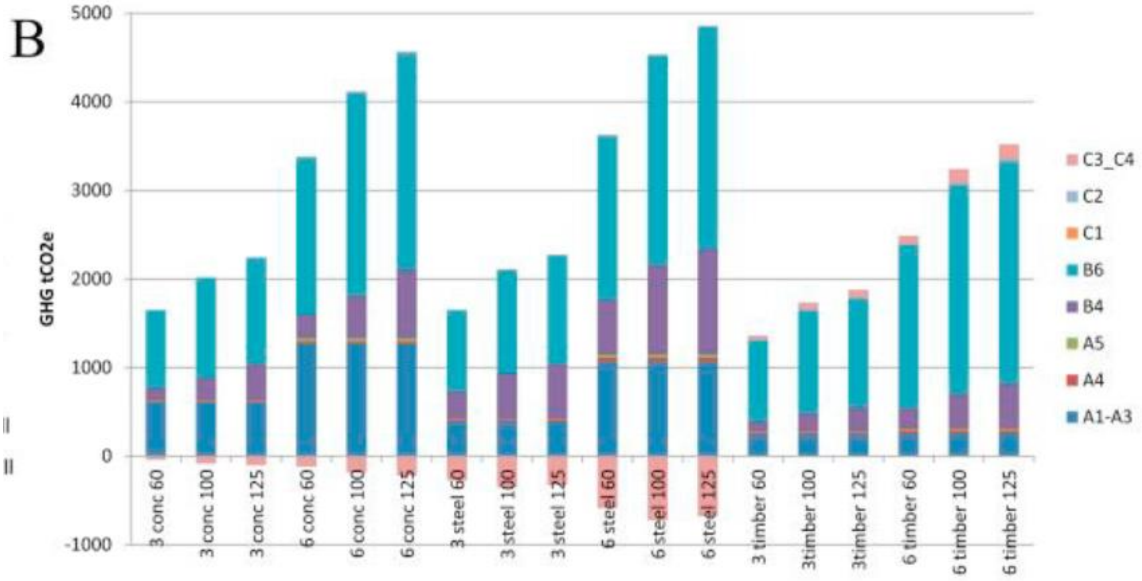


Figure 6. Aggregated GWP of assessed modules for Companies 1, 2 and 3 as a percentage of Company 1.

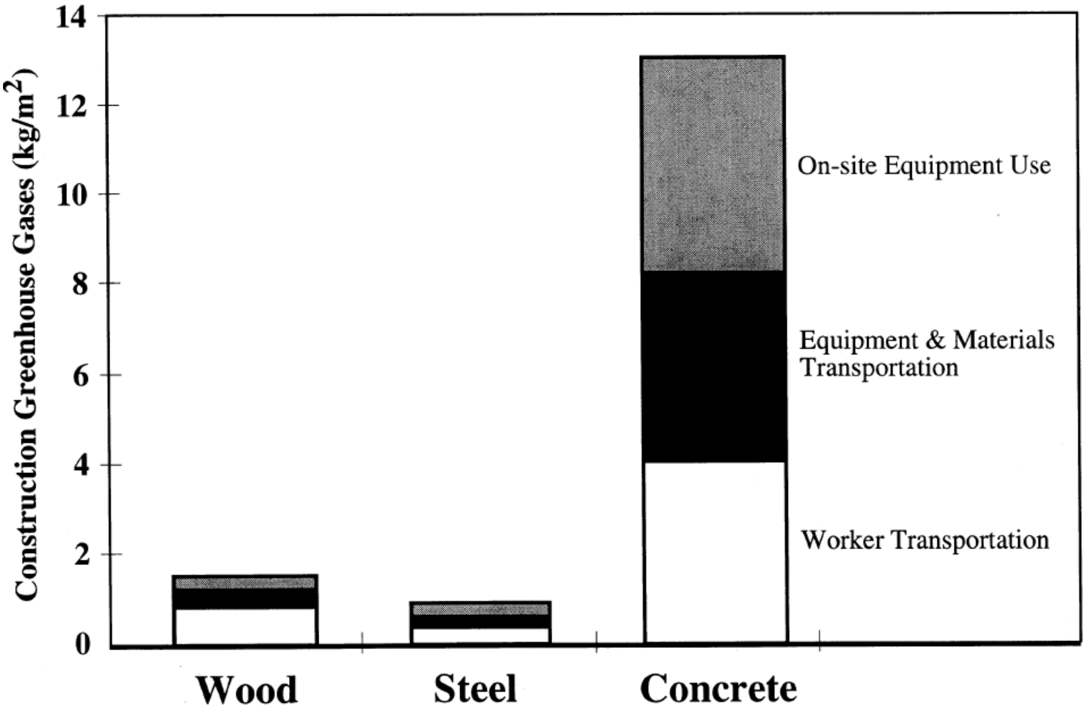
Appendix G: Result of comparative LCA between timber, steel and reinforced concrete construction for 3- and 6-storey for an apartment building performed by Din, A.U. & Brotas, L.

Table 1 Construction specification of each model

Structure	Timber	Steel	Concrete
stairs	wood	sheet steel	precast concrete
lift core	cement board	cement board	concrete block
foundation			
3st	450 concrete strip	concrete pad	600 concrete strip
6st	600 concrete strip	precast pile	precast pile
ground floor	concrete slab	concrete slab	concrete slab
party floor	timber I joists	steel web	hollowcore
ext wall	timber, insulation, sw boards	met sec, insulation, cement board	block, insulation, block
internal wall	timber	met sec	timber
windows	double glazed timber	double glazed timber	double glazed timber



Appendix H: Results from the study 'Energy and greenhouse gas emissions associated with the construction of alternative structural systems' performed by Raymond J. Cole



Appendix I: Results from the study 'Assessing Cross Laminated Timber (CLT) as an Alternative Material for Mid-Rise Residential Buildings in Cold Regions in China—A Life-Cycle Assessment Approach'

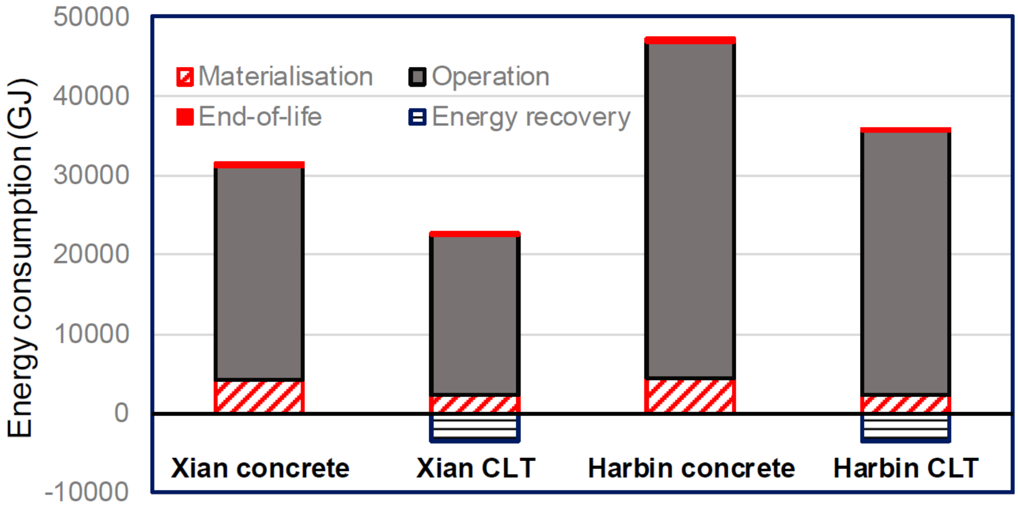


Figure 8. Comparison of energy consumption of concrete and CLT buildings in both cities

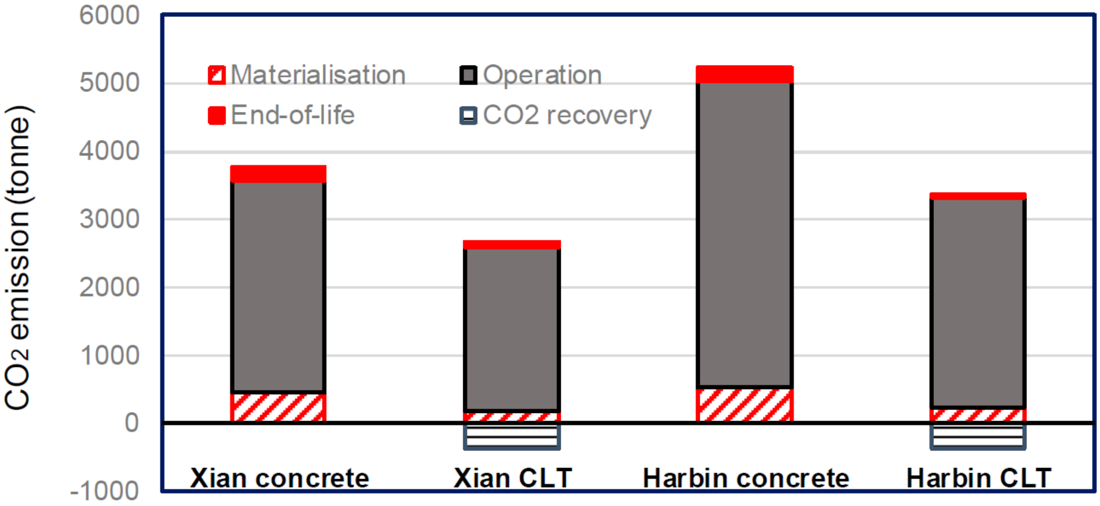


Figure 9. Comparison of CO_2 emissions of concrete and CLT buildings in both cities.

Appendix J: Results from the study ‘Effect of thermal mass on life cycle primary energy balances of a concrete- and a wood-frame building’

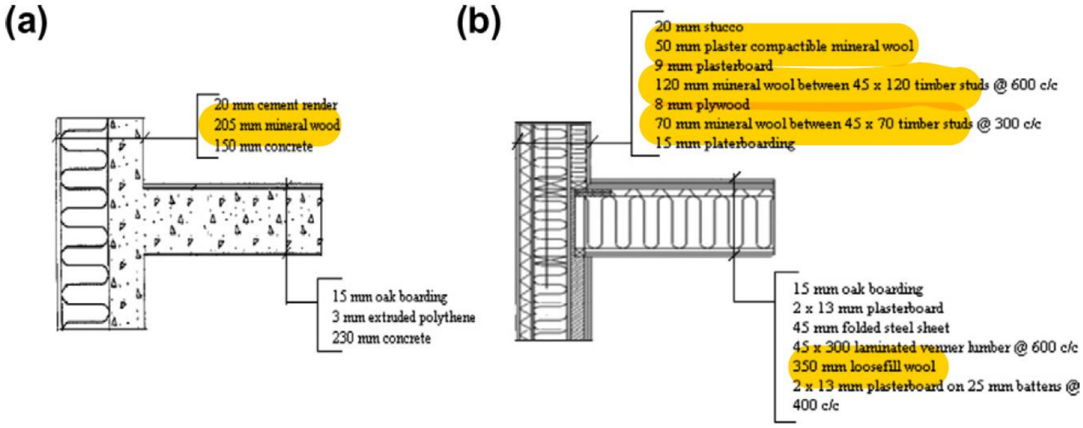


Fig. 2. Wall and floor construction details for the functionally equivalent (a) concrete-frame and (b) wood-frame reference building.

Table 4

Mass of principal materials used in the buildings, and the primary energy for the materials' production.

Material	Mass (kg of air-dry material/m^2)						Primary energy use (kW h/m^2)					
	Reference		Current code		Passive standard		Reference		Current code		Passive standard	
	Concrete frame	Wood frame	Concrete frame	Wood frame	Concrete frame	Wood frame	Concrete frame	Wood frame	Concrete frame	Wood frame	Concrete frame	Wood frame
Concrete	1136	187	1142	193	1144	195	292	48	293	50	293	50
Iron/steel	21	13	21	13	21	13	187	116	187	116	187	116
Lumber	28	50	28	57	28	59	34	61	34	70	34	72
Particle board	15	15	15	15	15	15	42	44	42	43	42	43
Plywood	17	18	17	18	17	18	78	84	78	84	78	84
Insulation	8	18	19	28	20	31	29	62	67	100	70	110
Plasteboard	21	75	21	75	21	76	27	96	27	97	27	97
Crushed stone	265	265	270	270	271	271	6	6	6	6	6	6
Mortar	19	21	20	21	20	21	7	7	7	7	7	7
Blocks	3	3	3	3	3	3	3	3	3	3	3	3
Glass	3	3	5	5	5	5	9	9	13	13	13	13
Paper	2	2	2	2	2	2	16	16	16	16	16	16
Paint	1	1	1	1	1	1	5	5	7	7	7	7
Putty/fillers	3	3	3	3	3	3	8	8	8	8	8	8
White goods	2	2	2	2	2	2	8	8	8	8	8	8
Porcelain	1	1	1	1	1	1	3	3	3	3	3	3
Copper/zinc	1	1	1	1	1	1	3	3	3	3	3	3
Krypton	0	0	<1	<1	<1	<1	0	0	<1	<1	<1	<1
Lowe-coating	0	0	<1	<1	<1	<1	0	0	<1	<1	<1	<1

Table 6

Annual final energy use for space heating (kW h/m^2) of the buildings at different locations.

Location	Reference			Current code			Passive standard		
	Concrete frame	Wood frame	Difference	Concrete frame	Wood frame	Difference	Concrete frame	Wood frame	Difference
Växjö	68.30	68.95	0.65	23.92	24.32	0.40	14.73	15.08	0.35
Östersund	93.65	94.27	0.62	37.66	38.16	0.50	24.51	24.95	0.44
Kiruna	129.43	130.08	0.65	57.77	58.12	0.35	39.74	40.15	0.41

Table 8

Annual primary energy use for operation (kW h/m^2) for buildings located in Växjö.

Description	Reference		Current code		Passive standard	
	Concrete frame	Wood frame	Concrete frame	Wood frame	Concrete frame	Wood frame
Electric resistance heated						
Space heating	203.9	205.9	71.4	72.6	44.0	45.0
Ventilation electricity	12.1	12.1	25.4	25.4	25.4	25.4
Tap water heating	74.5	74.5	44.7	44.7	44.7	44.7
Household electricity	133.7	133.7	133.7	133.7	133.7	133.7
Total from operation	424.2	426.2	275.2	276.4	247.8	248.8
Heat pump heated						
Space heating	76.1	76.8	26.7	27.1	16.4	16.8
Ventilation electricity	12.1	12.1	25.4	25.4	25.4	25.4
Tap water heating	28.1	28.1	16.8	16.8	16.8	16.8
Household electricity	133.7	133.7	133.7	133.7	133.7	133.7
Total from operation	249.9	250.7	202.6	203.1	192.4	192.8
District heated						
Space heating	45.4	45.8	15.9	16.2	9.8	10.0
Ventilation electricity	12.1	12.1	25.4	25.4	25.4	25.4
Tap water heating	16.6	16.6	9.9	9.9	9.9	9.9
Household electricity	133.7	133.7	133.7	133.7	133.7	133.7
Total from operation	207.7	208.1	184.9	185.2	178.8	179.1

Appendix K: Results from the study ‘Energy Saving and Carbon Reduction in the Operation Stage of Cross Laminated Timber Residential Buildings in China’

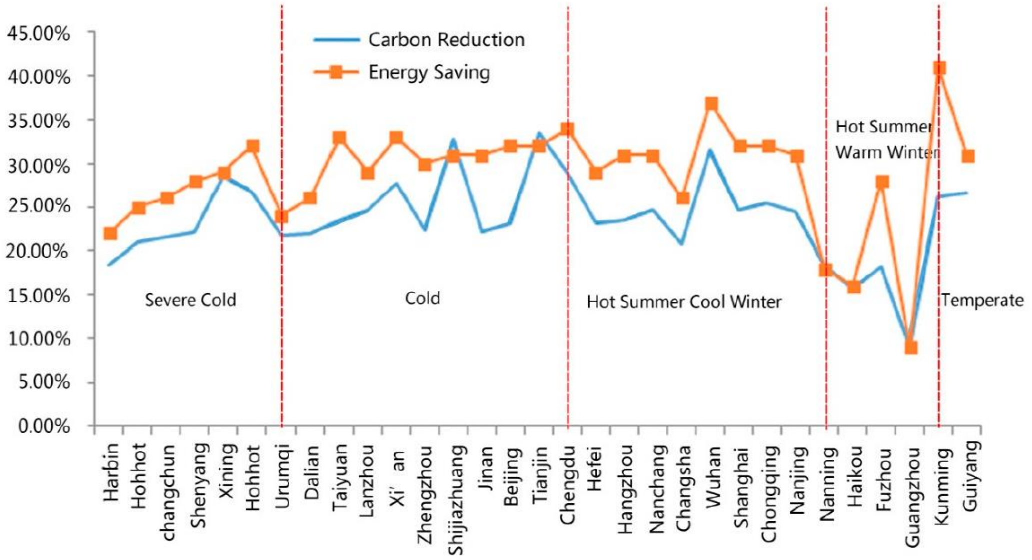


Figure 11. Carbon reduction and energy saving performance of CLT buildings.

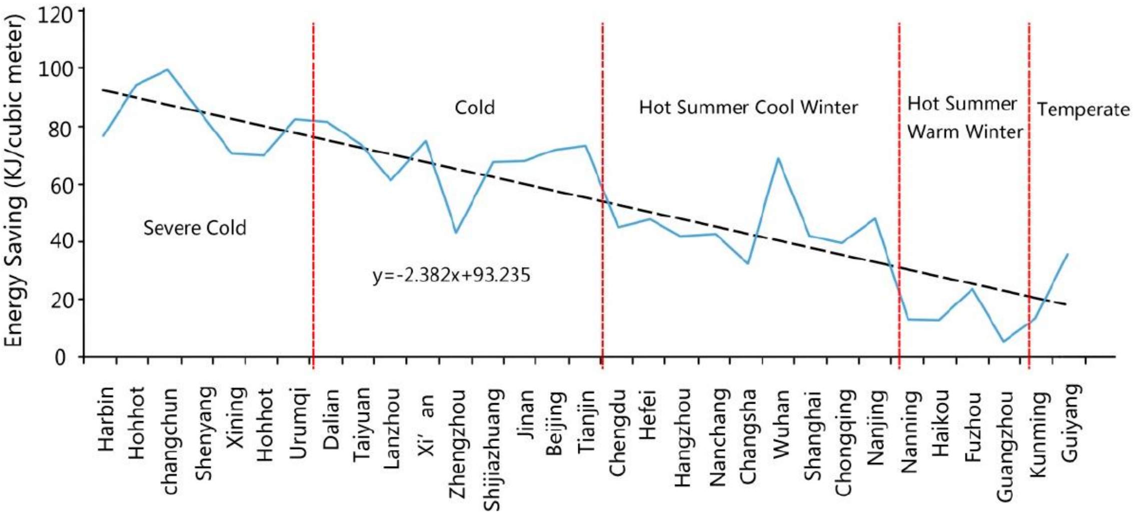


Figure 12. Energy savings of 1 cubic meter CLT in 31 key cities.

Appendix L: Results from 'Assessment of Energy Saving Potential by Replacing Conventional Materials by Cross Laminated Timber (CLT)—A Case Study of Office Buildings in China'

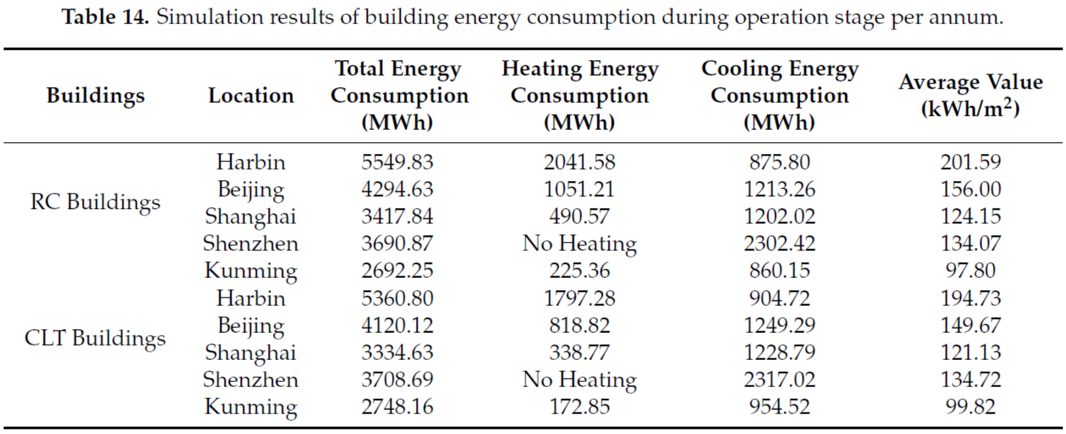


Table 14. Simulation results of building energy consumption during operation stage per annum.

Buildings	Location	Total Energy Consumption (MWh)	Heating Energy Consumption (MWh)	Cooling Energy Consumption (MWh)	Average Value (kWh/m^2)
RC Buildings	Harbin	5549.83	2041.58	875.80	201.59
	Beijing	4294.63	1051.21	1213.26	156.00
	Shanghai	3417.84	490.57	1202.02	124.15
	Shenzhen	3690.87	No Heating	2302.42	134.07
	Kunming	2692.25	225.36	860.15	97.80
CLT Buildings	Harbin	5360.80	1797.28	904.72	194.73
	Beijing	4120.12	818.82	1249.29	149.67
	Shanghai	3334.63	338.77	1228.79	121.13
	Shenzhen	3708.69	No Heating	2317.02	134.72
	Kunming	2748.16	172.85	954.52	99.82

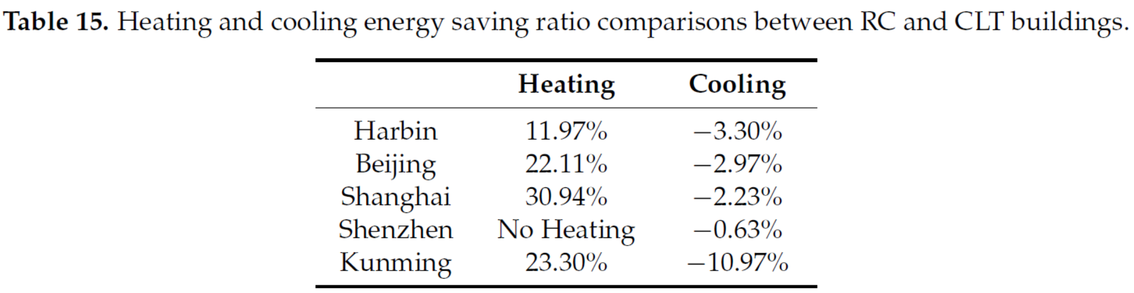


Table 15. Heating and cooling energy saving ratio comparisons between RC and CLT buildings.

	Heating	Cooling
Harbin	11.97%	−3.30%
Beijing	22.11%	−2.97%
Shanghai	30.94%	−2.23%
Shenzhen	No Heating	−0.63%
Kunming	23.30%	−10.97%

Appendix M: Differences in GWP for harvested and recovered wood – from 'Energy and carbon balances of wood cascade chains' of Sathre, R. & Gustavsson, L.

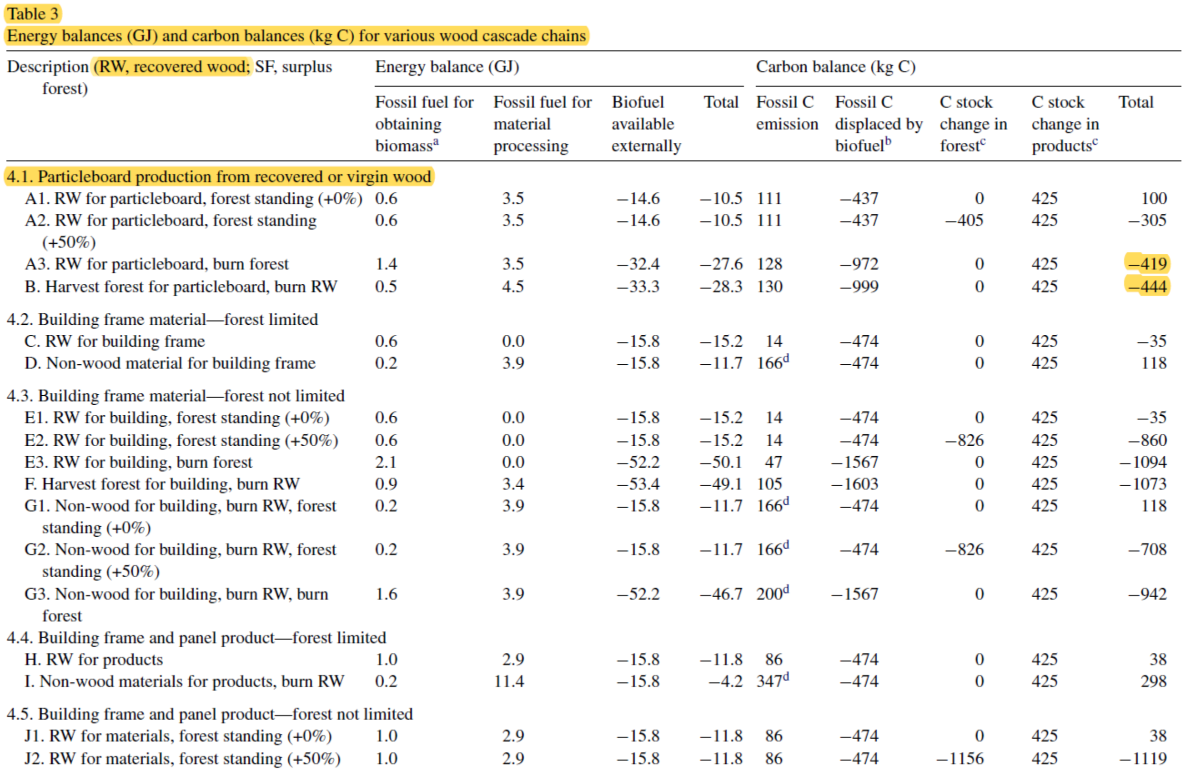


Table 3

Energy balances (GJ) and carbon balances (kg C) for various wood cascade chains

Description (RW, recovered wood; SF, surplus forest)	Energy balance (GJ)				Carbon balance (kg C)				
	Fossil fuel for obtaining biomass^{a}	Fossil fuel for material processing	Biofuel available externally	Total	Fossil C emission	Fossil C displaced by biofuel^{b}	C stock change in forest^{c}	C stock change in products^{c}	Total
4.1. Particleboard production from recovered or virgin wood									
A1. RW for particleboard, forest standing (+0%)	0.6	3.5	−14.6	−10.5	111	−437	0	425	100
A2. RW for particleboard, forest standing (+50%)	0.6	3.5	−14.6	−10.5	111	−437	−405	425	−305
A3. RW for particleboard, burn forest	1.4	3.5	−32.4	−27.6	128	−972	0	425	−419
B. Harvest forest for particleboard, burn RW	0.5	4.5	−33.3	−28.3	130	−999	0	425	−444
4.2. Building frame material—forest limited									
C. RW for building frame	0.6	0.0	−15.8	−15.2	14	−474	0	425	−35
D. Non-wood material for building frame	0.2	3.9	−15.8	−11.7	166^{d}	−474	0	425	118
4.3. Building frame material—forest not limited									
E1. RW for building, forest standing (+0%)	0.6	0.0	−15.8	−15.2	14	−474	0	425	−35
E2. RW for building, forest standing (+50%)	0.6	0.0	−15.8	−15.2	14	−474	−826	425	−860
E3. RW for building, burn forest	2.1	0.0	−52.2	−50.1	47	−1567	0	425	−1094
F. Harvest forest for building, burn RW	0.9	3.4	−53.4	−49.1	105	−1603	0	425	−1073
G1. Non-wood for building, burn RW, forest standing (+0%)	0.2	3.9	−15.8	−11.7	166^{d}	−474	0	425	118
G2. Non-wood for building, burn RW, forest standing (+50%)	0.2	3.9	−15.8	−11.7	166^{d}	−474	−826	425	−708
G3. Non-wood for building, burn RW, burn forest	1.6	3.9	−52.2	−46.7	200^{d}	−1567	0	425	−942
4.4. Building frame and panel product—forest limited									
H. RW for products	1.0	2.9	−15.8	−11.8	86	−474	0	425	38
I. Non-wood materials for products, burn RW	0.2	11.4	−15.8	−4.2	347^{d}	−474	0	425	298
4.5. Building frame and panel product—forest not limited									
J1. RW for materials, forest standing (+0%)	1.0	2.9	−15.8	−11.8	86	−474	0	425	38
J2. RW for materials, forest standing (+50%)	1.0	2.9	−15.8	−11.8	86	−474	−1156	425	−1119

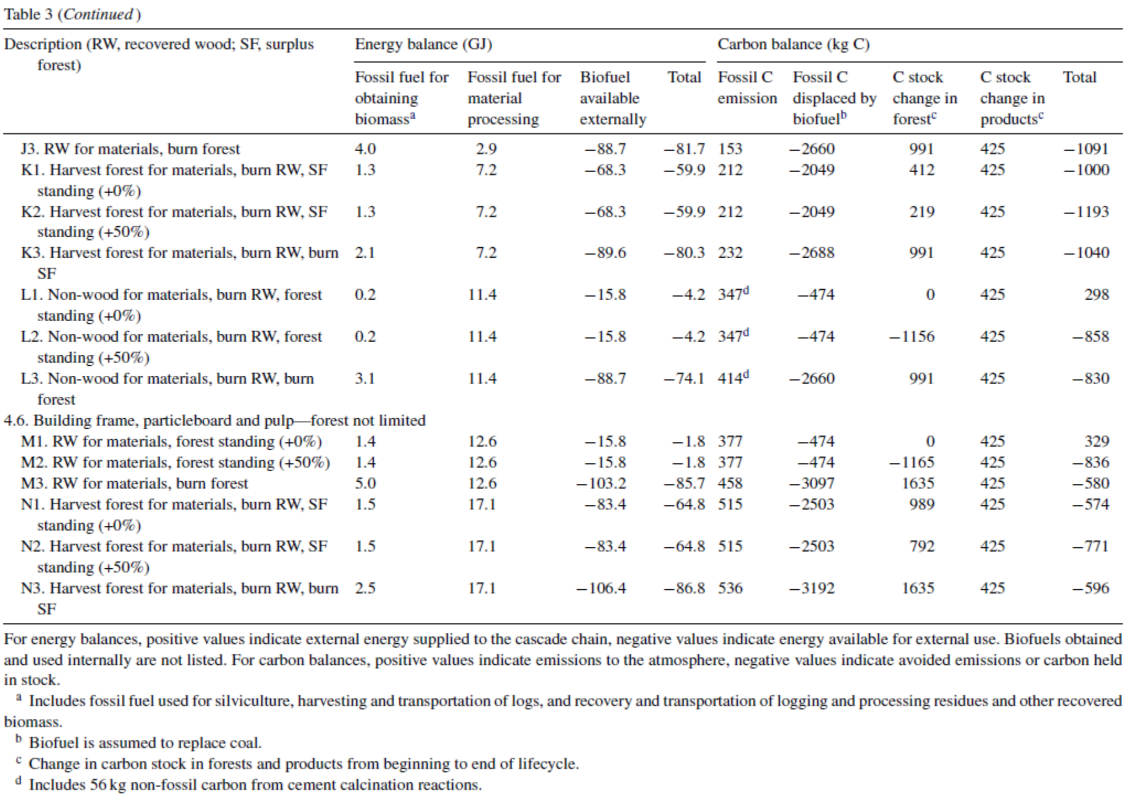


Table 3 (*Continued*)

Description (RW, recovered wood; SF, surplus forest)	Energy balance (GJ)				Carbon balance (kg C)				
	Fossil fuel for obtaining biomass[a]	Fossil fuel for material processing	Biofuel available externally	Total	Fossil C emission	Fossil C displaced by biofuel[b]	C stock change in forest[c]	C stock change in products[c]	Total
J3. RW for materials, burn forest	4.0	2.9	−88.7	−81.7	153	−2660	991	425	−1091
K1. Harvest forest for materials, burn RW, SF standing (+0%)	1.3	7.2	−68.3	−59.9	212	−2049	412	425	−1000
K2. Harvest forest for materials, burn RW, SF standing (+50%)	1.3	7.2	−68.3	−59.9	212	−2049	219	425	−1193
K3. Harvest forest for materials, burn RW, burn SF	2.1	7.2	−89.6	−80.3	232	−2688	991	425	−1040
L1. Non-wood for materials, burn RW, forest standing (+0%)	0.2	11.4	−15.8	−4.2	347[d]	−474	0	425	298
L2. Non-wood for materials, burn RW, forest standing (+50%)	0.2	11.4	−15.8	−4.2	347[d]	−474	−1156	425	−858
L3. Non-wood for materials, burn RW, burn forest	3.1	11.4	−88.7	−74.1	414[d]	−2660	991	425	−830
4.6. Building frame, particleboard and pulp—forest not limited									
M1. RW for materials, forest standing (+0%)	1.4	12.6	−15.8	−1.8	377	−474	0	425	329
M2. RW for materials, forest standing (+50%)	1.4	12.6	−15.8	−1.8	377	−474	−1165	425	−836
M3. RW for materials, burn forest	5.0	12.6	−103.2	−85.7	458	−3097	1635	425	−580
N1. Harvest forest for materials, burn RW, SF standing (+0%)	1.5	17.1	−83.4	−64.8	515	−2503	989	425	−574
N2. Harvest forest for materials, burn RW, SF standing (+50%)	1.5	17.1	−83.4	−64.8	515	−2503	792	425	−771
N3. Harvest forest for materials, burn RW, burn SF	2.5	17.1	−106.4	−86.8	536	−3192	1635	425	−596

For energy balances, positive values indicate external energy supplied to the cascade chain, negative values indicate energy available for external use. Biofuels obtained and used internally are not listed. For carbon balances, positive values indicate emissions to the atmosphere, negative values indicate avoided emissions or carbon held in stock.

[a] Includes fossil fuel used for silviculture, harvesting and transportation of logs, and recovery and transportation of logging and processing residues and other recovered biomass.

[b] Biofuel is assumed to replace coal.

[c] Change in carbon stock in forests and products from beginning to end of lifecycle.

[d] Includes 56 kg non-fossil carbon from cement calcination reactions.

Appendix N: The relative differences in operational energy consumption and GWP

	Operational Energy consumption [kWh/m²]			Relative difference [%]	
	Concrete	Timber	Steel	Timber/Concrete	Timber/Steel
(Guo et al, 2017)	6916,7	6314,1		8,71	
	6698,7	6121,8		8,61	
	6596,2	6025,6		8,65	
	6532,1	5967,9		8,64	
(Buchanan et al, 2012)	1238,9	1223,7	1260,1	1,23	2,89
(John et al, 2008)	1156,1	1215,2	1177,3	-5,11	-3,22
(Din & Brotas, 2017)	948,4	992,42		-4,64	
	965,47	1009,48		-4,56	
	1224,4	1264,89		-3,31	
	1250	1290,49		-3,24	
	1299,27	1338,56		-3,02	
	1329,14	1368,42		-2,96	
(Gong et al, 2012)	348,84	347,05	352,42	0,51	1,52
(Bowick, 2018)	1542,3	1617,1		-4,85	

Reference	Annual operational energy usage [kWh/m²/year]			Relative difference [%]	
	Concrete	Timber	Steel	Timber-Concrete	Timber-Steel
(Dodoo & Gustavsson, 2016)	60	41,3		31,17	
(Guo et al, 2017)	190,63	174,75		8,33	
	185,11	170,12		8,10	
	182,44	167,56		8,16	
	180,77	166,03		8,15	
(Dodoo et al, 2012)	68,3	68,92		-0,91	
	93,65	94,27		-0,66	
	129,43	130,08		-0,50	
(Khavari et al, 2016) (HVAC)	17	14,3		15,88	
(Khavari et al, 2016) (B6)	144,96	137,62		5,06	
(Liu et al, 2016)	50,18	30,4		39,42	
	75,11	51,38		31,59	
(Dong et al, 2019) (B6)	201,59	194,73		3,40	
	156	149,67		4,06	
	124,15	121,13		2,43	
	134,07	134,72		-0,48	
	97,8	99,82		-2,07	
(Dong et al, 2019) (HVAC)	105,98	98,15		7,39	
	82,26	75,12		8,68	
	61,48	56,94		7,38	
	83,63	84,16		-0,63	
	39,43	40,95		-3,85	
(Chen, 2012)	123,35	121,8		1,26	
(Bowick, 2018)	224,14	205,05		8,52	
(Buchanan et al, 2012) HVAC	38,84	37,58	38,18	3,24	1,57
	24,44	24,65	24,75	-0,86	0,40
(Buchanan et al, 2012) B6	53,39	52,13	52,73	2,36	1,14
	38,93	39,14	39,24	-0,54	0,25
(John et al, 2008)	84,72	87,96	85,65	-3,82	-2,70
(Pal et al, 2017)	111,65	108,35	115,6	2,96	6,27
(Cole & Kernan, 1996)	354,11	352	356,56	0,60	1,28
	551,61	549,5	554,06	0,38	0,82
(Gong et al, 2012)	70,96	75,83	65,89	-6,86	-15,09

Timber-concrete = **[**1-[(energy consumption)$_{\text{Timber}}$/ (energy consumption)$_{\text{Concrete}}$] **]** x 100

Timber-steel = **[**1-[(energy consumption)$_{\text{Timber}}$/ (energy consumption)$_{\text{steel}}$] **]** x 100

Appendix O: Relative difference in operational energy consumption ranged from colder to hotter climates

Reference	Average temperature coldest month - hottest month	Location	Relative difference [%]	
			Timber-Concrete	Timber-Steel
(Dodoo et al, 2012)	-12 - 13°C	Kiruna, Sweden	-0,50	
(Dong et al, 2019)	-18 - 23 °C	Harbin, China	3,40	
(Dodoo et al, 2012)	-6 - 15°C	Östersund, Sweden	-0,66	
(Pal et al, 2017)	-4 - 18°C	Helsinki, Finland	2,96	6,27
(Dodoo et al, 2012)	-1 - 17°C	Växjö, Sweden	-0,91	
(Chen, 2012)	4 - 18°C	Vancouver, Canada	1,26	
(Bowick, 2018)			8,52	
(Buchanan et al, 2012)	6-17°C	New-Zealand	2,36	1,14
			-0,54	0,25
(John et al, 2008)		Christchurch, New-Zealand	-3,82	-2,70
(Gong et al, 2012)	-3 - 27°C	Beijing, China	-6,86	-15,09
(Dong et al, 2019)		Beijing, China	4,06	
(Dong et al, 2019)	10 - 21°C	Kunming, China	-2,07	
(Dong et al, 2019)	5 - 29 °C	Shangai, China	2,43	
	16 - 29°C	Shenzhen, China	-0,48	

Appendix P: The relative differences in the GWP during the C- and D-stage

End-of-Life scenario	Reference	'C+D'-GWP [kg CO2 eq/m²]			Relative difference [%]	
		Concrete	Timber	Steel	Timber-Concrete	Timber-Steel
Combustion for energy	(Tettey et al, 2019)	-157	-336		114,01	
		-157	-198		26,11	
		-132	-212		60,61	
		-132	-127		-3,79	
	(John et al, 2008)	31,8	2,6	-56,7	91,82	-104,6
	(Dodoo et al, 2009)	-9	-4		-55,56	
	(Bowick, 2018)	16,7	13		22,16	
50% energy recovery 50% recycled	(Guo et al, 2017)	18	45,6		-153,33	
		18	46,5		-158,33	
		18	52		-188,89	
		18	52,3		-190,56	
Landfill + recycling	(Din & Brotas, 2017)	-30,9	65,3	-288,8	-311,33	-122,61
		-54,4	56,1	-313,4	-203,13	-117,90
		-75,3	98,6	-372,5	-230,94	-126,47
		-89,1	98,6	-387,7	-210,66	-125,43
		-95,7	109,5	-343,2	-214,42	-131,91
		-107	105,9	-361,7	-198,97	-129,28
Landfill	(Buchanan et al,	16,7	89,9	-64,6	-438,32	-239,2
	(John et al, 2008)	39,6	124,6	22,4	-214,65	-456,3

$$\text{Timber-concrete} = [1-(GWP_{timber}/GWP_{concrete})] \times 100$$

$$\text{Timber-steel} = [1-(GWP_{timber}/GWP_{steel})] \times 100$$

Appendix Q: The differences in overall GWP

	GWP [kg CO_2 eq/m²]			Relative difference [%]	
	Concrete	Timber	Steel	Timber/Concrete	Timber/Steel
(Guo et al, 2017)	7242,9	6275,7		13,35	
	7009,3	6082,6		13,22	
	6884,2	5980,7		13,12	
	6815,4	5922,8		13,10	
(Tettey et al, 2019)	472	-566		219,92	
	472	-15		103,18	
	378	-311		182,28	
	378	33		91,27	
(Bowick, 2018)	1968	1944,4		1,20	
(Liu et al, 2016)	1870	1070		42,78	
	1870	990		47,06	
	1350	820		39,26	
	1350	730		45,93	
(Lu et al, 2017)	260,4	47,1	189,1	81,91	75,09
	260,4	75,8	189,1	70,89	59,92
	260,4	61,7	189,1	76,31	67,37
(John et al, 2008)	1599,7	1408,5	1620,7	11,95	13,09
	1596,9	1415,1	1546,3	11,38	8,48
(Buchanan et al, 2012)	1462,1	1338,9	1456,6	8,43	8,08
(Din & Brotas, 2017)	1762,3	1488,8	1506,9	15,52	1,20
	1785,8	1361	1662,3	23,79	18,13
	2117,5	1894,8	1921,7	10,52	1,40
	2152,1	1773,2	2083,3	17,61	14,89
	2341,9	2055,2	2131,3	12,24	3,57
	2377,8	1925,5	2286,2	19,02	15,78
(Townsend & Wagner, n.d.)		112,8	348,7		67,65
		-153,8	348,7		144,11

Appendix R: Relative differences in GWP ranged by their end-of-life scenario

Reference	End-of-Life scenario	Relative difference [%]	
		Timber/Concrete	Timber/Steel
(Townsend & Wagner, n.d.)	ER		144,11
(Tettey et el, 2019)		219,92	
		103,18	
		182,28	
		91,27	
(John et al, 2008)		11,95	13,09
		11,38	8,48
(Guo et al, 2017)	50% R; 50% ER	13,35	
		13,22	
		13,12	
		13,10	
(Liu et al, 2016)	55% R; 45% ER	42,78	
		39,26	
(Liu et al, 2016)	90% R	47,06	
		45,93	
(Din & Brotas, 2017)	R+L	15,52	1,20
		23,79	18,13
		10,52	1,40
		17,61	14,89
		12,24	3,57
		19,02	15,78
(Bowick, 2018)	L + ER	1,2	
(Buchanan et al, 2012)		8,43	8,08

Appendix S: GHG emissions from [tonnes CO_2 eq] from UK apartment construction impact on carbon life cycle calculations

	A1-A3	A4	A5	B4	B6	C1	C2	C3_C4	
3 conc 60	606,2114	14,65244	10,96499	140,2794	866,8361	2,80704	11,53523	-42,5793	1610,707
3 conc 100	606,2114	14,65244	10,96499	253,3096	1119,102	2,80704	12,31232	-83,9702	1935,389
3 conc 125	606,2114	14,65244	10,96499	408,6062	1187,532	2,80704	14,20121	-104,512	2140,464
6 conc 60	1268,193	23,43891	36,79078	270,5233	1764,872	5,61408	15,26948	-120,237	3264,465
6 conc 100	1268,193	23,43891	36,79078	483,531	2285,003	5,61408	16,36571	-184,854	3934,084
6 conc 125	1268,193	23,43891	36,79078	784,0888	2429,665	5,61408	19,50803	-220,694	4346,605
3 steel 60	385,5578	18,9514	9,82724	319,8588	907,0733	1,87136	10,43455	-276,257	1377,318
3 steel 100	385,5578	18,9514	9,82724	526,4206	1156,105	1,87136	11,00065	-353,33	1756,404
3 steel 125	385,5578	18,9514	9,82724	623,9316	1223,44	1,87136	11,54298	-327,113	1948,009
6 steel 60	1063,214	47,5595	34,51528	620,8219	1845,347	3,74272	13,00503	-589,586	3038,619
6 steel 100	1063,214	47,5595	34,51528	1012,637	2359,011	3,74272	13,44912	-725,86	3808,269
6 steel 125	1063,214	47,5595	34,51528	1193,492	2501,48	3,74272	13,7564	-678,643	4179,118
3 timber 60	243,2772	20,25158	9,82724	122,2908	907,0733	1,87136	9,992127	46,15022	1360,734
3timber 100	243,2772	20,25158	9,82724	212,2289	1156,105	1,87136	11,60594	76,65559	1731,823
3timber 125	243,2772	20,25158	9,82724	281,6177	1223,44	1,87136	12,61662	85,57469	1878,477
6 timber 60	251,2583	33,92156	19,65448	235,1002	1845,347	3,74272	10,77483	88,04859	2487,847
6 timber 100	251,2583	33,92156	19,65448	396,8488	2359,011	3,74272	14,37689	162,5652	3241,379
6 timber 125	251,2583	33,92156	19,65448	519,8141	2501,48	3,74272	16,01146	173,8738	3519,757