Global Warming Potential of multi-storey timber buildings

State-of-the-art review

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Extended Abstract of the Master Thesis in Civil Engineering

1. Introduction

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 this time of writing[1] the world population totals a number of 7.708 billion [1]. 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 [2]. 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 [3]. The amount of proper living units and work units will have to increase along with the growing population.

Not only should the amount of living units and work units increase, they also have to be built more concentrated. The amount of people living in rural areas decrease and the amount living in urban areas increases. 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 this share will grow to 60% by 2030 and 66% by 2050. The UN also states that nearly the complete global population growth between 2017 and 2030 will be absorbed by the cities [4] [5]. The problem of a growing population living on a smaller scale has been solved throughout history by building multi-storey constructions. High-rise buildings mainly consist from building materials such as reinforced concrete and steel, two materials with a significant carbon footprint which gets to the third problem, namely global warming. The global construction sector emits 23% of the CO_2 emissions produced by the global economic activities [6]. Since high-rise buildings contain more materials, their production emits more masses of CO_2. Especially cause materials as steel and reinforced concrete are very common in multi-story buildings because of their strength. The production of cement, the raw material needed to produce concrete, accounts for approximately 8% of the global CO_2-emissions [7]. In order for the building industry to lower its carbon emissions it should shift to 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. Whereas steel and cement emit CO_2 during their production. So initially timber has a negative carbon footprint.

Since the mid 1990's, a new structural product made its entrance to the market, CLT (cross laminated timber). This material in combination with other EWP's (Engineered Wood Products) such as glulam and LVL made wooden high-rise buildings possible. The rising consciousness about global warming and the development of CLT has led to the idea of building high-rise constructions using timber as the structural material. In 2015 a residential building in Norway, Treet was completed. It is a 14-storey building with a load-bearing structure made of wood reaching a height of 49 m [8]. Currently research is carried out on hybrid wooden skyscrapers with an approximate height of 300 m [9].

[1] 2 June 2019
[2] By the United Nations in 2005

2. Objective and method

2.1 Objective

The last decade, research has been carried out to the ecological benefits of timber as the main building material. 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. The main goal of this paper is making a state-of-art-review, about the difference in GWP of multi-storey buildings when built with timber instead of concrete or steel.

2.2 Method & Data collection

To achieve the objective, a meta-analysis review is performed on the existing research concerning timber multi-storey buildings. The set tasks for this research are the following:

1) Comparing the GHG emissions from both timber materials and multi-storey buildings with their steel and concrete counterparts during the different life-stages of the LCA. Buildings will be compared during the production (A) and operational (B) phase. The materials during their production (A) phase. For this comparison it will be verified if multi-story buildings emit less GHG's when realized in timber. The relative differences in GWP's will be ranged according to their end-of-life scenario to determine which scenario results in the greatest reductions in GHG emissions.

2) Comparing the GHG emissions from both timber materials and buildings with their steel and concrete counterparts for their full lifecycle. It will be verified if it can be stated if multi-story buildings emit less GHG's when realized with timber in their full lifetime.

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 for timber buildings. Also, the difference in energy usage for space heating and cooling when building with timber will be examined.

To make the comparison on a material level, 60 EPD's for 77 materials were collected, 23 for timber, 20 for steel and 17 for concrete. These EPD's were collected online. The comparison between the materials will be performed using boxplots. The data for these boxplots are the materials GWP expressed per volumetric unit and mass unit. The boxplot of the timber materials will also be split up according to the different possible end-of-life scenarios for the construction waste in order to verify which scenario is the most favorable in terms of carbon emissions. The investigated timber materials in this research are CLT, glulam and LVL.

For the comparison on a building level, comparative LCA's were collected. 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 for a certain timeframe. At the end the results for both constructions are compared with each other. These comparative LCA's were online collected using the Web of Science, Google Scholar and Mendely. The collected LCA's concern mid-rise buildings (3-10 floors) and high-rise buildings (>10 floors). The used parameter for comparison on the building level is the GWP per unit of area expressed as 'kg CO_2 eq/m²'. When comparing the operational phase of the buildings, the operational energy consumption expressed as 'kWh/m²' is applied. The absolute values of the GWP and operational energy consumption are compared as bars on a chart. The relative differences in GWP or energy usage between the timber and the concrete or steel variant of the multi-storey building are shown as a graph line. Presenting the relative differences as a graph line allows to spot for any potential trends in increasing or decreasing carbon and energy reductions. This relative differences in operational energy consumption will be ranged from colder to hotter climates to see if the colder climates result in increased energy reductions for timber buildings. The percentage differences in the GWP of buildings will be ranged according to the different end-of-life scenario to see which scenario causes the greatest carbon reductions.

The criterium that's used to range cold to warm climates to examine the effect on the operational energy is the average temperature of the coldest and hottest month. This data was obtained from the Climate data from the timeanddate.com who gives the average monthly temperature from the period of 1985-2015.

To plot both the boxplots, bars and graphs, Microsoft Excel 2016 is used.

To gain insight in the factors and assumptions that can influence the difference in GWP and energy usage, existing literature on this matter was collected. For the gathering of this literature the Web of Science and Google Scholar were used.

3. Life stages

3.1 Production phase

During its growth, timber takes up CO_2 from the atmosphere. The collected EPD's for this research show that for every m^3 of wood, 741 – 874 kg CO_2 is taken out of the atmosphere. This makes timber initially carbon negative, resulting in a negative GWP. Still some LCA's start the timeframe when the wood is being harvest, meaning that the carbon removal from the atmosphere during its growth is excluded. For this a distinction needs to be made between the LCA's that include and exclude the effect of carbon sequestration.

Most of the GHG emissions during the production of structural timber is due to the kiln drying process. Wood can have a moisture content of 25 – 35%. 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. The drying of timber is energy and equipment intensive. Puettmann & Wilson showed that the kiln drying can make up to 92% of the full energy usage during the cradle-to-gate process (A1-A3) [10]. The amount of energy required to dry the timber depends on the tree species. Also the adhesives used for the production of EWP's cause an increase in its GWP. These adhesives are required to glue the several layers within the panels and beams together, as well as to construct strong connections between the several timber elements in the building frame.

During the production stage, both concrete and steel achieve a high GWP. This is due to the energy-intensive production of steel and the calcination process during the cement production. However, during its lifetime, concrete elements reabsorb a share of the emitted CO_2 from the production. The latter effect isn't usually included in the A-phase of an LCA.

It should be noted however that timber buildings need additional materials. Because of its light weight slabs made out of CLT requires more acoustic insulation materials than their concrete counterpart to achieve an equal sound comfort [11]. This can have a negative influence on the timber buildings GWP, depends on the chosen acoustic material. In one LCA, a 4-storey student house, the CLT panels were layered with additional cementitious materials for acoustic separation [12]. This cementitious layer increases the carbon footprint of the timber building. An alternative is the use of cork as acoustic insulation. Cork is also a wooden material since its extracted from the bark from the cork oak tree, making it more environmentally friendly [13]. Also timber high-rise constructions aren't likely to be complete concrete-free. Because of the lighter weight of wood, timber framed constructions have a smaller resistance against the wind. With an increasing building height, this becomes more problematic. To prevent timber-framed buildings from swaying in strong winds a specific amount of concrete is added to multi-storey timber buildings. The additional concrete increases the horizontal rigidity of the building making the structure less vulnerable for high wind loads [14].

In the production phase a distinction needs to be made between the LCA's that consider the cradle-to-gate phase (from raw material extraction till manufacturing), and the ones that consider cradle-to-site phase (from raw material extraction till on-site erection).

3.2 Operational phase

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 [15]. So the B-stage is the dominant stage for the outcome of a buildings LCA. The operational phase is responsible by 72% from the CO_2 emitted by the global building sector [16].

Timber has a lower thermal conductivity than steel and reinforced concrete (respectively 0.13 W/m²K; 45.3 W/m²K and 2.5 W/m²K). 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. In the second case the smaller GWP is obtained through diminished embodied energy and carbon.

When it comes to cooling and ventilation, 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. Timber may have a higher specific heat capacity than concrete, 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.

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 climatic regions are convective heat gains. Therefore, higher U-values in cooling season perform better in warmer locations and lower U-values in cooler [17].

Guo et al (2017) studied the operational carbon and energy of a 7-storey concrete building located in Xi'an and its timber equivalent. Both buildings were hypothetically relocated over the five climatic regions in China. Little correlation was found between the percentages of energy saving (and carbon reduction) and the climatic zone. Still when the energy saving between the CLT and concrete building is expressed in function of the used volume of CLT, colder climates achieve higher energy savings [18].

Another research performed an LCA on a 15-storey concrete office building in Harbin and its variant using a CLT structure. Again the building was hypothetical relocated over the five climatic regions of the Chinese mainland. The results show that for all the climatic regions in China the CLT building requires less energy for space heating. 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 climates, the CLT-building used more energy for space cooling. The smallest raise was observed in the 'Hot Summer Warm Winter'-region, the biggest in the temperate climate [19].

Some LCA's only focus on the energy consumed by the operational activities affected by the structural material. Other LCA's include the activities which aren't related to the thermal envelope, like water heating and lighting. Because they aren't related to the construction material, they are identical for the concrete, the steel and the timber version of the building. This means that including them results in a reduction in the difference between the different buildings for both the GWP as for the energy usage. A distinction needs to be made between the LCA's that include non-affected activities, and the ones that exclude them.

3.3 End-of-Life phase

The GWP for the ‘C+D’-phase of an LCA is the one that varies the most between the different timber buildings. This is because there are four different scenarios possible for the construction waste from timber buildings: re-use (D), recycling (D), bioenergy (C3), and disposal (C4) [20].

The scenario of energy recovery consists in combusting the wood to generate energy. 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 if the energy-recovery from the wood substitutes energy production from fossil fuels.

The use of wood as a renewable energy source and a mitigation for climate change is a heavily discussed topic. Leturcq found that the replacement of fossil fuels by wood fuel does not reduce short term carbon emissions. Wood has a higher emission factor than that of other fuels in common use [21]. 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. The potential benefit of substituting fossil fuels by wood waste is highly dependent on the considered timeframe. 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 emitted carbon. It also takes many years of forest regrowth to achieve substantial GHG reductions. 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 [22].

Landfilling of wood waste seems to be the least favorable option according to the EU’s cascading system for wood waste. On the landfills biodegradation of the timber takes place, causing 0 – 3% of the carbon in wood to be emitted as landfill gas. The rest of the carbon remains in the landfill indefinitely [23]. To estimate the GHG emissions from landfilling, most European countries use the default values of the IPCC 2006 Guidelines for National GHG Inventories. The IPCC provides a DOCf factor of 50% for wood products in landfilled waste, which is very likely to be a gross overestimation. One study investigated the DOCf 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% [24]. Ximenes et al examined the carbon loss of EWP’s on landfills. They found that for these EWP’s the carbon loss ranged from 0.6 – 9% [25]. Wang et al researched the carbon decay of four types of EWP’s with a landfill simulation via a bioreactor. Still the carbon loses were 0%; 1.1%; 1.4% and 19.9% [24]. 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. 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 [26]. 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 estimate that only 5% of the wood carbon is converted into methane [27]. The several studies mention here above state that the calculation of carbon decay in landfills of wood by using the IPCC default factor of 0.5 turns out to be a gross overestimation. No papers determining the carbon decay at landfilling of constructive EWP’s like CLT, glulam and LVL could be obtained.

Most of the steel waste is recycled for the production of new steel. Global steel recovery rates estimate that about 85 % of all scrap from construction steel was recycled on a global scale [28]. Manufacturing steel from scrap requires one third of the energy compared with the energy needed to produce it from iron ore [29].

Demolished concrete, if not landfilled, is usually crushed into recycled aggregate as a road sub-base layer or as aggregate for new concrete products. However, because of the larger surface of the coarse when using recycled aggregates a higher amount of cement is required. Knoeri et al found similar GWP's for recycled and conventional concrete [30]. The landfilling of concrete can have a CO_2-sequestrating effect. This is because of the carbonation reaction taking place in the concrete, which isn't finished at time of demolition [31].

4. Results & discussion

4.1 During the different life stages

4.1.1 Production phase

From the collected ten comparative LCA's who focus on the cradle-to-gate phase of the building, eight of them discussing eleven cases included the carbon sequestrated during the A1-phase. All eleven cases show a lower GWP for the timber variant when compared with its concrete counterpart. The GHG reduction for 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%. One case even had a negative GWP for the steel building. Because the steel variant in this particular research contained a big amount of wooden materials. For this reason the steel building had a lower GWP than its timber equivalent.

Three LCA's that excluded the carbon sequestration when determining the 'A1-A3'-GWP were collected. Three comparative LCA's show a reduction in GHG emissions of 33.62; 38.27 and 66.15% when building with timber instead of concrete. Between timber and steel the reductions are 2.10% and 39.74%.

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 amount of GHG's. Two more papers both by Hafner & Schäfer performed a comparative LCA on multi-storey buildings using different structural materials. No specific quantitative data was given in these papers, but it was shown that the timber variant achieved the smallest GWP.

Five papers concerning eight cases that focused on the cradle-to-site phase (A1-A5) were found that included the carbon sequestration during wood growth. Their results are shown in fig. 1. In all cases the timber variant had the lowest GWP. The reductions in GWP between concrete and timber ranged from 40.46% to 172.94%. For the two cases that compared steel with timber, the reductions were 0.92% and 90.29%. Six LCA's excluded the benefit of carbon sequestration when determining the cradle-to-site GWP. Their results are presented in fig.2. Again in all six papers the multi-story building resulted in the lowest GWP. The GHG reductions when concrete is switched for timber range from 2.83% - 60.82%.

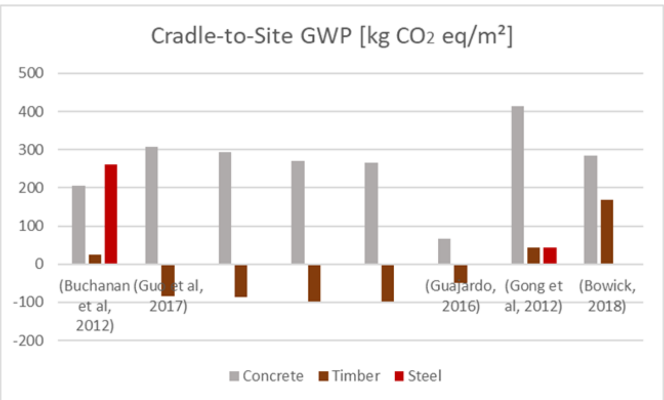

Fig. 1. Cradle-to-Site GWP of multi-storey buildings made out of concrete, timber or steel when carbon sequestration by timber is taken into account

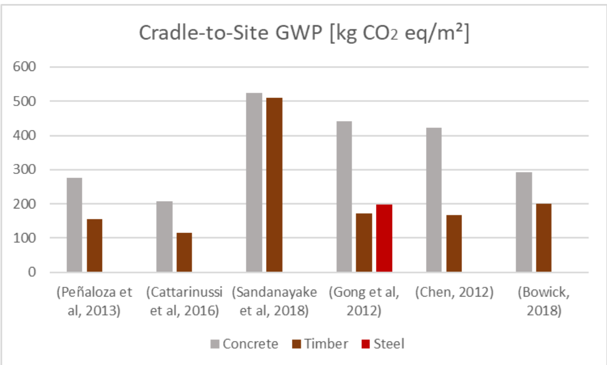

Fig. 2. Cradle-to-Site GWP of multi-storey buildings made out of concrete, timber or steel when carbon sequestration by timber is excluded

The one case that included steel found a reduction of 12.86%.

Three remaining comparative LCA's that focused on the cradle-to-site 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.

To make the comparison on a material scale, 60 EPD's were collected. The boxplots of their Cradle-to-Gate GWP's are shown in fig.3 and fig.4 respectively for when the carbon uptake of wood is included and excluded. Timber seems to outperform both steel and concrete in frame of climate change. However when excluding the sequestrated carbon in the timber, concrete seems to have a lower GWP per mass unit. It has to be mentioned that concrete has a density of approximately five times that of timber. In fig.5 both materials were plotted in a boxplot expressing the GWP in function of volumetric unit. This shows that concrete elements produce more GHG emissions than the timber elements.

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.

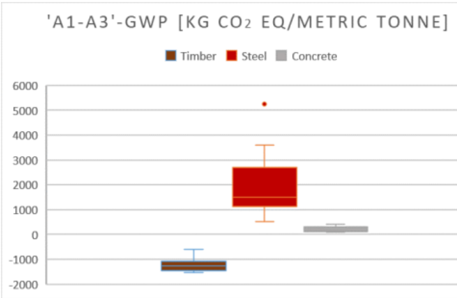

Fig. 3. Cradle-to-Gate GWP of structural elements made out of concrete, timber or steel when carbon sequestration by timber is taken into account

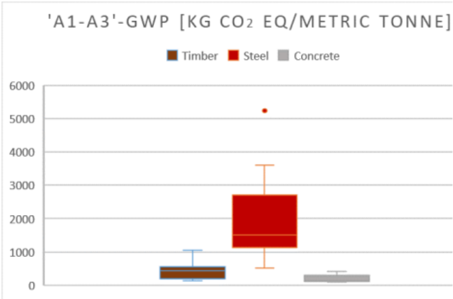

Fig. 4. Cradle-to-Site GWP of structural elements made out of concrete, timber or steel when carbon sequestration by timber is excluded

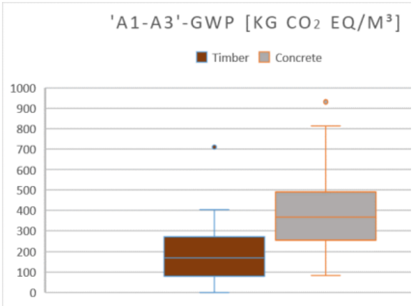

Fig. 5. Cradle-to-Site GWP per volumetric unit of structural elements made out of concrete or timber when carbon sequestration by timber is excluded

4.1.2 Operational phase

For the comparative LCA's discussing the B-phase, six LCA's gave the amount of GHG's emitted for fourteen cases. In fig.6 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 emitted more GHG in the usage phase. Still these differences remain rather small (-5.11% and 8.71%). The different annual energy consumptions are presented in fig.7. Thirteen comparative LCA's were collected calculating 33 cases. From these 33 cases, 22 of them had a smaller energy consumption for the timber building than the concrete and/or steel equivalent. The energy savings when using timber instead of concrete vary

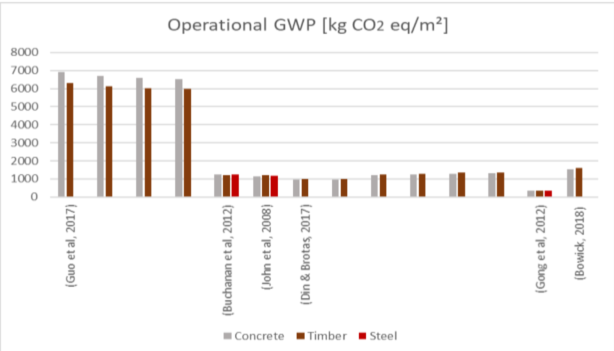

Fig. 6. Operational GWP of multi-storey buildings made out of concrete, timber or steel

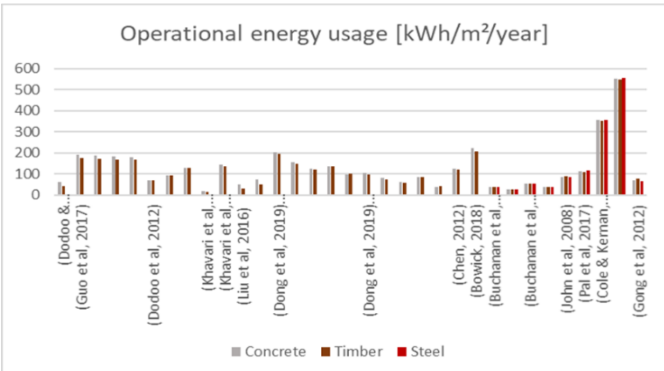

Fig. 7. Annual operational energy consumption of multi-storey buildings made out of concrete, timber or steel

between 39.42% and -6.86%. For the comparison between steel and timber these values are 6.27% and -15.09%.

The ranging of the operational energy usage 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. Not enough comparative LCA's who only included HVAC were available to spot a trend when ranged from cold to warm climates. The ranging of the relative difference in operational energy is shown in fig.8. Eight comparative LCA's were collected discussing fourteen cases. The LCA's selected all considered similar U-values. No trend could be spotted through the different climatic zones for the differences between the concrete and timber variant. Between steel and timber from cold to warm climates, a strict declining graph is observed. However the latter was plotted only using five cases who correspond with a declining line in the Timber/Concrete graph.

The annual energy consumption for heating from several comparative LCA's is shown in fig.9. The same was done for the energy usage for cooling in fig.10. For the heating energy, 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. From the twelve cases in fig.9, seven consumed less energy for heating. Six from these seven cases had a different U-value than the 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 concrete version of the building.

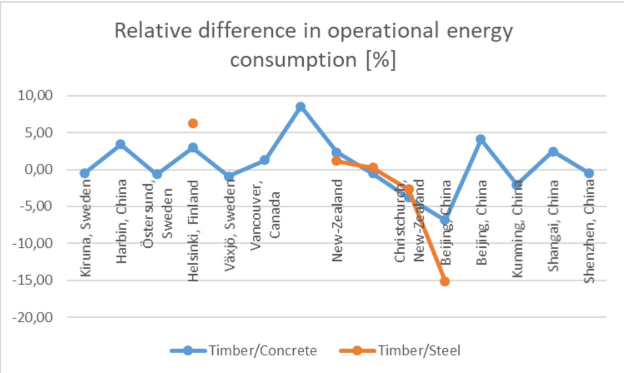

Fig. 8. Relative difference in operational energy consumption between timber multi-storey buildings and its concrete or steel equivalent, ranged from cold to hot climates

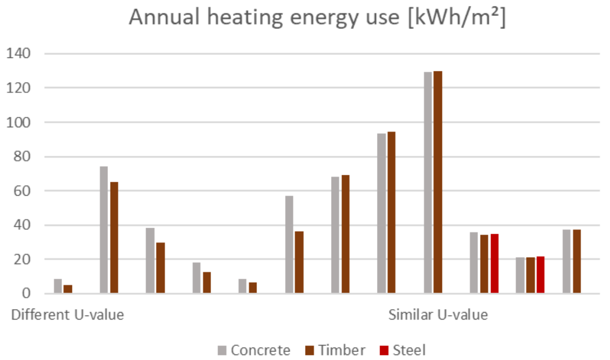

Fig. 9. Annual energy consumption for heating in multi-storey buildings made out of concrete, timber or steel

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

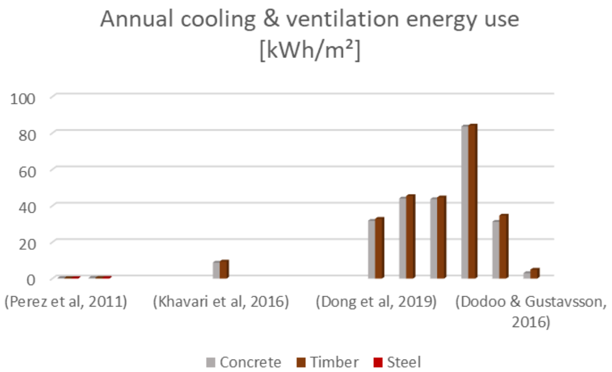

Fig. 10. Annual energy consumption for cooling & ventilation in multi-storey buildings made out of concrete, timber or steel

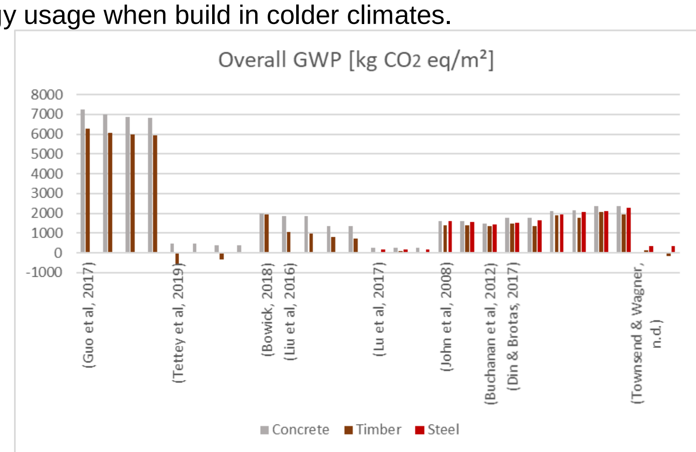

Fig. 11. Overall GWP of multi-storey buildings made out of concrete, timber and steel

4.2 Full lifecycle

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-story building has the smallest carbon footprint. This is shown in the fig.10. When comparing the timber variant of the multi-story construction with concrete, the reduction in GWP varies between 1.22% and 219.92%. For steel this reduction varied between 1.20% and 144.11%. Three extra comparative LCA's were found who left out the B-phase because it was assumed to be identical. Their results are shown below in fig.12. For all three of these LCA's, the timber variant of the multi-story building seems to emit the least GHG's. From this it can be concluded that multi-story buildings have a lower carbon footprint when realized with timber.

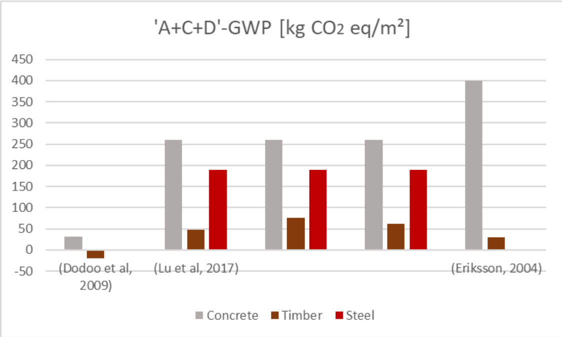

Fig. 12. 'A+C+D'-GWP of multi-storey buildings made out of concrete, timber and steel

4.2.1 Different End-of-Life scenarios

The relative difference in overall GWP have been ranged according to their end-of-life scenario. This is shown in the graph of fig.13. Seven LCA's were selected discussing seventeen cases. 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 GHG emissions. In fig.14 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 less GHG emissions than concrete. Recycling or landfilling of timber waste doesn't necessarily results in a reduction or increase in GWP when compared with concrete. The results of the gathered data for both materials and buildings show that the energy recovery for timber waste is the most beneficial towards GHG reductions, landfilling is the least favorable and recycling is in between these two options. However the collected literature for this thesis shows that there is little to no information about the GHG emissions during the landfilling or recycling of CLT, glulam or LVL. The 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 time period of the usage of the product into account. 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 research is that current data shows that the greatest reduction in GHG emissions is achieved when the construction wood is combusted for energy use after its usage. Still further research on this matter is required.

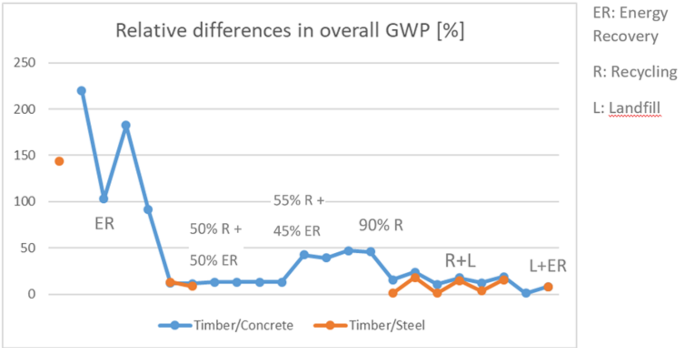

Fig. 13. End-of-Life GWP of multi-storey buildings made out of concrete, timber and steel, ranged according to the different end-of-life scenarios

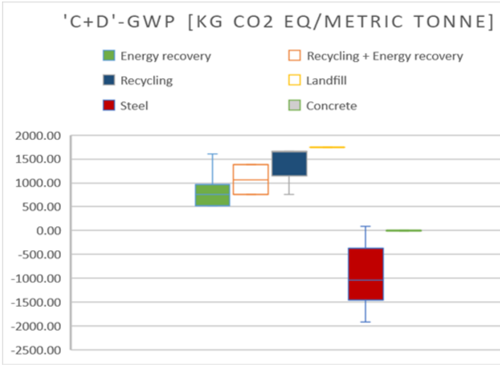

Fig. 14. Overall GWP of structural elements made out of concrete and steel. The four left boxplots represent the GWP of structural timber waste according to chosen end-of-life scenario

4.3 Recommendations for further research

- There is no existing information about the long-term effects of landfilling CLT, glulam or LVL. Current data about the GWP during landfilling is likely to be an overestimation.
- More research is required to both the short-term and long-term effects of burning structural EWP's for energy generation.
- 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 according to the same standard.

5. Conclusion

The main outcomes of this research are the following:

• For the production phase the timber variant of the multi-storey building seems to have the lowest carbon emissions when compared with steel and concrete, even if the benefit of carbon sequestration during growth is excluded. This is both true for the cradle-to-gate phase as for the cradle-to-site phase. 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.

• 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 reductions in GWP in colder climates.

• For the overall GWP of the building the outcome is unanimously, timber always resulted in a smaller GWP. The reductions between timber and steel ranged from 1.20% to 144.11%, for the comparison between concrete and timber these values were 1.22% and 219.92%.

• On the overall GWP, the greatest reductions when using timber can be seen when the waste is reused for energy recovery. The smallest ones in case of landfilling. The scenario of recycling is situated in between.

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