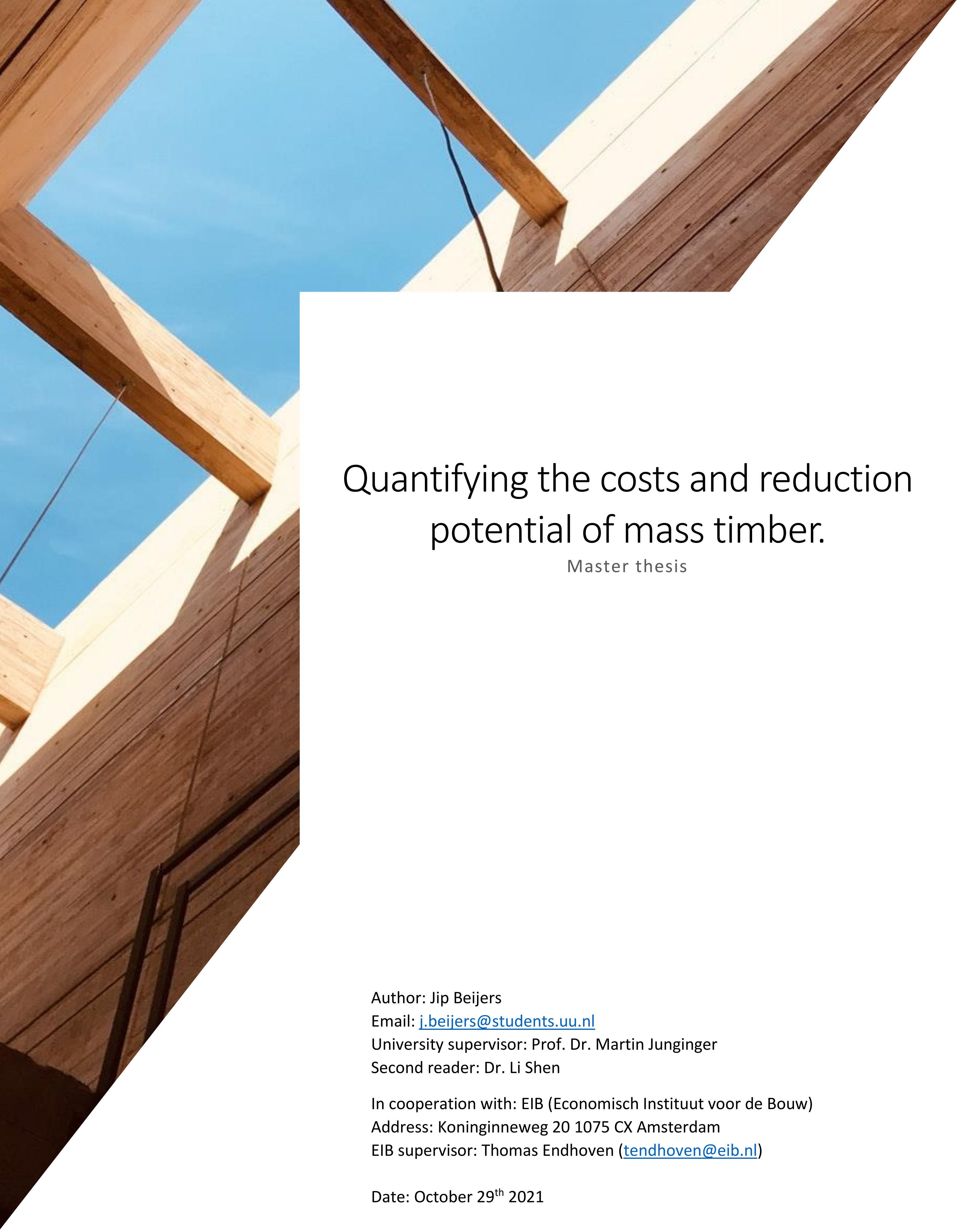

Quantifying the costs and reduction potential of mass timber.

Master thesis

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Abstract

The building and construction sector was in 2018 responsible for 39% of the global CO_2 emissions. Majority of this 39% is linked to the operational energy usage of buildings. As a result of shifting towards buildings with better energy performance, the environmental impact due to construction materials is becoming more relevant. Mass timber, a biobased alternative for high energy intensity materials such as steel and reinforced concrete, can significantly reduce construction material related impacts. Although mass timber is increasing in popularity, a massive switch to mass timber constructions in the Dutch built environment is not witnessed despite the significant demand for new buildings. Studies quantifying the expected costs and environmental impact reduction of mass timber remain scarce but can aid in making mass timber more accessible for construction companies.

This study combines a LCA, LCC and scenario analysis to quantify the costs related to reducing environmental impacts and specifically GWP by constructing a mass timber case house instead of a reference traditional house. Via the EN 15804 LCA framework, the mass timber case house proves to reduce the total environmental score related to 11 impact categories, with 27% compared to a reference traditional case house. The GWP specifically was reduced with 66%. CO_2-eq mitigation significantly increases when delay in emissions via temporary biogenic carbon storage is taken into consideration via a DLCA. The mass timber case house has a net negative GWP over a 100 year timespan and emits 108% less CO_2-eq per m^2GFA compared to the reference house.

The global warming reduction potential of the mass timber case house goes accompanied by an increase in construction costs of 35%. The higher costs are caused mainly by the LVL frame, which is 88% more expensive than the reinforced concrete frame of the reference house. When taking discounted O&M costs and demolition costs into account, the LCC of the mass timber house is 13% higher compared to the traditional reference house. Assuming a scenario in which all 267 thousand Dutch terraced houses built in 2020-2030 are constructed in mass timber and a carbon tax would be applied, 710 Kton CO_2 can be mitigated against 10% higher LCC costs. This reduction would attribute and additional 0,11% to reducing annual emissions in order to reach the Dutch 2030 climate goal.

Key words: Mass timber, Timber construction, LCA, DCLA, Biogenic carbon storage, EN 15804, MPG, LCC, Scenario analysis

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Table of abbreviations

Table 1: Table of abbreviations

Abbreviation	Description
BENG	Nearly zero-energy buildings (NL: Bijna energie neutrale gebouwen)
BOM	Bill of Material
CLT	Cross laminated timber
EoL	End-of-life
EWPs	Engineered wood products
EPD	Environmental Product Declaration
EPDM	Ethylene-Propylene-Diene-Monomer
EPG	EnergiePrestatie van Gebouwen (EN: Energy Performance Buildings)
EPS	Expanded Polystyrene
EU	European Union
FU	Functional Unit
FV	Future Value
GFA	Gross floor area
GHG	Green House Gasses
GWP	Global Warming Potential
HTP	Human Toxicity Potential
LCA	Life Cycle Analysis
LCC	Life-Cycle Costs
LCCA	Life-Cycle Cost Analysis
LFS	Lettable floor space
LVL	Laminated veneer Lumber
MDF	Medium Density Fibreboard
MKI	Milieu Kosten Indicator
MPG	Environmental Performance Buildings (NL: Milieu Prestatie van Gebouwen)
NMD	Nationale Milieu Database (EN: National Environmental Database)
nZEB	Nearly zero-energy buildings
O&M	Operation & Management
OSB	Oriented Strand Board
PCR	Product Category Rules
PUR	Polyurethane foam insulation
PV	Present Value

Introduction

Global warming is an increasingly growing threat to humanity. In order to minimalize its devastating effects, a number of countries signed the Paris Agreement which aims to limit global warming to well below 2 degrees Celsius by lowering greenhouse gas emissions (GHG-emissions) (United Nations, 2015). One of the big global emitters of CO_2 is the building and construction sector. In 2018 this sector was accountable for 36% of the world's final energy demand and 39% of global CO_2 emissions related to energy and processes, according to the global status report 2019 (IEA, 2019). IEA (2019) shows that the majority of these emissions come from power generation to provide heat and electricity to buildings in the use phase (so-called 'operational energy'). In the Netherlands, operational energy accounts for 80% of the CO_2 emissions of the built environment according to EIB et al. (2020). Of the remaining 20%, construction of new buildings makes up for 80%.

Reducing built environment emissions

In order to lower the environmental impact of the built environment, the European Union (EU) developed legislative frameworks, such as the 'Energy Performance of Buildings Directive', in order to focus on lowering the operational energy demand (Lavagna et al., 2018). In the Netherlands, these frameworks are put in to practice in the EPG calculation method (Dutch abbreviation for 'Energy Performance Buildings') and in the recently introduced BENG (Dutch abbreviation for 'nearly zero-energy-buildings') requirements (RVO, 2021b). These requirements solely focus on the operational energy use and involve insulation values, energy efficiencies of installations and limit the usage of fossil fuels according to RVO (2021b).

As a result of, a decline in operational energy and energy related emissions is witnessed in newly constructed energy efficient buildings (Sartori & Hestnes, 2007). One of the observations by Sartori & Hestnes (2007) and Hafner et al. (2013) regarding this trend, is the increase in the share of embodied energy (energy needed for production of a product e.g. construction material) compared to the operational energy. Similar observations are made by Koezjakov et al. (2018) regarding energy usage specifically in the Dutch built environment. Koezjakov et al. (2018) shows that the embodied energy share (as part of the total energy) in the Netherlands in 2015 was 10-12% in standard houses compared to 31-46% in newly constructed energy efficient houses. Furthermore, an increase in energy efficient houses in the future is expected due to more strict energy performance regulations such as the BENG requirements. This will lead to a decline in the total energy usage (sum of embodied energy and operational energy) of the average Dutch building, but an increase in the share of embodied energy, according to Koezjakov et al. Figure 1 shows a visualization of the findings of Koezjakov et al. (2018). The findings of Koezjakov et al. (2018) and Sartori & Hestnes (2007) show that reducing operational energy can lead to an increase in the embodied energy of a building.

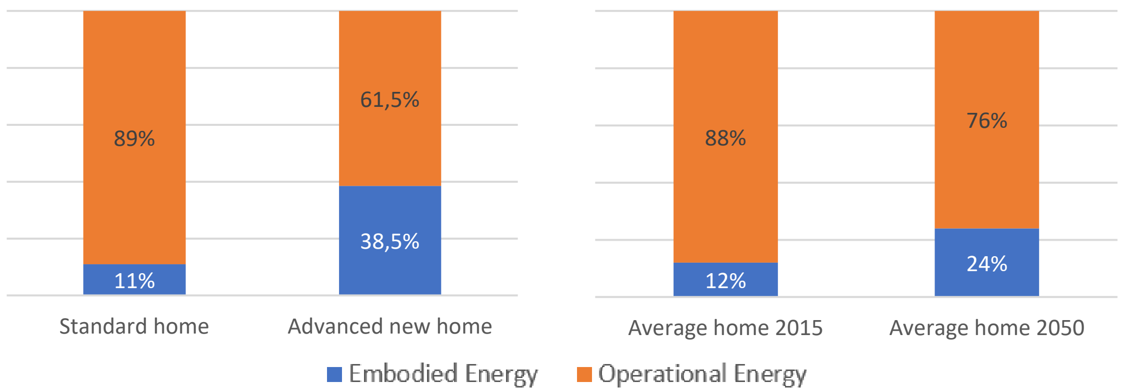


Figure 1: Embodied energy- and operational energy share of total energy use. Graph constructed by author, based on findings in Koezjakov et al. (2018).

Embodied energy

The higher embodied energy share in energy efficient houses can partially be attributed to the usage of energy installations that are high in embodied energy such as solar panels. Besides specific energy installations, energy efficient buildings usually require thicker layers of insulation (Tettey et al., 2014). Frequently used insulation material such as expanded polystyrene (EPS) requires a lot of energy during production which contributes to high embodied energy of energy efficient houses. An even bigger contributor to embodied energy in conventional houses are standard construction materials such as reinforced concrete, steel and aluminium. A lot of energy is required to produce the needed quantities, resulting in high associated GHG emissions compared to biobased alternatives (Venkatarama Reddy & Jagadish, 2003; Woodard & Milner, 2016). More specifically for the Dutch built environment, EIB et al. (2020) shows that two-thirds of new house construction related emissions are attributed to the production of concrete and steel. These observations indicate the growing attribution of embodied energy in building related environmental impact and incentivize the usage of low embodied material usage.

Biogenic storage in wood-based products

As an alternative to energy intensive conventional construction materials, wood-based construction materials are witnessing an increase in popularity due to their unique characteristics and application potential in near-Zero Energy Buildings (nZEBs, or BENG in Dutch) (Arumägi & Kalamees, 2020). Their main distinctive characteristics is that they are a renewable material resource in which carbon is stored. Trees take in CO_2 via photosynthesis in order to grow. This stored carbon in wooden biomass referred to as 'biogenic storage'. Approximately 50% of the tree biomass consists of stored carbon (Pittau et al., 2018). Consequently, increased wood usage in the construction sector is endorsed by several by several institutions and studies (Hart & Pomponi, 2020).

Engineered wood products

Wooden usage in the built environment has been increasing and more specifically a shift from solid sawn lumber towards engineered wood products (EWPs) has been witnessed (Lam, 2001; McKeever, 1997). EWPs features more efficient use of wood resources, increased design freedom and more uniform mechanical properties (Lam, 2001; McKeever, 1997). EWPs are made up of laminated timber beams and sheets or wooden chips bonded together via adhesives. Examples of EWPs are particleboards, cross-laminated-timber (CLT) and laminated-veneer-lumber (LVL), shown in Figure 2. In addition to providing structural integrity to a buildings, EWPs can be utilized as both internal and external walls and are applicable for a wide range of functions in constructions (Lam, 2001).

 [1]  [2]  [3]

Figure 2: Engineered Wood Products, [1] particleboard (from: homelane.com), [2] CLT (from: woodteq) & [3] LVL (from: pollmeier.com).

Mass timber constructions

Wood-based construction materials can be utilized in timber frames and mass timber constructions. Timber frames are made of solid wooden structural beams. Constructions with timber frames made from EWPs, such as CLT or LVL, are called mass timber constructions (Harte, 2017; Kremer & Symmons, 2015). EWPs and timber frames offer numerous advantages over conventional materials. When compared with conventional materials such as steel and concrete, EWPs offer the same functional value against significantly lower weight and lower embodied energy (Woodard & Milner, 2016). Life-Cycle-Analysis (LCA) studies focussed on the impact of different building materials, furthermore show that EWPs have lower GHG emissions than conventional materials due to lower energy consumption during manufacturing (Hangyong et al., 2017; Milner & Woodard, 2016). When biogenic carbon storage is taken into account, EWPs can even have a negative impact on global warming potential in LCAs depending on the end of life (EoL) of the wood-based product (TNO, 2021a). A negative impact means that despite emissions during production and during the product lifetime, more carbon is stored in the woody biomass.

Emission mitigation

Utilization of EWPs in buildings substitutes conventional high embodied energy materials such as concrete and steel. In addition, fossil fuels can be substituted at the EoL by burning the woody biomass as biofuel. This substitution effect can also result in negative GHG emissions according to Sathre & Gustavsson (2009). Švajlenka et al. (2017) explored the differences in environmental impact in the production phase of a mass timber houses compared to a masonry variant. They found a 156% reduction in emitted CO_2-equivalents (CO_2-eq, an unit to measure global warming potential), 35% reduction in emitted sulphur dioxide equivalent (SO_2-eq, an unit to measure acidification potential) and 54% less embodied energy.

Furthermore, emissions are mitigated by the lower weight of wood-based products compared to steel and concrete. Due to a lower weight of a timber frame or mass timber building, the foundation of the building can be smaller (Woodard & Milner, 2016). This saves material and decreases transport emissions due to lower truck load weight. Pajchrowski et al. (2014) found a decrease 30 to 60% in total building weight and a 75% reduction in their transport indicator (calculated by weight*distance) for a timber frame building in comparison with a reference masonry building.

Another factor that influenced the lower transport indicator in Pajchrowski et al. (2014) was the prefabrication of wooden elements. EWPs offer a lot of design freedom since they are often modified via large milling machines. This way of manufacturing allows for high precision and delivers custom elements that can be assembled in a factory (Sustainer Homes, personal communication, 2021). This can result in significant decreases in construction time. A six fold decrease was found in Pajchrowski et al. (2014) and a 48% decrease in construction time for a wooden building variant compared with a masonry building was found in Švajlenka et al. (2017). Furthermore, design for disassembly can be taken into account which can lead to faster and less intensive demolition at the EoL. Pajchrowski et al., (2014), for instance, showed a decrease in demolition time and an approximately 38% decrease in energy needed during demolition.

Financial aspects of building with wood

The economic costs of mass timber constructions have been studied less extensively than the environmental benefits (Winchester & Reilly, 2020). Thus far the most comprehensive economic study has been done by Švajlenka et al. (2017). Švajlenka et al. (2017) show a 15% reduction in costs in the production phase for a mass timber house compared to a masonry variant. Costs reduction originated mainly at the foundation due to the lower amount of material needed for the wooden building foundation (Švajlenka et al., 2017). Furthermore, costs differences were found due to the higher completion work of integrating water supply and electricity in the masonry house. These are already included in the prefabricated house during the production stage. Lastly, a big difference was found in construction time, namely 48% shorter construction time for the wooden variant compared to the masonry building (Švajlenka et al., 2017).

Carbon tax and wooden buildings

Another study investigating the financial aspect of wooden buildings was done by (Sathre & Gustavsson, 2007). Sathre & Gustavsson (2007) investigated the effect of a carbon tax rate on the costs of a timber frame building and reference house with reinforced concrete frame. The costs were based on energy and materials needed for production and the profit of energy generation from biomass incineration. In all carbon tax scenarios the wooden frame building proved to be cheaper, mostly due to the usage as biofuel. Noteworthy is that even in the zero tax scenario, the timber frame building was approximately 28% cheaper (Sathre & Gustavsson, 2007). Further research by Sathre & Gustavsson (2009) showed that the financial energy costs for the production of a concrete building are 40% higher compared to a wooden variant and 60% higher when a carbon tax was included that covered all social costs of carbon emissions.

Mass timber in the Netherlands

Due to the lack of knowledge and overall inertia in the building sector (Noora et al., 2021), wood has not found its way into the mainstream Dutch building construction sector. A report from 2020 by Studio Marco Vermeulen (2020) shows that mass timber constructions remain fairly rare in the Netherlands. In 2020 there were 32 realized CLT structures and 14 planned structures.

Reduction in environmental impact due to mass timber or timber frames has been proven by W/E adviseurs (2016). W/E adviseurs (2016) show that a transition to timber frames in combination with the application of wooden cladding for new land-bound houses could result in a CO_2 reduction of 42% compared to a scenario with traditional houses. A similar conclusion has been drawn by NIBE (2019), who has shown that if the share of wood in new houses is increased from the current 1% to 50% (share based on weight), a 40% reduction in CO_2 emissions compared to traditional houses can be achieved.

Economic studies in the Netherlands

Similarly to global studies, economic studies regarding the costs of wooden constructions in the Netherlands remain scarce as well. A study done by Inbo (2021) specifically looked into the costs of CLT in the Netherlands. Inbo (2021) found that, in contrast to Švajlenka et al. (2017), material costs are 30 to 40% higher compared to traditional construction materials. Cost reductions in the mass timber construction were also found, due to shorter construction times, decreased amount of workforce due to prefabrication, lower transportation costs and lighter foundation. Inbo (2021) stresses that its study is based on three Dutch ambitious pilot timber constructions. The ambitious nature of the projects might have had an effect on the costs.

A more recent study by Centrum Hout (2021), studied the difference in costs between a timber frame, CLT frame and traditionally built constructions. In their study (Centrum Hout, 2021b), a CLT building is 18% more expensive than a traditional variant. A timber frame building however, proved to be 8% cheaper. Centrum Hout (2021b) found a 45% and 49% reduction in construction time, compared to traditional land-bound buildings, for the CLT and timber frame respectively. Noteworthy is that this study has also been based on ambitious pilot buildings. An economic breakdown of the costs of a more mainstream mass timber building has yet to be done. This indicates a gap in the available information regarding costs related to the reduction potential of mainstream mass timber buildings.

Plans for mass timber

The governmental motivation to construct with wood-based products has been growing in the Netherlands. A recently signed Dutch covenant (green deal houtbouw) by Metropool Regio Amsterdam (2020) strives to construct 20% of new houses near Amsterdam in mass timber in 2050. Furthermore, at the time of writing there is strong incentive in the Netherlands to build new houses for the expected increase in households. Between 2020 and 2035 approximately 900.000 new houses need to be constructed according to EIB (2020). This offers opportunity to decrease emissions from the construction sector by storing carbon in wooden buildings.

The potential of reducing environmental impact and specifically global warming potential via wood-usage in buildings has been studies extensively. Academic studies specifically aiming at quantifying the reduction potential of mass timber constructions however remain scarce. Only Centrum Hout (2021b) and Švajlenka et al. (2017) have explored environmental impact reduction of mass timber constructions. Furthermore, differences in costs between mainstream mass timber houses and traditional houses is absent. This knowledge gap combined with the inertia in the construction sector (Noorman, 2019) obstructs the adoption of mass timber and reduction in construction material related environmental impact.

Research framework

Research aim

The aim of this study is to quantify the environmental reduction potential of mass timber and explore the related costs. Results of this study will provide legislators and construction companies with relevant knowledge regarding the costs and environmental impact reduction potential of mass timber buildings.

This study will do so by comparing the economic costs and environmental benefits of a mainstream mass timber house in the Dutch built environment, with a reference traditional house. The research framework is shown in Figure 3. Results from this study will show whether building with wood is a cost effective approach to reduce emissions in the construction sector. Secondly, a detailed breakdown of the different costs related to mass timber constructions might make wood-based construction materials more accessible for the Dutch construction sector. Lastly, this research will show how costs are divided over different building phases. Singling out the highest costs can help creating accurate policies to stimulate wood usage.

This study aims to answer the following research question:

How do the economic costs and climate impact reduction of a mass timber house in the Dutch building sector compare to a traditional house?

The research framework used to answer the research question is shown in Figure 3.

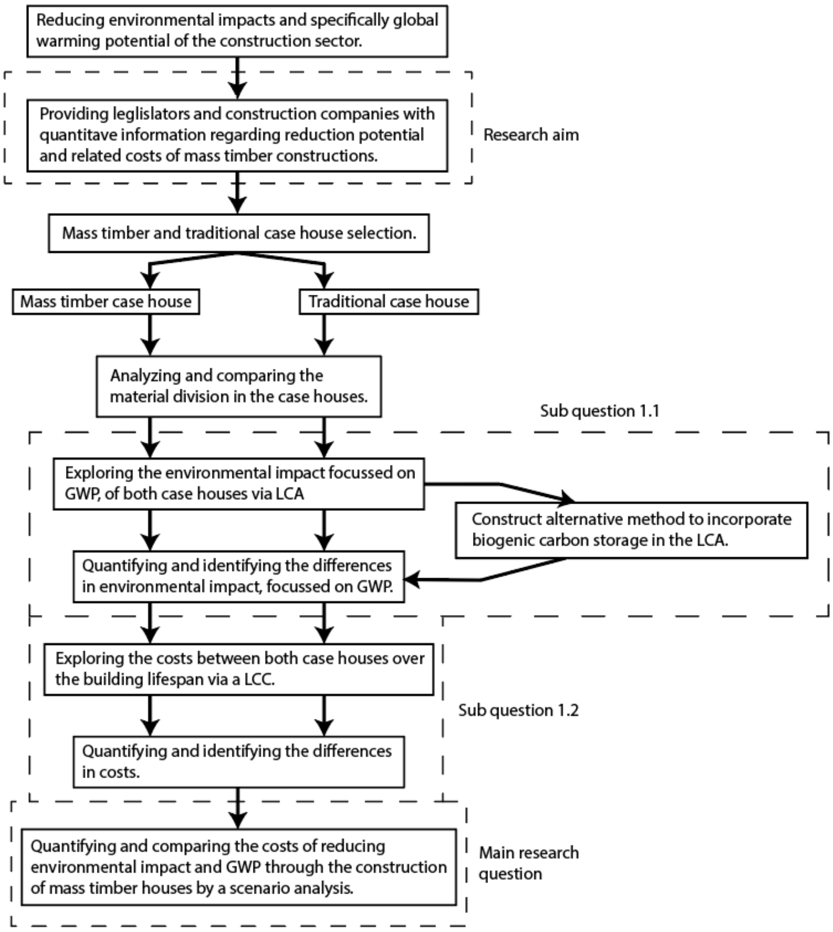


Figure 3: Research framework.

Framework explanation

In order to answer the research question, a mass timber case house and a reference traditional house are selected. Both houses will need to be energy efficient, in order to take the shift to more energy intensive materials into account. An inventorization of the construction materials of both houses will show the share of wood and conventional construction materials in both case houses. The climate impact of the houses will be measured via a Life-Cycle-Assessment (LCA). Special focus will lay on CO_2 emissions, since mass timber has the highest reduction potential in this impact category. By comparing the LCA results of the mass timber house with traditional house, the reduction potential of mass timber can be explored over the whole building life cycle. A crucial aspect in the comparison is the similarity between both case houses. Significant difference in living area or typology limits comparability.

Furthermore, this research focusses on the effect of different construction materials. Hence, energy usage in the use-phase is disregarded in the impact comparison. In order to remove energy usage from the comparison, both buildings need to have a similar energy demand and energy efficiency.

The Dutch determination method (Nationale Milieudatabase, 2021c) that is used to reflect the environmental impact of construction materials and buildings, is explored and modified. Currently the MPG-score, a score that reflects the environmental impacts of buildings, does not value temporary biogenic storage. This study will express the environmental impact of both case houses with and without taking biogenic carbon storage into account.

The following sub-question covers the exploration of differences in CO_2-eq emissions between the mass timber house and the traditional variant.

1.1 What is the difference in CO_2-eq emissions between a mass timber house and a traditional house over the whole life cycle with the exclusion of the use-phase?

Once the environmental benefits have been quantified, the difference in economic costs between both case houses is investigated. A Life-Cycle-Cost-Analysis (LCCA) will be used to explore and compare the costs of both houses. This comparison shows the magnitude and origin of differences in costs. In order to focus on the construction material related costs, the costs from operational energy are neglected in the comparison

The following sub-question represent the economic cost assessment.

1.2 What is the difference in costs between a mass timber house and a traditional house over the whole life cycle with exclusion of operational energy in the use-phase?

The final step is the extrapolation of the environmental impacts and economic costs to a macro level. A scenario analysis of the extrapolated results will show the large scale economic costs and environmental effects of constructing a share of the Dutch houses in 2021-2035 in mass timber. Via the scenario analysis the mitigation costs of reducing the environmental impact of construction materials are calculated.

Theory

Carbon storage in the built environment

Biogenic carbon storage process

Biogenic carbon storage in wood-based products is a result of sequestration during tree growth. CO_2 is taken in by trees via photosynthesis. Consequently, CO_2 is partially converted to biomass for tree growth. The remaining CO_2 is transpired at night. Over time, less CO_2 is stored in biomass and more CO_2 is transpired at night and eventually a tree reaches a steady-state in which almost all CO_2 uptake is transpired again (Broadmeadow & Matthews, 2003). Figure 4 shows this process via the uptake of carbon of a forest over time. The wave in the carbon stock is carbon released from trees via decomposition of tree litter and dead trees. Which is restocked by the growth of new trees. According to Broadmeadow & Matthews (2003) and Ouden et al. (2020), forest growth is eventually limited by the presence of old trees which results in a carbon stock equilibrium. This is visualised in the time period 100 to 200 years in Figure 4. Worth mentioning is that the time periods of carbon accumulation in Figure 4 strongly depend on the tree species in forests. Tree growth and decomposition occurs in different rates depending on tree species and forest management.

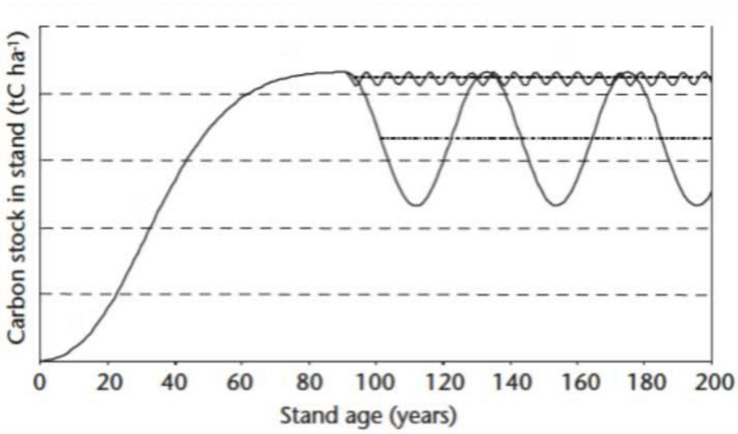


Figure 4: Carbon uptake by forests over time, image from Broadmeadow & Matthews (2003).

Sustainable managed forests

By logging trees, the biogenic carbon is withdrawn from a forest. By using rejuvenating and thinning methods for instance, trees can be logged in a way that allows new trees to grow and maximize carbon sequestration (Ouden et al., 2020). In order to battle deforestation from logging but still acquire lumber, sustainable forest management is preferred by wood companies. According to Boyle et al. (2016, p.1), ''sustainable forestry, or sustainable forest management, is the practice of managing forests to meet current needs and desires of society for forest resources, ie, products, services, and values, without compromising the availability of these for future generations''. In the European forests this comes into practice by utilizing only a part of the annual wood growth for timber products (European Commission, 2016). No more than the annual additional biomass can be logged. Otherwise deforestation occurs and the forest carbon sink would see an annual decrease.

Wood-based products in the carbon cycle

The utilization of wood from sustainable forests has an effect on the carbon cycle. The carbon cycle is ,according to the IPCC (2018), the movement of carbon between three carbon reservoirs: the atmosphere, ocean and terrestrial biosphere. This process is shown in Figure 5. Wood-based construction materials impact the CO_2 balance in the carbon cycle in a number of ways. First, the biogenic carbon stored in trees in the terrestrial biosphere is partially removed by logging for utilization in society. Part of the remaining biogenic carbon remains in the tree roots and tree litter in and on the forest floor. When this organic material is decomposed below the ground, it adds to the carbon sink of the forest soil. The logged wood is either used for energy- or heat generation or converted to building material. In the latter case, after the product's life time, the biomass is incinerated or landfilled. Biogenic carbon is released again into the atmosphere during incineration or decomposition in landfills.

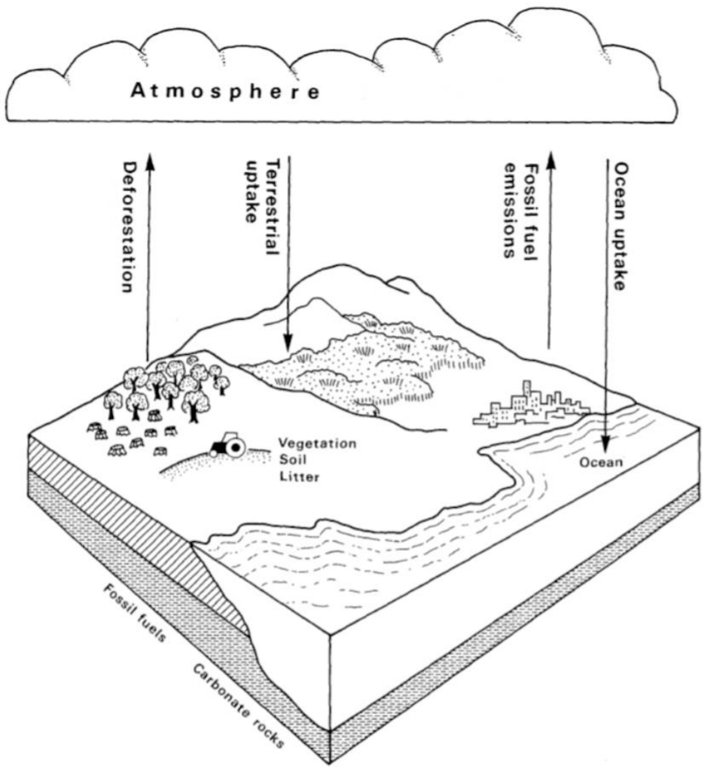


Figure 5: global carbon cycle, from (Grace, 2004).

Conventional construction material substitution

One of the applications of wood-based products in the built environment is as construction material. Several studies reviewed in Sathre et al. (2013) show that wood-based construction materials require a significantly lower amount of energy during production compared to concrete and steel, which is furthermore often supplied by bioenergy,. One study by Buchanan & Levine (1999) reported substitution factors of 260-280 kg carbon avoided per m^3 wood when wood products substitute concrete in a building. Up to 300-400 kg carbon is avoided per m^3 wood when wood products replaced steel.

Fossil fuel substitution

Another utilization of wood is energy generation via incineration. Using virgin wood or discarded wood-based products as fuel for bioenergy, mitigates emissions related to fossil fuel combustion. Bioenergy is regarded as a carbon neutral energy source, because all the combusted biomass is expected to regrow over time (IEA Bioenergy, 2021). Therefore, energy generation via bioenergy is regarded as a way of mitigating emissions from e.g. energy generation via fossil fuel combustion. Worth mentioning is that 24% of the wood usage in the Netherlands is energy generation via combustion of wooden biomass (NIBE, 2019a). The remaining wood is used for paper, cardboard, sheet material or timber.

Land Use and Land Use Change

Another effect on the carbon cycle occurs due to Land Use and Land Use Change (LULUC), indicated as 'deforestation' in Figure 5. As previously shown in Figure 4, forests sequester carbon over a significant period of time. Logging trees and utilizing the land for other purposes than to grow new trees is called deforestation. This change in land use results in a decrease in carbon uptake in the carbon cycle if trees aren't replanted. In the case of sustainable forest management, trees can be expected to grow back which would result again in uptake of CO_2 during tree growth. Various methods of accounting for LULUC exist. The IPCC (2003) argues that globally no big changes in annual CO_2 uptake by forests are witnessed, which therefore must be reflected in the LULUC calculation method. As a result, some LULUC methodologies such as the European Standardization (2019) do not reward the growth of new trees after logging.

Temporary biogenic carbon storage

The IPCC (2003) recommends LCA practitioners to assume that all biogenic carbon in harvested trees is emitted within one year after logging. In reality though, biogenic carbon in wood-based products is not emitted one year after harvesting. Depending on the type of wood-based product, exposure conditions and quality maintenance, the service life time can vary between several years up to 400 according to Reinprecht (2016). During the product's lifespan, biogenic emissions are postponed. Since the biogenic carbon will eventually be released when wood-based products are burned as biofuel or decomposed in landfills, a more preferable option is cascading. The definition of cascading according to Höglmeier et al. (2013, p. 82) is ''to enhance the efficiency of resource utilization by a sequential re-utilization of the same unit of a resource for multiple high-grade material applications followed by a final use for energy generation''. This principle is shown in Figure 6. Not only leads cascading to longer temporary biogenic carbon storage and thus a delay in CO_2 emissions, it also stimulates circularity in the built environment. By maximizing and reusing wood-based products in the built environment, significant amounts of carbon can be stored for a long period of time. Van Stijn (2021) shows that the (cumulative) carbon storage potential in the Dutch built environment for example is 0,3 to 8,2 Mton over the period 2020-2050.

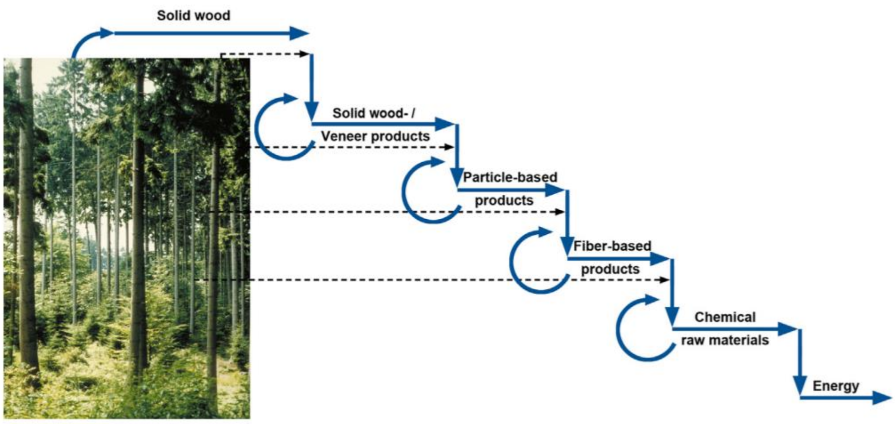


Figure 6: Cascading wood in wood-based products (image from: Höglmeier et al. (2013))

Sustainable forest management versus postponed logging

Due to the above mentioned beneficial impacts of wood-based products, logging trees can result in CO_2 mitigation due to product substitution. According to Ouden et al. (2020), especially in long term CO_2 mitigation routes, logging is favoured over an alternative scenario with postponed logging. Ouden et al. (2020) compared a scenario in which wood is used to substitute energy intensive construction materials and fossil fuel energy generation, against a scenario in which logging is postponed from 2013 till 2030. In the latter scenario traditional construction materials and fossil fuels are used but forests are allowed uninhibited growth. Ouden et al. (2020) shows that while carbon sequestration in a forest is bound to a maximum (as seen in Figure 4), carbon sequestration in wooden products is cumulative. Over time, the substitution of energy intensive construction materials and fossil fuels will therefore accumulate and result in more CO_2 mitigation compared to uninhibited forest growth. Furthermore Ouden et al. argue that, in a postponed logging scenario, carbon sequestration mainly occurs in already existing trees instead of new trees. As a result, carbon sequestration rates decreases over time. Partially due to the absence of rejuvenation and thinning methods, less young trees are able to develop. The absence of forest management furthermore results in less resilient forests (Ouden et al., 2020). These findings argue in favour for utilizing wood-based construction materials in the built environment.

Carbon storage in concrete

Wood-based products are not the only construction products that sequester carbon. Academic literature suggests that CO_2 absorption by concrete might be an additional relevant factor when comparing CO_2 emissions of different types of building materials (Dodoo et al., 2019; Lagerblad, 2005; Pade & Guimaraes, 2007). The process of CO_2 absorption in concrete is called ‘carbonation’. Since this study aims to take natural carbon storage in construction products into account in a LCA, the attribution of carbonation is taken in consideration as well. Appendix I shows the relevant theory behind the carbonation process.

Life cycle analysis via EN 15804

In order to assess and compare environmental impacts of a product, process or system, a life cycle analysis (LCA) is a useful tool. LCA frameworks allow researchers to link quantifiable environmental impacts over a full life cycle to the core function of a product (Jolliet et al., 2015). Consequently, the impacts of different products which have the same function can be compared. This study will conduct a LCA according to the European EN 15804 standard and the Dutch implementation framework.

Dutch implementation framework

The Dutch implementation framework (Nationale Milieudatabase, 2020a) is based on the EN 15804 (European Standardization, 2019) and is shown in Figure 7. The EN 15804 prescribes general rules, called 'core Product Category Rules' (cPCR), to construct 'Environmental Product Declarations' (EPDs). These EPDs contain the environmental impact of different construction products used in buildings and infrastructural constructions. Based on the cPCR, countries develop specific Product Category Rules (PCR) for country specific EPDs (Allacker et al., 2013). The Dutch PCR are shown in Stichting Nationale Milieudatabase (2020). This document (Nationale Milieudatabase, 2020a) is the Dutch determination method which provides the PCR and calculation rules to calculate the MPG-score. The 'MPG score' stands for 'Milieu Prestatie Gebouwen' in Dutch which translates to 'environmental performance buildings'. The MPG reflects the score of a building based on a number of impact categories.

Via the calculation rules in the Dutch determination method (Nationale Milieudatabase, 2020a), EPDs are used to calculate the environmental impact of the whole life cycle of a building. This is done via certified calculation tools based on the calculation rules prescribed in the Dutch determination method (Nationale Milieudatabase, 2020a). These certified calculation tools use a database with Dutch EPDs called the 'Nationale Milieu Database' (NMD, 'National Environment Database' in English). The EPDs in this database are mainly provided by product manufacturers and are validated by the NMD. EPDs are divided over category 1 and category 2 (see Figure 7). Category 1 EPDs are bound to a specific brand and category 2 EPDs represent industry group products (Nationale Milieudatabase, 2021a). When no validated EPDs are available in the NMD, default EPDs created by the NMD based on EcoInvent 3.5 (Nationale Milieudatabase, 2020a). The EcoInvent 3.5 process database also functions as LCA input for category 1 and 2 EPDs according to Stichting Nationale Milieudatabase (2020).

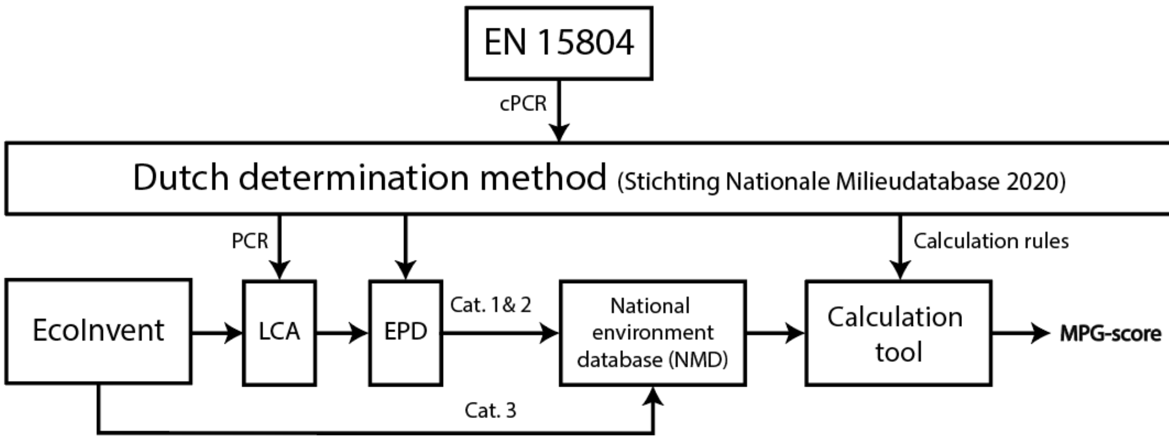


Figure 7: Dutch framework used to calculate MPG score based on the EN 15804 (based on Stichting Nationale Milieudatabase, 2020).

Functional Unit

The environmental impacts of Dutch buildings are summarized in a single MPG-score and normalized to a building's 'functional unit' (FU). A FU reflects the core function of a system or product (Jolliet et al., 2015). For building LCAs, the most commonly used FU is 1 m^2 of floor space over a time period (Abd Rashid & Yusoff, 2015). Other examples of FU in building LCAs are a single building or a m^2 of wall or other building element. In the Dutch determination method, the MPG score is expressed in m^2 Gross-Floor-Area (GFA) per year (Nationale Milieudatabase, 2020a).

Global Warming Potential

This study uses the Dutch implementation of the EN 15804 LCA framework and the Dutch PCR to calculate the impacts of a mass timber building and a reference traditional building. Although the PCR allows a number of environmental impacts to be explored, the 'Global Warming Potential' (GWP) is focussed upon. This impact category is most relevant for mass timber buildings due to the effects of wood-based construction products on the carbon cycle. The GWP is the most commonly used indicator to shows a subject's related contribution to climate change (Breton et al., 2018). It indicates the increases in radiative forcing due to Green House Gas emissions (GHG) such as CO_2.

According to the IPCC (2001), radiative forcing is the phenomenon of changes in the earth's climate due to differences in the amount of energy entering and leaving the earth. GHG emissions, such as CO_2, N_2O and CH_4, absorb energy and thus prevent energy from leaving earth (US EPA, 2016). This increase in energy in the earth's atmosphere results in global warming. More specifically, the GWP measures the energy absorption of a specific Green House Gas over a specific time period. Usually this time period is 100 years and expressed as GWP_{100}. The GWP_{100} is also used in the EN 15804 (Nationale Milieudatabase, 2020a). Since different gasses have different absorption characteristics, the GWP of various gasses is measured relative to 1 ton of CO_2 emissions and therefore expressed in 'CO_2-equivalents' (CO_2-eq).

Spatial and temporal scope

The period of time in which environmental impacts are measured in a LCA can differ depending on the goal and scope of the project. A cradle-to-grave LCA or cradle-to-cradle LCA covers the time period from the start of resource extraction (cradle) to the EoL (grave) or recycling (cradle). A LCA focussed on the production phase is called a cradle-to-gate LCA, which covers the point of resource extraction to product release from the factory gate (Jolliet et al., 2015). The MPG-score is calculated via a cradle-to-grave or cradle-to-cradle LCA over a time period of 100 years. 75 years of this time period are regarded as the building's lifespan. All environmental impacts from resource extraction till End-Of-Life are taken into account.

Table 2 shows all relevant LCA phases in the MPG calculation according to the EN 15804 standard.

Table 2: MPG time scope (Nationale Milieudatabase, 2020a).

LCA timespan 100 years (building lifespan 75 years)				
Production	**Construction**	**Usage**	**Demolition**	**Recycling**
[A1] Resource extraction [A2] Resource transport [A3] Production processes	[A4] Material transport to site [A5] installation on site	[B1] Product use [B2] Maintenance [B3] Reparation [B4] Replacement [B5] Renovation [B6] Energy usage product [B7] Water usage product	[C1] Demolition [C2] Waste transport [C3] Waste disposal [C4] Landfill	[D] Energy recovery & recycling

CO_2 balance in EN 15804

CO_2 emissions, uptake and storage in- and from wood-based products happens in various phases described in Table 2. Figure 8 shows where CO_2 emissions from wood-based products are relevant in the life cycle of a building, based on the EN15804 (European Standardization, 2019). Appendix II shows a larger depiction of Figure 8. On the bottom of Figure 8 the different life cycle phases are shown, with the respective temporal boundaries above. In the EN 15804, environmental impacts start being counted from the moment of resource extraction at [A1] till EoL in the demolition phase [C]. Along the process of building a house, using it and demolishing it a number of emissions occurs. For instance, emissions for the production of materials needed for reparation at [B3] in Figure 8. The EN 15804 prescribes that the GWP of all GHG emissions are measured over a time period of 100 years. After 75 years of building usage, the building is assumed to be demolished. Various EoL scenarios are applicable depending for wood-based products in the waste disposal phase at [C3] in Figure 8. In case of energy generation via incineration of biomass, emission mitigation can be expected as previously explained. In addition, emission mitigation also occurs when products are recycled and prevent the production emissions of a virgin product. According to the European Standardization (2019), these beneficial substitution effects are shown in module [D] in Table 2 and Figure 8. As shown in Figure 8, biogenic carbon is stored during the whole life cycle till EoL.

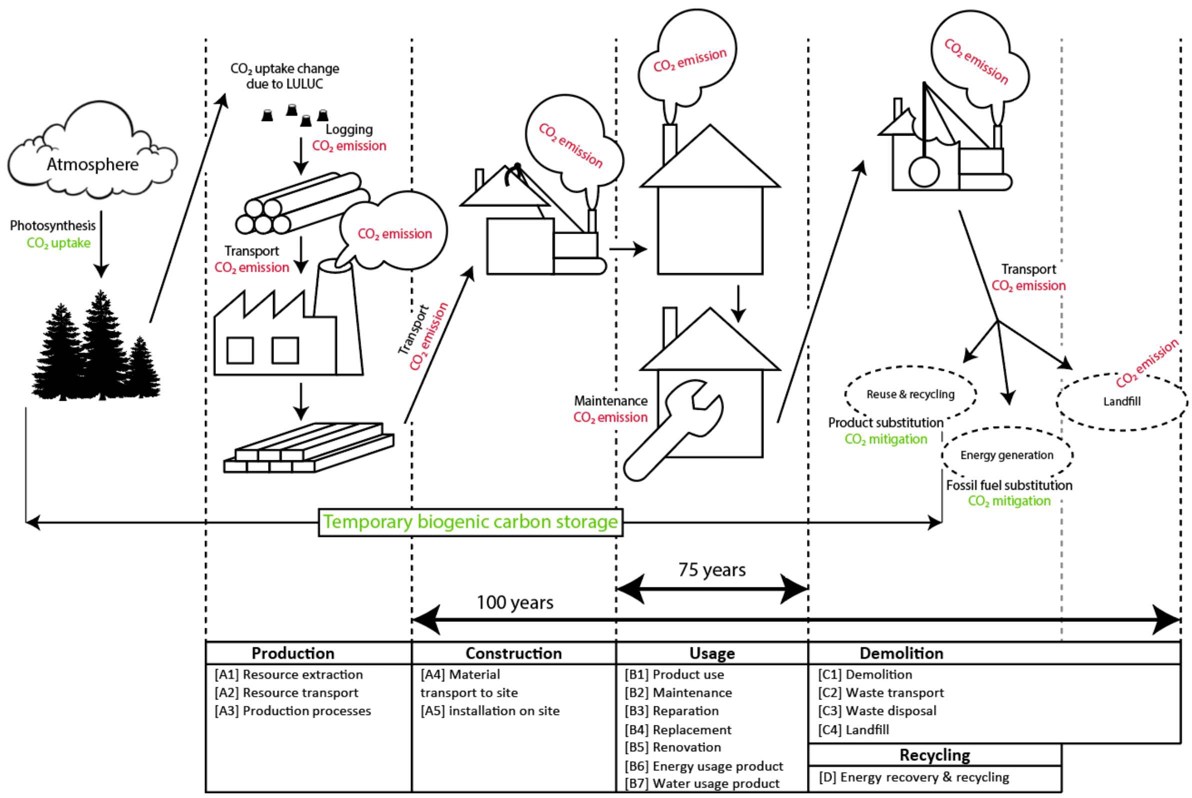


Figure 8: CO_2 emissions of wood-based products in the life cycle of a building, implemented on EN15804 LCA framework.

Allocation of loads and benefits of recycled materials in module D in EN 15804

Since EN 15804 amendment A2 (European Standardization, 2019), loads and benefits due to processes that fall outside the product system have to be shown in module D (see Table 2). Virgin material substitution and energy substitution via waste incineration are regarded as benefits. On the other hand, according to EN 15804 (European Standardization, 2019), loads are assigned when material loss occurs. In module D, only the net output of secondary material can deliver loads or benefits because all secondary material input into the system is regarded as load free until the point the material exits the recycling facility. A product system can lose material when more secondary material is input than output. Due for example to material loss via landfill or incineration.

End-of-waste

The allocation of benefits and loads in module D depends on the different End-of-Life (EoL) scenarios in module C (Nationale Milieudatabase, 2020a). In case of recycling or incineration, environmental impacts of construction materials are taken into account in the LCA until the 'end-of-waste' phase is reached (Nationale Milieudatabase, 2020a). This phase is reached when the former 'waste' material is ready to be used for a new purpose and when the material does not have negative impacts on the environment anymore.

Waste classification in module D

The PCR (Product Category Rules) provide default EoL scenarios for different types of products. These scenarios can be found in Nationale Milieudatabase (2021c). An example of the waste scenarios of concrete and wooden beams are shown in Table 3. When an EPD is constructed, the LCA executer can also choose to develop their own EoL scenarios (European Standardization, 2019). If this option is chosen, the secondary material output must be classified either as 'product for reuse', 'material for recycling', 'material for energy recovery' or 'exported energy' (European Standardization, 2019). The distinction between 'material for energy recovery' and 'exported energy' depends on whether the energy recovery happens in the respective system or in a new system. In the case of wood-based products in this category, the wood is shredded before it reaches the 'end-of-waste' phase and is regarded as 'material for energy recovery' (Nationale Milieudatabase, 2020a). In case of reuse and recycling, a resource equivalent is constructed which is compensated for quality loss and representativity of the recycled material (European Standardization, 2019).

Table 3: waste scenario of concrete and wooden beams, according to Nationale Milieudatabase (2021c).

Division of EoL destinations [%]					
Construction product	*Leave in construction*	*Landfill*	*Incineration (energy generation)*	*Recycling*	*Reuse*
Concrete	0	1	0	99	0
Wooden beams	0	5	80	10	5

Default references product & fuel substitution

According to the Dutch determination method several default values are applicable in the recycling phase [D] (Nationale Milieudatabase, 2020a). Besides standard transport distances and methods, the determination method prescribes default references for fuel and product substitution. Nationale Milieudatabase (2020) prescribes that in both fuel and material substitution, a resource-equivalent needs to be specified. This equivalent reflects the amount of primary material or fuel can be substituted in by the usage of secondary material. Material losses in the recycling or reusage process are taken into account (Nationale Milieudatabase, 2020b). Furthermore, a quality factor is taken into account that incorporates a decrease in the quality of reused products (Nationale Milieudatabase, 2020b). In the case of fuel substitution via waste incineration, the Nationale Milieudatabase (2020) provides efficiencies of 18% for electricity generation and 31% for heat generation. In addition, a reference is provided for both fossil based waste materials as renewable waste materials. Nationale Milieudatabase (2020a) shows that the reference fuels reflect the current emissions of the electricity and heat generation. Grid decarbonisation is not taken into account (Royal Institution of Chartered Engineers, 2017). A reference of electricity & heat generation via natural gas for fossil fuels and wood chips incineration for renewable waste materials such as wood.

Methods for accounting for carbon storage in LCAs

As shown in Figure 8, biogenic carbon is stored for a significant amount of time in the building life time. Different academic methods and opinions regarding allocating a value to the delay in emissions due to carbon storage in LCAs exist (Hoxha et al., 2020). Hoxha et al. (2020) conducted a study in which the three most common biogenic allocation approaches were explored. These approaches are: the ‘carbon neutral approach’ (also known as ‘0/0 approach’), ‘-1/+1 approach’ and a ‘dynamic LCA approach (DLCA)’.

Static approaches

The carbon neutral and ‘-1/+1 approach’ are dubbed static approaches, since they do not take the time aspect of biogenic storage into account (Hoxha et al., 2020). The carbon neutral approach assumes that no net difference in CO_2 emissions occurs since all biogenic storage is released during incineration or decomposition at the EoL. This approach does not require tracking the biogenic carbon through the LCA. Figure 9 shows this approach. The different modules from Table 2 are shown in the illustration as well. The dotted lines between the systems show the systems that fall outside the LCA scope. Hoxha et al. (2020) claims that in contrast to biogenic carbon, the release of biogenic methane (CH_4) does have to be mentioned in the carbon neutral approach.

Hoxha et al. show that the -1/+1 approach on the other hand does track all the biogenic carbon flows through the LCA. This approach also shows the amount of biogenic carbon in secondary materials (module [D]), but assumes eventually their emissions at EoL result in no net GWP impact. Figure 10 shows the ‘-1/+1 approach’ with the respective GHG that are tracked, according to Hoxha et al. (2020). The carbon neutral approach and -1/+1 approach are similar in the way that they both do not award a value to the temporary biogenic carbon storage.

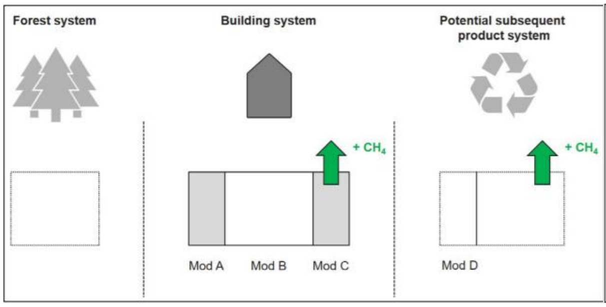


Figure 9: Carbon neutral approach, (figure 1from Hoxha et al. (2020).

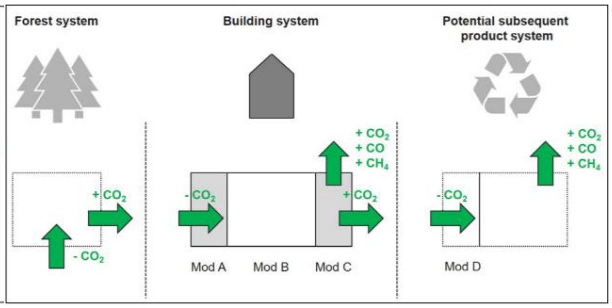


Figure 10: '-1/+1 approach', (figure 2 from Hoxha et al. (2020).

Dynamic approach

The third approach that is explored in Hoxha et al. (2020) is often referred to as a 'dynamic LCA approach' (DLCA). In contrast to static approaches, this approach takes temporal considerations into account. Within DLCAs there exist two ways of timing the carbon sequestration in biomass (Levasseur et al., 2010). One DLCA approach assumes the respective forest is fully regrown after tree harvesting before the respective building is constructed. This means the LCA assumes the building construction starts off with negative emissions due to biogenic storage in the wood-based construction products. This approach is visualized in Figure 11. The other approach accounts for sequestration gradually after logging. During the full LCA time scope, the forest regrows the removed biomass which results in an uptake of CO_2 emissions over time. This approach is depicted in Figure 12. Both approaches are based on sustainable forest management and hence assume that all harvested biomass will be regrown. Worth mentioning is that the above mentioned DLCA approaches do not take additional carbon sequestration into account when traditional construction materials are used instead of wood-based materials. One could argue that by mitigating logging, additional CO_2 is harvested in the respective forest. This approach is only featured in the comparison of logging versus postponed loggin by Ouden et al. (2020).

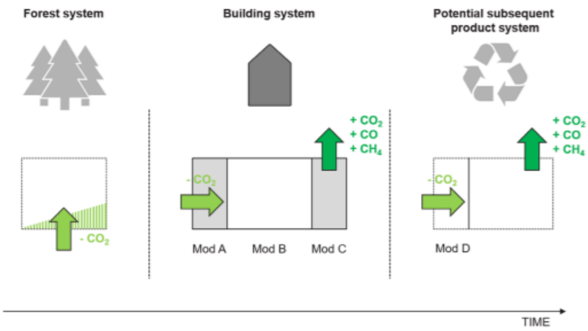


Figure 11: DLCA approach assuming fully regrown forest before building construction, (figure 3 from Hoxha et al. (2020).

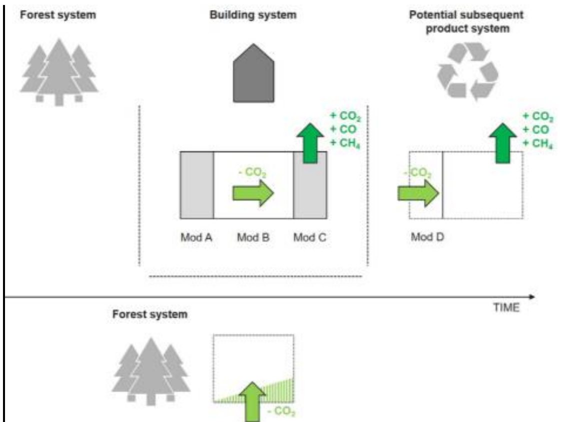


Figure 12: DCLA approach assuming carbon sequestration during LCA scope, (figure 4 from Hoxha et al. (2020).

Static versus dynamic approaches

In their study Hoxha et al. (2020) concluded that the DLCA approach (with CO_2 sequestration after construction in Figure 12) proved to be most transparent and reliable, although it presented difficulties in determining temporal boundaries. One version of this DLCA approach is the GWP_{bio}. This approach includes the temporal aspects of biogenic storage in a conventional 'static' value. The GWP_{bio} includes a mathematical approach to calculate an emission profile, which includes temporary biogenic carbon storage and sequestration in carbon sinks. Although methods such as DCLA are preferred in academic literature (Breton et al., 2018), there is currently no official EU LCA model that incorporates the benefits of temporary carbon storage.

Biogenic carbon storage in the EN15804

The present biogenic storage valuation in Dutch buildings is based on the European Standard amendment EN 15804/A2:2019 (Nationale Milieudatabase, 2020a). This standard prescribes that the amount of biogenic carbon content in a construction product at the factory gate needs to be visible in the LCA. Furthermore, according to this amendment the climate change impact indicator needs to be broken down into three subcategories: GWP_{fossil}, GWP_{luluc} and $GWP_{biogenic}$. Before amendment A2:2019 only the GWP_{100} had to be shown in LCAs based on EN 15804.

GWP subcategories

GWP_{fossil} shows the GHG emissions related to burning fossil fuels during the life cycle of a construction material product (European Standardization, 2019). The GWP_{luluc} shows the product related GHG emissions from Land Use and Land Use Change (LULUC). Following the recommendations of the IPCC (2003), the EN15804 assumes that CO_2 uptake in forests due new tree growth after biomass removal via logging is zero (European Standardization, 2019). The $GWP_{biogenic}$ indicator shows the CO_2 removal from the atmosphere into biomass and the release of biogenic emissions back into the atmosphere at the EoL. According to the European Standardization (2019), $GWP_{biogenic}$ also takes into account biogenic carbon transfer from a previous product system. For instance, when wood-based materials are recycled.

'-1/+1 approach' in the EN15804

These additional impact categories allow a clearer view of different emission sources, but do not account a value to temporary carbon storage. The European Standardization (2019) assumes all biogenic carbon is released in the demolition module [C], which therefore results in a net zero effect. Despite the fact that the biogenic emissions are postponed for several years by utilization of wood-based construction materials in the built environment. Important to mention is that the EN 15804/A2:2019 (European Standardization, 2019) makes a distinction between temporary carbon storage (<100 years) and permanent storage (>100 years). Since the start of 2021, the Dutch PCR calculation method has implemented the changes mentioned in amendment A2:2019 (Nationale Milieudatabase, 2020a).

TNO's DLCA approach

A Dutch research institute called TNO has suggested a modification to the GWP_{bio} indicator currently used in EN 15804/A2:2019 (TNO, 2021b). As mentioned before, the EN 15804 assumes that postponing biogenic emissions does not have a beneficial effect on the GWP_{100}. (TNO, 2021a) however, argues that the net amount of emissions in the atmosphere over a 100 year timespan are significantly lower when biogenic emissions are postponed.

GWP_{100} with postponed biogenic emissions

TNO (2021b) uses the Impulse Response Function (IRF) from Joos et al. (2013) to assess the decrease in global warming potential of a delayed biogenic emissions. The IRF shows the time-dependent fraction of an emission pulse of one kg CO_2 into the atmosphere with the current background CO_2 concentration. Unlike other emissions, CO_2 is sequestrated in natural carbon sinks instead of being destroyed via chemical processes (IPCC, 2018). The IRF expresses the uptake of 1kg of CO_2 emission in these carbon sinks over time. Figure 13 shows the IRF of an emission of 1 kg CO_2 at year 0 versus a postponed emission at year 60. The emission at year 0 (blue line) represents the biogenic emission of a wood-based product according to the EN 15804. Even though the EN 15804 assumes emission happen at EoL, it does not assign a temporal value (European Standardization, 2019). Therefore in this comparison the biogenic emission can be assumed to occur at year 0. The red line represents emissions at the EoL of a wood-based product with a lifespan of 60 years. In both cases a rapid decline after emissions can be witnessed, due to the uptake in natural carbon sinks. This uptake increasingly slows down over time since not all CO_2 can be taken in by the natural carbon sinks in this timeframe (Joos et al., 2013). A significant amount of the initial emission remains in the atmosphere for millennia due to slow natural carbon storage processes explained in Joos et al. (2013).

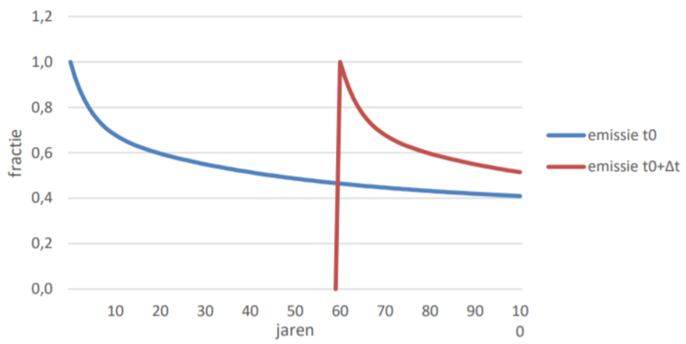


Figure 13: GWP_{100} emission with an initial emission at t=0 compared to a postponed emission at t=60 (figure 1 in TNO 2021b).

The area underneath the lines in Figure 13 shows the Absolute Global Warming Potential (AGWP) (Joos et al., 2013). By comparing the areas underneath the two lines, the difference in AGWP can be calculated. In postponed emission scenario, the area is 50% smaller compared to the scenario with emissions at year 0. This results in a halving of the global warming effect over 100 years (TNO, 2021b). Important to mention is that the TNO study only explores the potential of their GWP_{bio} indicator for the production module of the EN 15804. TNO (2021b) does not take into account the construction, usage, demolition phases and different EoL scenarios. Especially the latter is relevant since that is where biogenic emissions occur. Important to mention is that similarly to the DLCA approaches explored in Hoxha et al. (2020), the TNO GWP_{bio} is only applicable when sustainable forests management can be assumed.

The MPG score

As previously mentioned, environmental impacts of buildings and infrastructure related construction works in the Netherlands are reflected in the MPG-score (MPG stands for 'Milieu Prestatie Gebouwen' in Dutch which translates to 'environmental performance buildings'). Both the construction materials and the installations inside the building are taken into account in the MPG-score. The MPG-score expresses the shadow costs of a building per m^2 Gross-Floor-Area (GFA) per year. Therefore m^2GFA*year is the FU. Shadow costs (or MKI 'Milieu Kosten Indicator' in Dutch) are values that reflect the costs society has to pay to counter the effects of various environmental impacts (TNO et al., 2004). This monetary value depends on the costs of various methods to counter environmental impacts and takes governmental policy goals into account. Based on these inputs a weighting can be assigned to reflect the severity of impacts. The most recent shadow costs that are used in the MPG are based on TNO Milieu Energie en Procesinnovatie et al. (2004). Shadow costs have been calculated for all 11 impact prescribed by EN 15804 (European Standardization, 2019; Nationale Milieudatabase, 2020a).

Table 4 shows these impact categories with their respective most recent shadow costs. EPDs contain all 11 environmental impacts of specific construction products. By using the certified calculation tools, the EPDs are used to calculate the impact of a building over its full life cycle. The shadow costs of all construction products and installations over the full life cycle are added up and normalized to 1 m^2 GFA per year (Stichting bouwkwaliteit, 2019a). This single score is the MPG-score. The Dutch government has established a maximum MPG-score. This maximum has been changed on July 2021 from 1,0 to 0,8 and will be set to 0,5 in 2030 (RVO, 2021d).

Table 4: Impact categories and shadow costs based on (Nationale Milieudatabase, 2020a; TNO et al., 2004)

Impact category	Equivalent unit	Shadow costs [€/kg]
Abiotic resource depletion	kg Sb eq.	€ *0,16*
Fossil fuel depletion	kg Sb eq.	€ *0,16*
Global warming 100 year	kg CO_2 eq.	€ *0,05*
Ozone depletion	kg CFK-11 eq.	€ *30,00*
Photo-oxidant creation	kg C2H2 eq.	€ *1,00*
Acidification	kg SO2 eq.	€ *4,00*
Eutrophication	kg PO4 eq.	€ *9,00*
human toxicity	kg 1,4-DCB eq.	€ *0,09*
Freshwater ecotoxicity	kg 1,4-DCB eq.	€ *0,03*
Marine ecotoxicity	kg 1,4-DCB eq.	€ *0,0001*
Terrestrial ecotoxicity	kg 1,4-DCB eq.	€ *0,06*

Life Cycle Cost Analysis

When comparing two different building designs, like a mass timber house and a traditional house, the costs play an important role. Despite the general consensus being that increased wood usage in the built environment lowers CO_2 emissions (Börjesson & Gustavsson, 2000; Dodoo et al., 2019; Pajchrowski et al., 2014; Švajlenka et al., 2017; Tettey & Gustavsson, 2019), costs are as important in decision making. Life-Cycle Costing Analysis (LCCA) provides a method to evaluate all costs regarding the life cycle of a product (Petersen & Fuller, 1995). These costs can be normalized to a functional unit, similarly as by a LCA (Fuller, 2016). For building LCCA, the same units as discussed in the paragraph 'Life cycle analysis via EN 15804' apply.

Types of costs over time

According to Fuller (2016), the Life-Cycle Costs (LCC) is the sum of the costs denoted in Table 5. In the description column in Table 5, specific costs related to a building are noted. Important to mention is that the residual value in Table 5 is not a cost but an income, which needs to be subtracted from the LCC. Added to these costs are the demolition costs at the end of life of a building (also done in Marszal & Heiselberg, 2011).

Costs are often divided over 'operational expenditures' (OPEX) and 'capital expenditures'(CAPEX). LCC costs that are capitalized and part of the investment (Internal Revenue Service, 2021) are called CAPEX. OPEX costs on the other hand, are the costs related to operating the respective product/or system (Ross, 2021). Table 5 shows whether the respective cost is an operational or capital expenditure.

Table 5: Costs in a LCCA according to (Fuller, 2016).

Costs over building life time	Description	OPEX/ CAPEX
Investment costs (Invst.)	*Land costs.* Buying land for to construct a building on. *Construction costs.* Costs a contractor and construction company make. Since this is the initial expenditure, the current material prices can be used. Labour and machinery costs are also included.	CAPEX
Replacement costs (Rc)	Several building elements need to be replaced over time. These costs are recurrent depending on the specific building element's life span and the building life span. Material prices can differ over time. Labour costs are also included.	OPEX
Residual value (Rv)	*Residual value of building elements.* When building elements are replaced after their lifetime, the waste material can occasionally be sold. *Residual value of building.* After the building's lifetime the construction often still holds resale or salvage value.	-
Energy costs (Ec)	During the usage of a building, the building installations need energy. Energy prices can differ over time.	OPEX
Water costs (Wc)	During the usage of a building, the building installations use water. Water prices can differ over time.	OPEX
Operating, maintenance and repair costs (O&Mc)	Before building elements are replaced, they are first maintained and repaired. Labour costs are also included.	OPEX
Demolition costs (Dc)	At the end of the lifespan the building needs to be demolished. Life spans can differ per type of building. Labour and machinery costs are also included.	OPEX
Other Costs (Oc)	Taxes that are not related to land, construction, water or energy usage.	-

Present value

The timing of these costs is important in the LCCA due to the time-value of money. Money in the present can be lent in order to generate more money over time (Lokken, 1987). If money is not invested its value corrodes over time due to inflation. Therefore money spent to future costs needs to be discounted to a Present Value (PV) in order to reflect the current value of the future expenditures. LCC is expressed in PV by discounting the future costs to the current time via a discount rate (Petersen & Fuller, 1995). This rate shows the rate of return that an investor regards as acceptable. It can be formulated based upon the expected return of an alternative investment (Fuller, 2016). Costs are discounted yearly. Due to this mechanism, costs that occur later in the LCCA time scope are discounted more than costs that happen earlier. Figure 14 shows which costs from Table 5 happen during the building lifetime. The increments of replacement-, operations-, maintenance- and repair costs are purely visual. These costs are recurrent but the frequency is product specific.

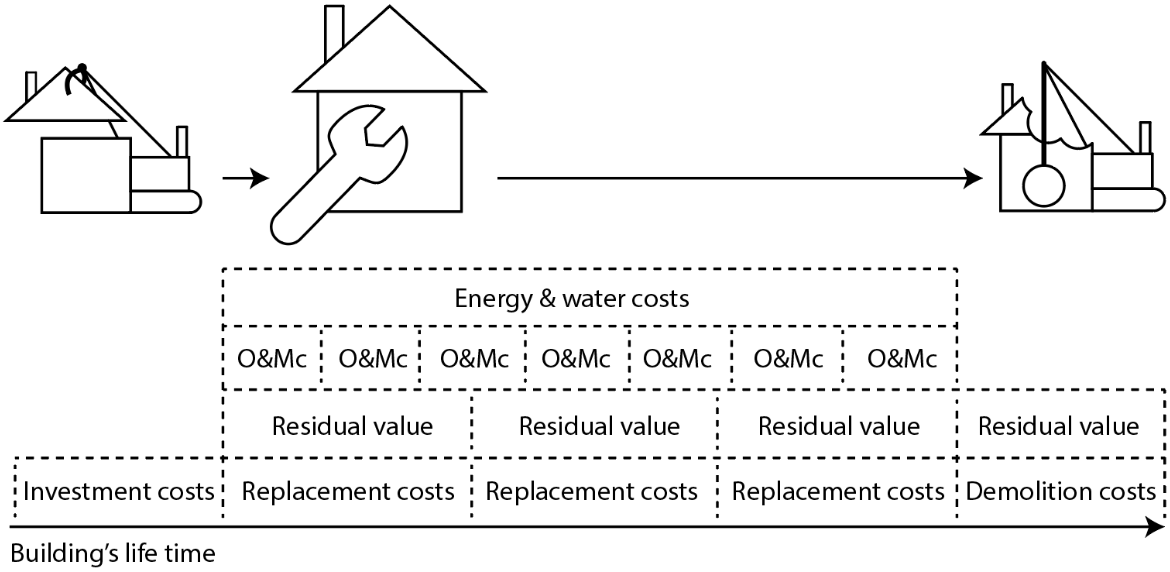


Figure 14: Occurrence of costs in a building LCCA based on Fuller (2016).

Price predictions

The costs in Table 5 depend on the amount of material, energy, water and labour used. Energy, water, material and labour prices are expected to differ in the future from the current price. Price predictions can be used to incorporate the change in prices over time. However, when the PV method is used, the price fluctuations are already taken into account in the discount factor (Fuller, 2016).

Methods

This study is an exploratory quantitative study that compares global warming potential and costs of a mass timber house and a traditional house. The CO2-eq emissions are calculated through the MPG-score calculations according to EN 15804 (European Standardization, 2019). Costs are analysed through a LLCA based on Fuller (2016). Furthermore, the effect of valuating temporary biogenic carbon storage in a LCA via TNO's (2021b) approach is explored. Since the approach in TNO (2021b) only involves the production phase, the method is extended so it takes the full EN 15804 life cycle into account. In addition to biogenic carbon storage, CO2 uptake via carbonation is also taken into account. The method used to incorporate carbonation can be found in appendix I.

Case houses

For the above mentioned calculations, two case buildings are selected that represent a mass timber house and a traditional house. Both houses are single family 3-layered flat roofed terraced houses in the Dutch built environment, shown in Figure 15. The case houses are selected based on the availability of a MPG report. MPG-scores are a mandatory deliverable when constructing a new building in the Netherlands (RVO, 2021d). The MPG calculation requires a building to be divided into building elements available in the NMD ('Nationale Milieu Database' or 'National Environment Database' in English). When a building is already divided according to this framework, conducting a LCA via EN 15804 can be done via certified calculation software.

Gross-floor-area as functional unit

Results from the LCA and LCCA are normalized to 1 m^2 GFA per year. The comparability of the LCA and LCC results is benefitted by minimum differences in GFA between the case houses. Results might be distorted when the respective buildings differ significantly in floor space. As case house GFA aim, the average GFA of a Dutch single family terraced house is used. According to Ministery van Algemene Zaken (2019), the Dutch average single family house had a Lettable-Floor-Area (LFA) of 113 m^2 in 2018. The LFA shows the functional area inside a building. This relates to a Gross-Floor-Area (GFA) of 143 m^2, when using a factor LFA/GFA of 0,76 (factor from IGG (2012)). The GFA takes the area underneath the walls into account.

Case houses are selected with 146 m^2 GFA for the traditional house and 164 m^2 GFA for the mass timber house. Using the LFA/GFA factor, the traditional house has a LFA of 111 m^2 and the mass timber house 125 m^2, see Figure 15. This means the mass timber house is slightly larger than average single family terraced house in 2018. The distortion of the LCA and LCC results due to this difference is expected to be negligible.

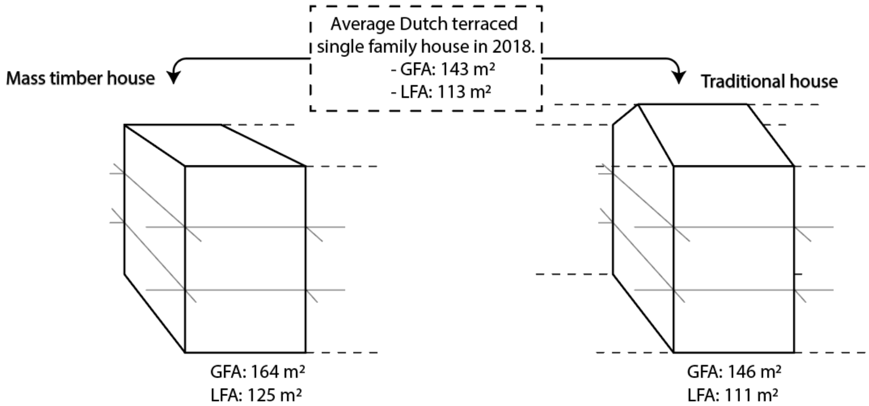


Figure 15: Case study buildings. Dotted lines show the connected buildings on the side.

Case houses descriptions

Mass timber house

The mass timber case house is depicted in Figure 15 and Figure 16. It is developed in 2020 by a Dutch modular mass timber construction company called 'Sustainer Homes'. Sustainer Homes has provided a Bill-Of-Material (Sustainer Homes, 2020a), a MPG calculation (Sustainer Homes, 2020c) and EPG calculation (Sustainer Homes, 2020b) of the mass timber case house. The mass timber house consists of several prefabricated modules which are installed and finished on site. As shown in Figure 16, the building is located on the corner and thus features one mutual wall and has a flat roof. As shown in Table 6, the building has a MPG-score of 0,59 €/m^{2}GFA*year. Furthermore, the EPG report (Sustainer Homes, 2020b) shows that the building has an Energy-Performance-Coefficient (EPC) of 0,37. The EPC was the previously mandatory score from the Dutch government to indicate the level of insulation and energy appliance efficiency (RVO, 2021c). An EPC of 0,37 correlates to A+++ energy label (A++++ being the best label possible) (TiMax, n.d.). The different construction products used in the mass timber house are shown in Table 6. Financial data of the case house, regarding material, construction, operation & management costs (O&M) or demolition costs are unavailable.

Figure 16: Conceptual visualization of terraced mass timber house

Traditional house

A MPG report of a traditional Dutch house has been supplied by 'Centrum Hout' (Centrum Hout, 2020). Centrum Hout is a representative organisation of the Dutch timber industry. The MPG calculation originates from a study (Centrum Hout, 2021b) in which traditional Dutch buildings are compared with buildings with wooden frames. The traditional terraced house's frame is made of prefabricated floors and walls which are assembled on site. All remaining construction processes, such as applying insulation and finishing layers happens on-site. A shown in Figure 15, the terraced house has two mutual walls and features a sloped roof with tiles. The house has a MPG-score of 0,68 €/m^{2}GFA*year (Centrum Hout, 2020).

Energy Performance Coefficient

Due to the unavailability of a EPG report, it is assumed that the traditional case house has an EPC of at least 0,4. According to one of the amendments in the EPC requirements of 2015 (Minister voor wonen en Rijksdienst, 2014), it is stated that new houses constructed in 2015 need an EPC of at least 0,4. The MPG calculation from Centrum Hout originates from 2020, which makes it assumable that the conceptual building had to comply with the EPC requirement of 2015. Since the requirement of 0,4 was set in 2015 it is a safe assumption that a building developed in 2020 has a minimal EPC of 0,4 (A+++ energy label). Furthermore a construction example with A+++ energy label, made by the government (RVO, 2021a), shows a similar façade construction as shown in Centrum Hout's MPG calculation (Centrum Hout, 2020). Lastly, the example construction (RVO, 2021a) features solar panels of 3,5 m^2 and a heat pump. Centrum Hout's traditional house also features a heat pump and 16,5 m^2 solar panels. This information combined leads to believe that an EPC of 0,4 is a valid assumption.

Table 6: Case house building specifics.

Building specifics	Case study buildings	
	Mass timber house	*Traditional house*
Foundation	• Reinforced concrete piles • Reinforced concrete beams	• Sand soil replenishment • Reinforced prefabricated concrete piles • Reinforced concrete beams
Frame (structural walls and floors)	• LVL beams (Laminated-Veneer-Lumber) • Metal connections & guide rails	• Precast concrete walls and floors w/ integrated Expanded-Polystyrene isolation (EPS)
Floors	• Wooden floor • Glass wool insulation • Medium-Density-Fibreboard (MDF) • Chipboard • Cement fibre board	• Ceramic tiles • Gypsum screed
Inside walls	• MDF • Chipboard • Cement fibre board • Ceramic tiles • Glass wool insulation.	• Plaster blocks • Ceramic tiles • Plasterboard • Plaster • polyurethane foam isolation (PUR)
Façade	• Masonry wall • Triple glass windows • Wooden window frames & doors	• Masonry wall • Triple glass windows • Wooden window frames & doors
Roof	• Chipboard • MDF • polyurethane foam isolation (PUR) • Ethylene-Propylene-Diene-Monomer roof finish (EPDM)	• Ceramic roof tiles • Glass wool insulation • Wooden roof elements
Energy installations	• Heat pump • Electric boiler • 8 m^2 solar panels • Ventilation system	• Heat pump • 16,5 m^2 solar panels • Grid electricity demand of 2.174 kWh
Heating	• Floor heating	• Floor heating • Radiators
MPG-score	0,59 €/GFA	0,68 €/m^2
EPG-score (& energy label)	0,4 (A+++)	0,4 (A+++)

Case house comparability

Besides different construction materials, the case houses differ in multiple ways.

One mutual wall

First of all the mass timber house has only one mutual wall, compared to two mutual walls in the traditional house, see Figure 15. This results in a difference in masonry and insulation usage. The traditional house features roughly 1/3 less masonry surface compared to the mass timber house. Furthermore, the amount of façade insulation in the traditional house corresponds to the area of the masonry cladding. Hence, the amount of masonry and façade insulation will be corrected with a factor of 1,50. The same factor will be applied to windows (glass & frames). After correction, both houses will conceptually have one mutual wall.

Flat roof

Another difference between the two case houses is the pitched roof of the traditional house and the flat roof of the mass timber house. The pitched roof will be switched to a flat roof to preserve comparability. Design of the flat roof is taken from a MPG calculation concerning a newly constructed building from the same typology from Noorman (2019). Material volumes are scaled based on the GFA.

Representativeness of the case houses

Mass timber house

Although the mass timber house from Sustainer Homes is a realized mass timber project, its composition might not reflect the average mass timber building. Different types of EWPs (Engineered Wooden Products) such as CLT could be used in other projects instead of LVL. It is assumed though that Sustainer Homes uses the most applicable EWP for their constructions.

Weights, costs and emissions of the mass timber house are compared to other studies for validation. Comparisons in weights, costs and CO_2 emissions between Dutch traditional buildings and timber frame constructions are found in (Centrum Hout, 2021b). This comparison is limited though. Centrum Hout (2021b) only shows differences in costs of a traditional house versus a mass timber house made from CLT frame (cross-laminated-timber) instead of LVL. Differences in CO_2 emissions from Dutch traditional and timber frame construction are found in W/E adviseurs (2016). Results of this study are compared with Centrum Hout (2021b) and W/E adviseurs (2016) in order to assess the differences in CO_2 mitigation between timber frame constructions, mass timber and traditional houses. Švajlenka et al. (2017) also shows a comparison of costs, weights and GWP with carbon storage of a traditional house and prefabricated wooden panel construction in Slovakia. This wooden panel construction is similar to a mass timber house. A difference compared to the mass timber house in this study is that the frame is made of beams and columns instead of panels (Sustainer Homes, 2020a). However, Švajlenka et al. (2017) only explores the cradle-to-gate (production phase). This makes GWP comparison difficult, but still allows comparison of construction costs and weights with this study. Studies from Sathre & Gustavsson (2007, 2009) also show costs and weights but differ too much in methodology or construction structure to be comparable with this study.

Traditional house

The traditional house from Centrum Hout (2020) validated in order to confirm that is an accurate representation of the average Dutch terraced building. First, the composition of the construction materials used in the traditional house will be compared with the conceptual average Dutch terraced building used in EIB et al. (2020). The MPG-score of the traditional house is compared with W/E adviseurs (2017). In W/E adviseurs (2017), the MPG-scores of 1000 existing and 200 more recent Dutch houses are thoroughly analysed. Average MPG-scores are divided over different typologies, among which corner terraced houses. Details regarding impact division over different impact categories or building elements is not shown.

Material comparison

A thorough analysis of the material composition of the case houses is required to get an understanding of the share of different materials in both buildings. The materials are compared based on their weight attribution.

Material division process

The MPG reports of both buildings (Centrum Hout, 2020; Sustainer Homes, 2020c) provides detailed information regarding the dimensions of specific construction products. All the construction products are listed in the NMD, which can be accessed via the online viewer of the NMD (Nationale Milieudatabase, 2021b). Most of the products in the NMD are provided with relevant product information (thickness, density and product composition). By combining the volumes acquired via the MPG reports and the product specifics in the NMD viewer, a material division based on weight is made. In case densities and material compositions are not specified in the NMD viewer, densities from Koezjakov et al. (2018) and Sustainer Homes (2020a) are used. Furthermore, specific material composition is shown in relevant EPD, if available. If the product information is not shown in the NMD viewer and respective EPD is unavailable, the material division will be based on comparable products found online. The division framework can be found in appendix III. The material division process is visualized in Figure 17.

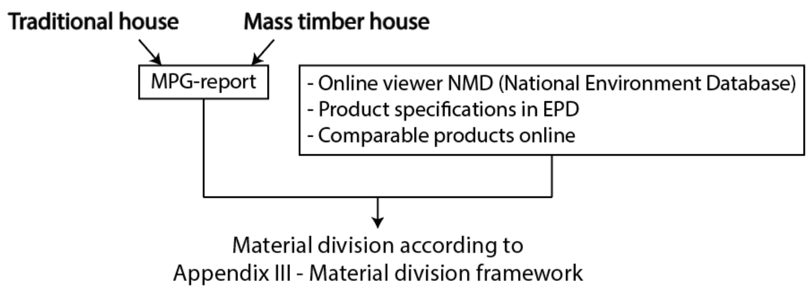


Figure 17: Material division process.

Installations, built-ins and soil replenishment

Important to note is that stairs, windows and doors are taken into account in the weight and material comparison. To ensure comparability, the same amount and type of doors and stairs are assumed. The type and characteristics of the doors and stairs can be found in appendix V. Windows and window frames are assumed to be case house specific. Both plastic, aluminium and wooden frames are frequently used. Therefore the decision to use wooden frames will be reflected in the environmental impacts and costs. Furthermore, built-ins such as kitchens, showers and toilets are not taken into account. In addition, installations such as heat pumps, solar panels and boilers are also disregarded in the material comparison.

It is assumed that the installations and built-ins do not depend on the different construction materials used in the case buildings. Furthermore, both buildings are assumed to have the same A+++ energy label, which makes it assumable that the buildings feature similar insulation values. Therefore, both case houses can have similar installations and built-ins without resulting in differences in the case house specific energy performance. When similar installations are assumed, they can be disregarded in the comparison because they will not result in material differences.

Built-ins, concerning sanitation and kitchens on the other hand, depend rather on the home owner's choice than on construction materials. Therefore these are assumed to be interchangeable as well. When similar built-ins are assumed, the related material use can be crossed out against each other as well. Lastly, soil replenishment is used only in the traditional house. It is assumed that the need for soil replenishment depends on the specifics of the soil of the relevant building plot and not on material differences between both case houses. This can therefore be left out in the comparison.

Environmental impact comparison

This study compares the environmental impact and global warming potential (GWP) of a mass timber building and a traditional building. A life cycle analysis based on EN 15804 and the Dutch implementation framework (see Figure 7) is used to calculate the MPG-score of both base houses. Since the MPG score reflects 11 impact categories (see Table 4), the general environmental impact is shortly explored. The main focus in this study is exploring the reduction in GWP. Since the MPG-score is expressed in shadow costs per m^2GFA per year, the same functional unit is used for the GWP. Hence, the GWP is expressed in kg CO_2-eq/m^2GFA per year.

Assessing the MPG score

The verified MPG calculation tool 'GPR Gebouw' (W/E adviseurs, 2021) is used to conduct the building LCA. This tool takes into account the calculation rules prescribed by the Dutch determination method. Via GPR Gebouw software (W/E adviseurs, 2021), the building elements provided by the MPG reports of the case houses are selected for the LCA. The software calculates the environmental impact of the 11 impact categories of all construction products for each phase (DGMR, 2011). Following up, the 11 impacts are added up per life cycle phases. This is shown in equation 1, from DGMR (2011). Next, each individual impact category is multiplied by their respective shadow costs as shown in equation 2. Lastly, the MPG-score is calculated via equation 3.

Worth mentioning is that the MPG calculation software (W/E adviseurs, 2021) does not show the results divided over the different life cycle phases. Therefore the analysis and comparison of environmental impacts is limited to the full life cycle and no particular life cycle phases.

$$\text{[Eq 1]} \quad Mef_{bw} = \sum_{ph}^{n} Mef_{ph}$$

$Mef_{wb,I}$ = environmental impact building over full life cycle [kg eq], ph = life cycle phases from Table 2, n = maximum of 5 phases, Mef_{ph} = environmental impact per life cycle phase [kg eq] from Table 2.

$$\text{[Eq 2]} \quad MKI_{bw} = \sum_{i}^{n} Mef_{bw,i} * Wef_{i}$$

MKI_{bw} = Shadow costs building over full life cycle [€], i = environmental impact from Table 4, n = maximum of 11 impacts, $Mef_{wb,I}$ = environmental impact building over full life cycle [kg eq], Wef_i = shadow costs per kg environmental impact [€/kg eq] from Table 4.

$$\text{[Eq 3]} \quad MPG = \frac{MKI_{bw}}{75\ years * GFA}$$

*MPG = impact score in [€/GFA*year], MKI_{bw} = Shadow costs building over full life cycle [€].*

GPR gebouw (W/E adviseurs, 2021) shows all 11 impact categories over the full building life cycle as well as the MPG-score. Hence, the GWP impact category can easily be singled out and normalised to the functional unit (m^2GFA per year). This is calculated via equation 4 and 5.

$$\text{[Eq 4]} \quad GWP = \sum_{ph}^{n} Mef_{ph,GWP}$$

GWP = global warming potential building over full life cycle [kg eq], $Mef_{ph,GWP}$ = global warming potential per phase [kg eq], ph = life cycle phases from Table 2, n = maximum of 5 phases.

$$\text{[Eq 5]} \quad GWP_{norm} = \frac{GWP}{75\ years * GFA}$$

*GWP_{norm} = global warming potential normalized to the functional unit [€/GFA*year]. GWP = global warming potential building over full life cycle [kg eq].*

Modified MPG calculation

Valuating the temporary biogenic carbon storage and carbonation during the life cycle of a building decreases the GWP of a building (Dodoo et al., 2019; Hoxha et al., 2020; Lagerblad, 2005; Pade & Guimaraes, 2007; TNO, 2021b). Therefore, the reduction will have to be subtracted from the original GWP of both case houses. Equation 6 and 7 are used to calculate the modified GWP of both case houses. Note that GWP_{bio} and GWP_{carb} are negative emissions. The MPG that takes temporary carbon storage and carbonation into account is denoted as 'MPG_m'. Equation 8 shows the modified MPG calculation (based on eq. 3).

$$\text{[Eq 6]} \quad GWP_m = GWP + GWP_{bio,red} + GWP_{carb,red}$$

GWP_m = global warming potential building over full life cycle, taking biogenic storage and carbonation into account [kg eq], GWP = global warming potential building over full life cycle [kg eq], $GWP_{bio,red}$ = decreased GWP due to delay in biogenic emissions [kg], $GWP_{carb,red}$ = decreased GWP due to uptake of carbon via carbonation.

$$\text{[Eq 7]} \quad GWP_{m,norm} = \frac{GWP_m}{75\ years * GFA}$$

*$GWP_{m,norm}$ = global warming potential (that takes biogenic storage and carbonation into account) normalized to the functional unit [€/GFA*year]. GWP_m = global warming potential building over full life cycle, taking biogenic storage and carbonation into account [kg eq].*

$$\text{[Eq 8]} \quad MPG_m = \frac{MKI_{bw} + (Wef_{GWP} * (GWP_{bio,red} + GWP_{carb,red}))}{75\ years * GFA}$$

*MPG_m = modified impact score in [€/GFA*year], MKI_{bw} = Shadow costs building over full life cycle [€], Wef_{GWP} = shadow costs of CO_2-eq [€/kg eq] from Table 4, $GWP_{bio,red}$ = decreased GWP due to delay in biogenic emissions [kg], $GWP_{carb,red}$ = decreased GWP due to uptake of carbon via carbonation.*

The method of calculating the GWP reduction due to temporary biogenic storage and carbonation is explained in the paragraph 'Biogenic carbon' and appendix I respectively.

Original MPG calculation

GPR Gebouw works with the newest release of the PCR (version 1.0 from July 2020) (Nationale Milieudatabase, 2020a). Therefore, the MPG results will differ slightly from the original MPG-score due to changes in the PCR.

LCA scope

The Dutch LCA calculation rules based on EN 15804 (European Standardization, 2019), prescribe a number of rules specified to the Dutch built environment. Stichting bouwkwaliteit (2019a), for instance, prescribes that impacts from life cycle phases [B6] 'energy usage product' and [B7] 'water usage product' is not taken into account in the LCA calculation. It is explained that the MPG focusses solely on material related impacts (Stichting bouwkwaliteit, 2019a). Furthermore 'energy usage of the product' concerns the efficiency of the energy installations. This is already reflected in the EPG. Hence, this study will also disregard life cycle phases [B6] and [B7].

Furthermore, important to mention is that changes in fuel related emissions due to grid decarbonisation are not taken into account in the EN 15804 (Royal Institution of Chartered Engineers, 2017). Therefore, grid decarbonisation is also not taken into account in the method of this study.

Figure 18 shows the scope and system boundaries of the LCA in this study. Figure 18 also shows the system boundaries of the original MPG calculation and the modified MPG calculation used in this study. Both MPG methods consider emission from resource extraction, till various EoL scenarios including loads and benefits in module [D]. As previously mentioned, the modified MPG will take temporary biogenic storage and carbonation into account. This is visualized on the bottom of Figure 18. The carbonation graph shows the gradual uptake of CO_2 over time. The temporary carbon storage graph shows the graph of TNO (2021b), which reflects the delay in biogenic emissions.

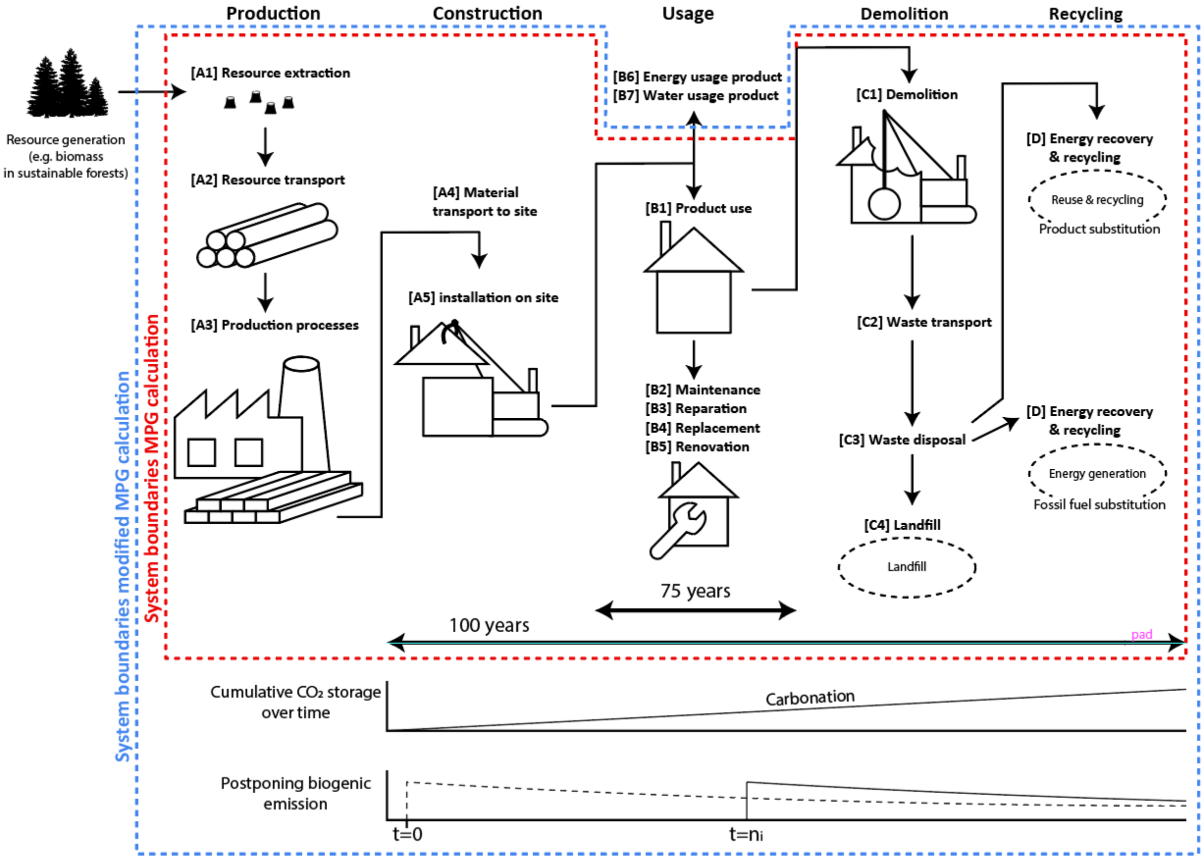


Figure 18: Scope of the LCA. Red dotted line shows the system boundaries of the original MPG calculation. Blue dotted line shows the system boundaries of the modified MPG calculation. LCA framework is based on EN 15804. N_i = time of biogenic carbon emission from construction product (i).

Installations, built-ins and soil replenishment

Similar to the material comparison, the environmental impact will assume that both case houses feature the same built-ins, installations and no soil replenishment. Appendix V, shows the type and characteristics of the installations and built-ins used in both case houses. Both buildings are assumed to have the built-ins from the mass timber case house. Therefore, the environmental impact of the built-ins and installations can be crossed out in the comparison. Hence, the environmental impact comparison will focus mainly on the construction material related impacts. Table 7 shows in which subdivision the MPG and GWP in the environmental results are expressed.

Table 7: Types of MPG-scores and GWP used to reflect the environmental impact of the case houses.

Type of MPG-score & GWP	Built-ins & installations	Biogenic storage and carbonation in to account
MPG	Built-ins & installations from original MPG reports.	No
MPG_{sim}	Same built-ins & installations shown in appendix V.	No
MPG_{mat} & GWP_{mat}	No built-ins & installations taken into account.	No
$MPG_{m,mat}$ & $GWP_{m,mat}$	No built-ins & installations taken into account.	Yes

Valuating biogenic carbon storage in the MPG

This study builds on the method of TNO (TNO, 2021b) to allocate a realistic value to the delay of biogenic emissions. Whereas TNO (2021b) only looked at the production phase of the EN 15804 norm, this study constructs a method that considers the full building life cycle. As a result, a GWP_{bio} indicator is developed that shows the reduction in GWP due to the delay in biogenic emissions. Similarly to the study from TNO (2021b) it is assumed that all wood originates from sustainable forests. This assumption is validated by the fact that the share of sustainable produced wood was 83% in the Netherlands in 2015 (CBS, 2021).

Biogenic carbon content

The European Norm EN 16449 'Wood and wood-based products' prescribes the standard formula to calculate the amount of biogenic CO_2 the stored carbon in wood-based products can result in. Note that the carbon needs to react with oxygen in order to result in a CO_2 emission. Centrum Hout (2021a) developed a carbon calculator tool based on this European norm. The carbon calculator requires the dimensions and wood species of the specific wood-based product. This information is provided either by the NMD (Nationale Milieudatabase, 2021b), specific EPD or in similar products in the NMD. Equation 9 shows the method from EN 16449 to calculate the amount of biogenic CO in wood-based products.

[Eq 9] $$P_{CO2} = \frac{44}{12} * F * \frac{\rho_\omega * V_\omega}{1+\frac{\omega}{100}} * V_p$$

P_{co2} = biogenic CO_2 potential of product [kg], F = carbon fraction in dry wooden biomass = 50% (Royal Institution of Chartered Engineers, 2017), ρ_ω = timber density at moisture content ω, V_ω = volume of timber at moisture content ω, ω = moisture content (assumed 12% based on Royal Institution of Chartered Engineers (2017)). V_p = timber volume of construction product.

Product replacement

Nationale Milieudatabase (2021b) shows the lifespan of all construction products in the built environment. When a product does not reach the 75 year lifespan of a building, it is replaced several times. Each replacement increases the environmental impact of the building. Equation 10 shows how product replacement is incorporated in the environmental impact of a product (DGMR, 2011).

For example, when a product with a lifetime of 50 is used in a building with a 75 year lifespan, 1,5 replacements are needed over time. When the product's lifespan exceeds the building lifespan, the lifespan is shortened to 75 years (DGMR, 2011). Replacements of sub-products in a construction product are already reflected in the shadow costs of a single construction product (DGMR, 2011). The same method used in equation 10 is utilized to calculate the total amount of biogenic CO_2 potential stored in a building in equation 11.

[Eq 10] $$MEF_{p:bw} = MAX\left(1; \frac{LD_g}{LD_p}\right) * MEF_p$$

$MEF_{p:bw}$ = environmental impact product in building [kg eq/building], MAX(x;y) = maximum value x or y, LD_g = lifetime building (75 years), LD_p = lifetime product [years], MEF_p = environmental impact product.

[Eq 11] $$P_{CO2:bw} = P_{CO2} * MAX\left(1; \frac{LD_g}{LD_p}\right)$$

$P_{co2:bw}$ = biogenic CO_2 potential of product in building [kg/building], MAX(x;y) = maximum value x or y, LD_g = lifetime building (75 years), LD_p = lifetime product [years].

The Impulse Response Function

The GWP_{bio} model from TNO (2021b) is based on the Impulse Response Function (IRF). This function shows the breakdown of 1 kg of CO_2 into carbon ocean and terrestrial carbon sinks over time (Joos et al., 2013). Equation 12 shows the IRF for the breakdown of 1kg CO_2.

$$[\text{Eq } 12] \qquad IRF_{CO2}(t) = \alpha_{CO2,0} + \sum_{i=1}^{N} \alpha_{CO2,i} \exp(-\frac{t}{\tau_{CO2,i}})$$

IRF_{CO2} = time dependent fraction of initial CO2 emission impulse in atmosphere, $\alpha_{CO2,i}$ = coefficient that represents a fraction related to a nominal time scale $\tau_{CO2,i}$. Parameter values are used from Table 8.SM.10 in (Myhre et al., 2013).

The area underneath the IRF over a given time period shows the amount of GWP of the 1 kg emission over that time period (Joos et al., 2013; TNO, 2021b). This area is the time integrated IRF and is called the absolute GWP (AGWP). Equation 13 shows the AGWP, based on Joos et al. (2013).

$$[\text{Eq } 13] \qquad AGWP = \alpha_{CO2,0} * t + \sum \alpha_{CO2,i} * -\tau_{CO2,i} * \exp\left(-\frac{t}{\tau_{CO2,i}}\right)$$

AGWP = Absolute Global Warming Potential [W m^{-2} yr kg^{-1}], $\alpha_{CO2,0}$ = fraction of CO_2 that remains permanently in atmosphere, t = time horizion (years), $\alpha_{CO2,i}$ = fraction of CO_2 associated with nominal time scale $\tau_{CO2,i}$. Parameter values are used from Table 8.SM.10 in (Myhre et al., 2013).

The AGWP shows the absolute GWP of a GHG emission at a specific point in time. Figure 19 shows the AGWP of an emission of 1 kg of CO_2 at two different emission times over a 100 year time period. The 100 year time period is chosen since the GWP_{100} is used in the European Standardization (2019), which also covers a 100 time period. The blue line with emissions at year 0 reflects the EN 15804. In the EN15804 it is assumed all biogenic carbon is released again regardless of the timing (European Standardization, 2019). Since no value is given to the timing, the emission in the dynamic model happen at year 0. The blue line according to the EN 15804, is dubbed as the reference. The AGP of the reference is used to compare the decrease in GWP due to a delay in biogenic emissions. In Figure 19 the AGWP of the biogenic emission of a wood-based product is also shown (orange line). This emission occurs at the EoL of the respective product, in this case after 60 years. As shown in the picture, both emissions result in an increase in AGWP (dubbed '$\Delta AGWP$').

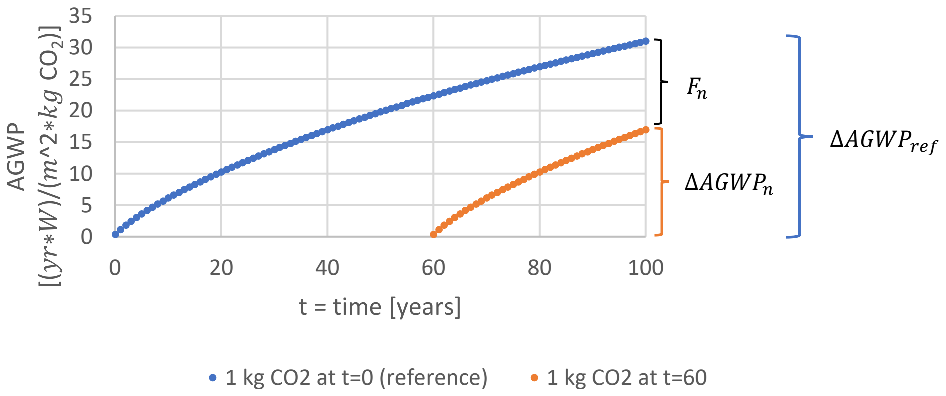


Figure 19: AGWP of 1kg of CO2 emission at t=0 and t=60; $\Delta AGWP_n$ = increase in AGWP due to biogenic emission at t=n=60; $\Delta AGWP_{ref}$ = increase in AGWP due to biogenic emission at t=0; F_n= reduction in AGWP due to biogenic emissions at year 'n' instead of year 0 [%] .

Due to the delay in emission, the AGWP increases less over the 100 year time period compared to the reference. The $\Delta AGWP_{ref}$ increases with 30,63 $\frac{yr*W}{m^2*kg\ CO_2}$, but the $\Delta AGWP_n$ only increases with 16,58 $\frac{yr*W}{m^2*kg\ CO_2}$. Thus, the delay in emission results in a 46% less AGWP increase (denoted as 'F_n'). Equation 14 shows how to calculate the reduction in AGWP due to a biogenic emission at year '*n*' instead of year 0.

$$\text{[Eq 14]} \qquad F_n = \frac{\Delta AGWP_n - \Delta AGWP_{ref}}{\Delta AGWP_{ref}} * 100$$

F_n= reduction in AGWP due to biogenic emissions at year 'n' instead of year 0 [%], $\Delta AGWP_n$ = increase in AGWP due to biogenic emission at year 'n' $[\frac{yr*W}{m^2*kg\ CO_2}]$, $\Delta AGWP_{ref}$= increase in AGWP due to biogenic emission at year 0.

The delayed emission method

Static biogenic emission framework of EN 15804

In the current Dutch determination method, which follows EN 15804, it is assumed biogenic carbon results to a negative GWP in the production phase [A1-A3] (Nationale Milieudatabase, 2020a). However, biogenic emissions are released eventually at their EoL in the demolition phase [C1-C4] (European Standardization, 2019). In case of recycling/reusage emissions are expected to be released in the demolition phase of the recycled/reused product [D]. As mentioned earlier the timing of the emissions is disregarded in the EN 15804 (European Standardization, 2019). Therefore, the division of biogenic emissions, according to the EN 15804, is dubbed as a 'static biogenic emission framework'.

Take for example the biogenic emissions of a wood-based product with 0,8 kg biogenic CO_2 potential and a lifespan of 60 years. The static biogenic emission framework of this product is shown in Table 8. The $P_{CO2:bw}$(see equation 11) of this product is 1 kg CO_2. Hence, the biogenic emissions in the production phase ($GWP_{bio,prod}$) are negative since 1 kg CO_2 is stored in the product. Furthermore, assume 10% of this product is recycled. All biogenic CO_2 is expected to be emitted within the 100 year time period used in the GWP_{100}. 90% of the 1 kg CO_2 is emitted during the demolition phase ($GWP_{bio,dem}$). The other 10% during the recycling/reusage phase ($GWP_{bio,recl\&reu}$). Table 8 shows that the net reduction due to biogenic carbon storage ($GWP_{bio,red}$) is 0.

Table 8: Static biogenic emission framework according to EN 15804, of biogenic emission of wood-based product with 1 kg biogenic CO2 potential & lifespan of 60 years.

	$GWP_{bio,p}$			
	$GWP_{bio,prod}$	**$GWP_{bio,dem}$**	**$GWP_{bio,recl\&reu}$**	
Equations:	$-P_{CO2:bw}$	$0{,}9*P_{CO2:bw}$	$0{,}1*P_{CO2:bw}$	**$GWP_{bio,red}$**$=\sum_p GWP_p$
Equations filled in:	-1 kg CO_2	0,9 kg CO_2	0,1 kg CO_2	0

Static biogenic emission framework of delayed emissions

As shown above, the current Dutch determination method results in a net reduction of 0 GWP due to carbon storage. However, Figure 19 and equation 14 show that the delay of 60 years of 1kg CO_2 emission results in a decrease of AGWP compared to reference of 46%. Furthermore, 10% of the product is recycled/reused which is released later than 60 years. As shown in Figure 19, the further an emission is pushed to the 100 year boundary, the higher the F_n becomes. Appendix VI shows the F_n of a number of biogenic emissions delayed to year '*n*'. Via equation 15, the static biogenic emission after correction for the reduced AGWP due to the delay can be calculated. Note that F_n is a negative factor.

$$\text{[Eq 15]} \qquad \mathrm{GWP}_{bio,p} = P_{CO2:bw,p} + \left(P_{CO2:bw,p} * F_n\right)$$

$$(with\ 'p' = 'dem'\ and/or\ 'recl\&reue')$$

$GWP_{bio,p}$= biogenic emissions in life cycle phase 'p' [kg CO_2]; $P_{CO2:bw,p}$= fraction of biogenic emission in life cycle phase 'p' [kg CO_2]; F_n= reduction in AGWP due to biogenic emissions at year 'n' instead of year 0 [%]; For p = demolition phase (dem) and/or recycle/reuse phase (recl&reu).

In order to calculate the $GWP_{bio,p}$ of different wood-based products, the lifespan and EoL scenarios needs to acquired. Product lifespans are shown in the NMD viewer (Nationale Milieudatabase, 2021b). The EoL scenarios are specified in the default EoL scenarios in Nationale Milieudatabase (2021c). Often EPDs specify different EoL scenarios than the default values. For instance, the EPD from NBvT (2014) shows that the wood-based product is 100% incinerated instead of being partially recycled according to (Nationale Milieudatabase, 2021d). When possible, the EPD is always preferred over the default values. Since the Dutch determination method does not provide data regarding the timing of recycling processes, recycled material losses and utilization of secondary wood material, a number of assumptions are made:

- All wood-based products reach **EoL after the 75 year lifespan** of the building. Worth mentioning is that some products have a lifespan that exceeds the 75 year lifespan of the building (Nationale Milieudatabase, 2021b). Hence, all products are expected to reach EoL after a maximum of 75 years.
- All fractions of woody biomass that are **incinerated or landfilled** at EoL result in biogenic emission at the end of the year when they reach EoL.
    - This disregards the time spent on converting the woody biomass to wood chips in case of incineration, transportation of waste and the process of incineration or decomposition itself.
    - Realistically, woody biomass can take a long time to decompose. Ximenes et al. (2008) shows that only approximately 9% of carbon was lost after 46 years of being buried in a landfill. The decomposition rate depends on a number of characteristics such as type of wood and exposure conditions (Ximenes et al., 2008). Furthermore part of the biogenic carbon is stored in the soil (Broadmeadow & Matthews, 2003).
    - This assumption simplifies the calculation because different recycling process, decomposition rates, transport times and incineration processes can be neglected.
- According to Nationale Milieudatabase (2021c), only a small percentage of wood is **recycled or reused** (5 to 10% depending on type of construction product). The specific utilization of the secondary wood is not shown in the EPDs, NMD viewer or default values (Nationale Milieudatabase, 2021b, 2021d). Hence assumptions are made regarding the usage of secondary materials.
    - Personal communication with a recycling company suggests that **100% of secondary wood goes to chipboard production**, if no other purposes are defined (Van Werven, personal communication, July 2021). This is also supported by the findings in Kim & Song (2014). Therefore, it will be assumed that all recycled woody material ends up in chipboards.
    - Furthermore, these chipboards have a **lifespan of 25 years** (Nationale Milieudatabase, 2021b). Since only a negligible fraction (5-10% according to Nationale Milieudatabase (2021c)) of the initially recycled biogenic carbon is recycled again, only one recycling cycle will be taken into account.
    - In the case of reusage, the timing of the biogenic carbon emission of the recycled biogenic carbon depends on the **lifespan of the reused product**.
- Product losses occur during the recycling and reusage process. A **wood recovery rate of 67,8%** from Kim & Song (2014) is used for the production of secondary chipboard material. Kim & Song (2014) based this recovery rate on the data of a large Korean chipboard producer.

- When reusage occurs, **a material loss of 5%** is assumed. Losses due to disassembly, possible refurbishment and material damage are assumed to be low. The 5% material loss is based on the losses of prefabricated products specified in (Nationale Milieudatabase, 2020a).
- **All material losses** are assumed to be either **decomposed** or **incinerated** and thus result in instant biogenic emission when EoL is reached.
- Emissions from the recycled/reused fraction of biogenic carbon that have a lifespan '*n*' ≥ *100*, are regarded as **permanently stored**. Appendix VI shows that at F_{99} the biogenic emission is reduced with 99,29%. In addition, reused products can have their EoL after the 100 year boundary. Therefore their emissions fall outside the GWP_{100}. Furthermore, only a small percentage is reused or recycled (5 to 10 % (Nationale Milieudatabase, 2021d)). These aspects result in a negligible contribution of emissions at the end of year 100.

Based on these assumptions the static biogenic emission of the relevant life cycle phases ($GWP_{bio,p}$) of a wood-based product can be calculated. Equation 16 – 21 shows the calculation rules of the relevant lifecycle phase.

$$\text{[Eq 16]} \quad \mathrm{GWP}_{bio,prod} = -P_{CO2:bw}$$

$GWP_{bio,prod}$= biogenic emission in the production phase [kg CO_2]; $P_{CO2:bw}$= biogenic CO_2 potential of product in building [kg/building].

$$\text{[Eq 17]} \quad \mathrm{GWP}_{bio,dem} = P_{CO2:bw,dem} + \left(P_{CO2:bw,dem} * F_n\right)$$

$GWP_{bio,dem}$= biogenic emission in the demolition phase [kg CO_2]; $P_{CO2:bw,dem}$= fraction of biogenic emission in the demolition phase [kg CO_2]; F_n= reduction in AGWP due to biogenic emissions at year 'n' instead of year 0 [%].

$$\text{[Eq 18]} \quad P_{CO2:bw,dem} = P_{CO2:bw,inc} + P_{CO2:bw,land} + (1 - 67{,}8\%) * P_{CO2:bw,recl} + (1 - 95\%) * P_{CO2:bw,reu}$$

$P_{CO2:bw,dem}$= fraction of biogenic emission in the demolition phase [kg CO_2]; $P_{CO2:bw,inc}$= fraction of biogenic emission incinerated [kg CO_2]; $P_{CO2:bw,land}$= fraction of biogenic emission landfilled [kg CO_2]; $P_{CO2:bw,recl}$= fraction of recycled biogenic emission [kg CO_2]; 22,2% material loss due to recycling; $P_{CO2:bw,reu}$= fraction of reused biogenic emission [kg CO_2]; 5% material loss due to reusage.

$$\text{[Eq 19]} \quad \mathrm{GWP}_{bio,recl\&reu} = P_{CO2:bw,recl\&reu} + (P_{CO2:bw,recl\&reu} * F_n)$$

$GWP_{bio,recl\&reu}$= biogenic emission in the recycling/reusage phase [kg CO_2]; $P_{CO2:bw,recl\&reu}$= fraction of biogenic emission in the recycling/reusage phase [kg CO_2]; F_n= reduction in AGWP due to biogenic emissions at year 'n' instead of year 0 [%].

$$\text{[Eq 20]} \quad P_{CO2:bw,recl\&reu} = 67{,}8\% * P_{CO2:bw,recl} + 95\% * P_{CO2:bw,reu}$$

$P_{CO2:bw,recl\&reu}$= fraction of biogenic emission in the recycling/reusage phase [kg CO_2]; $P_{CO2:bw,rec}$= fraction of recycled biogenic emission [kg CO_2]; 22,8% material loss due to recycling; $P_{CO2:bw,reu}$= fraction of reused biogenic emission reused [kg CO_2]; 5% material loss due to reusage.

$$\text{[Eq 21]} \quad \mathrm{GWP}_{bio,recl\&reu} = -P_{CO2:bw,recl\&reu} \; (for\; n \geq 100)$$

The decrease in global warming potential due to a delay in biogenic emissions ($GWP_{bio,red}$) can be calculated via Table 9. Table 9 shows equations 16 – 20 integrated in the static biogenic emission framework. Via this framework the $GWP_{bio,red}$ of a wood-based product with different fractions of biogenic emissions at different times can be calculated.

Table 9: Static biogenic emissions framework, via the delayed emission method.

Biogenic emissions at '*n*'	$GWP_{bio,p}$ **GWP$_{bio,prod}$**	**GWP$_{bio,dem}$**	**GWP$_{bio,recl\&reu}$**	
n1	$-P_{CO2:bw}$	$P_{CO2:bw,dem} + (P_{CO2:bw,dem} * F_{n1})$		$\sum_p GWP_p$
n2			$P_{CO2:bw,recl\&reu} + (P_{CO2:bw,recl\&reu} * F_n)$	$\sum_p GWP_p$
n ≥ 100			$-P_{CO2:bw,recl\&reu}$	$\sum_p GWP_p$
				GWP$_{bio,red}$ $=\sum_p GWP_p$

Chipboard example

For better understanding of the above mentioned calculations, an example calculation of a chipboard is given. The necessary information regarding a chipboard is shown in Table 10.

Table 10: Chipboard example, characteristics, values and sources.

Characteristics	**Values**	**Source**
Volume of wood content	1,82 m^3	(EGGER, 2021)
Biogenic CO_2 potential	1.133 kg CO_2	(Centrum Hout, 2021a)
Single lifespan	25 years	(Nationale Milieudatabase, 2021b)
$P_{CO2:bw}$	(75/25)*1.133 = 3.399 kg CO_2	
EoL scenario		
sheet material, 'clean'	5% landfill, 85% incineration and 10% recycling	(Nationale Milieudatabase, 2021d)
Material losses	22,2% due to recycling 5% due to reusage	(Nationale Milieudatabase, 2020a; Ximenes et al., 2008)

The static biogenic emissions profile of the chipboards over the full 100 year lifespan according to the EN 15804 are shown in Table 11. In total 3 chipboards are needed over the 75 year lifespan of a building in the MPG calculation. This corresponds to -3.399 kg CO_2 stored in the building's lifespan. A large part of the emissions is released at the EoL of each respective chipboard. Nationale Milieudatabase (2021c) shows that 90% of the chipboard is incinerated and landfilled. Only 10% is recycled after every product lifecycle. Via the Dutch determination method, the $GWP_{bio,red}$ of chipboard over 100 years is 0 kg CO_2.

Table 11: Static biogenic emission framework, according to the current Dutch determination method (Nationale Milieudatabase, 2020b).

$GWP_{bio,p}$ **GWP$_{bio,prod}$**	**GWP$_{bio,dem}$**	**GWP$_{bio,recl\&reu}$**	
-3.399 kg CO_2	3.059 kg CO_2	340 kg CO_2	**GWP$_{bio,red}$=0**

The biogenic emission profile becomes more complex when the delay of biogenic emissions is valuated. Figure 20 shows the dynamic biogenic emission profile of chipboard in the 100 year time period. The blue reference line shows the AGWP when all 3.399 kg biogenic CO_2 occur at year 0, as assumed in the EN 15804 (TNO, 2021b). The other lines show parts of the biogenic CO_2 being emitted at different points in time.

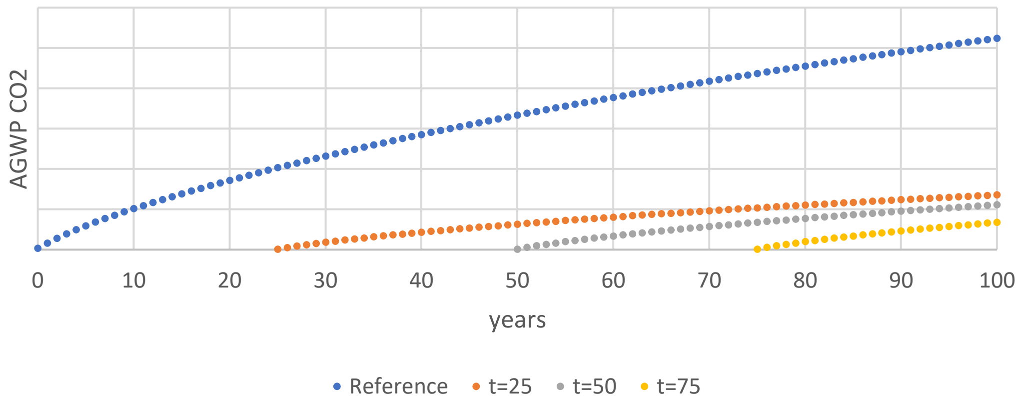


Figure 20: Dynamic biogenic emission profile of chipboard, reference line (blue) and emissions via 'delayed emission method' (orange, grey and yellow).

The delayed emission method divides the biogenic emissions in the following number of delayed emissions:

- **t=25 year** 1.056 kg CO_2 emission due to landfill and incineration of first chipboard lifecycle. ($P_{CO2:bw,dem}$= 3.399*5% + 3.399*85% + 3.399*10%*22,2% + 3.399*0%*5%)
- **t=50 year** 1.056 CO_2 emission due to landfill and incineration of second chipboard lifecycle + 77 kg CO_2 emission of recycled fraction of first chipboard cycle after 25 years.
- **t=75 year** 1.056 CO_2 emission due to landfill and incineration of third chipboard lifecycle + 77 kg CO_2 emission of recycled fraction of second chipboard cycle after 25 years.
- **t=100 year** 77 kg CO_2 emission of recycled fraction of third chipboard are regarded as permanent storage.

Table 12 shows the delayed emission method calculation based on Table 9. Reduction factors are taken from Appendix VI. The $GWP_{bio,red}$ of chipboard via the delayed emission method is -1.445 kg CO_2.

Table 12: Static biogenic emission framework of chipboard, via the delayed emission method.

Biogenic emissions at '*n*'	*GWP$_{bio,p}$*			
	GWP$_{bio,prod}$	**GWP$_{bio,dem}$**	**GWP$_{bio,recl\&reu}$**	
n=25	-1.133 kg CO_2	1.056+1.056*F_{25} = 879 kg CO_2		-254 kg CO_2
n=50	-1.133 kg CO_2	1.056+1.056*F_{50} = 669 kg CO_2	77+77*F_{50} = 49 kg CO_2	-415 kg CO_2
n=75	-1.133 kg CO_2	1.056+1.056*F_{75} = 404 kg CO_2	77+77*F_{75} = 29 kg CO_2	-699 kg CO_2
n=100			-77 kg CO_2	-77 kg CO_2
				-1.446 kg CO_2

Life Cycle Costs comparison

This study compares the life cycle costs (LCC) of a mass timber house versus a traditional house. Costs are calculated via the construction costs software from IGG (2021). This software uses a database with the most recent of energy, material, water and labour prices. Material inputs from the MPG reports (Centrum Hout, 2020; Sustainer Homes, 2020c) are denoted in the construction costs software and converted to costs. The construction costs database from IGG (2021) is classified according to the Dutch NEN 2699:2017 costs framework (NEN, 2017). This framework shows which CAPEX and OPEX costs are relevant for real-estate projects. Costs are normalized to annual costs and are shown for the construction phase, demolition phase, replacement and operational and maintenance phase. These costs occur at different times in the LCCA and therefore are discounted via the method suggested in Petersen & Fuller (1995). The LCC in this study is expressed in present value (PV) as well as in future value (FV) and normalized to the same functional unit (FU) as the LCA results, namely in €/m^2GFA*year.

Construction costs database

The construction costs software (IGG, 2021) operates in a similar modular way as the Dutch determination method. A cost database which entails cost data of numerous construction products and construction processes with variable product dimensions and construction tools. The costs are based on realized Dutch construction projects and updated frequently (IGG, personal communication, 2021). Important to mention is that the cost calculation software uses the current material, labour and energy prices (IGG, personal communication, 2021). Therefore, the demolition costs for instance, which occur at the EoL of a building, are calculated based on the current prices. Table 13 shows the modular costs framework which is used in the cost database. All costs are calculated on an annual base. Hence replacement and operation & management costs (O&M costs) that are recurrent over the building lifespan are also normalized to annual costs.

The LCC costs of a construction product in Table 13 are calculated per unit (e.g. per m^2 wall or m window frame). By denoting the construction product quantities from the MPG reports (Centrum Hout, 2020; Sustainer Homes, 2020c) in the cost calculation software (IGG, 2021), the costs of different life cycle phases of both case houses is calculated.

Table 13: Modular cost framework used in construction costs database (IGG, 2021). Q_m = material quantity [unit]; P_m = material price [€/unit]; C_m = material costs [€]; Mh = Man hours [hours]; P_{Mh} = labour costs per man hour [€/Mh]; C_{mh} = Labour costs [€]; Q_t = construction tool quantity [unit]; P_t = Construction tool price [€/unit]; C_t = Construction tool costs [€]; $C_{m\text{-}sub}$ = sub-contractor material costs [€]; $C_{Mh\text{-}sub}$ = sub-contractor labour costs [€]; C_x = type of costs (material, labour, construction and/or sub-contractors) [€]; x = life cycle phase; n = specific construction product.

Product 'n'	Construction costs (Invst)	Demolition costs (Dc)	Replacement costs (Rc)	Operation & maintenance costs (O&Mc)
Material costs	$Q_m*P_m = C_m$		$Q_m*P_m = C_m$	$Q_m*P_m = C_m$
Labour costs	$Mh*P_{Mh} = C_{Mh}$	$Mh*P_{Mh} = C_{Mh}$	$Mh*P_{Mh} = C_{Mh}$	$Mh*P_{Mh} = C_{Mh}$
Construction tools costs	$Q_t*P_t = C_t$	$Q_t*P_t = C_t$	$Q_t*P_t = C_t$	$Q_t*P_t = C_t$
Sub-contractors costs	$C_{m\text{-}sub} + C_{Mh\text{-}sub}$			
Total product costs	$Invest_n = \sum C_{x,n}$	$Dc_n = \sum C_{x,n}$	$Rc_n = \sum C_{x,n}$	$O\&Mc_n = \sum C_{x,n}$
Total building costs per life cycle phase	$Invest = \sum Invest_n$	$Dc = \sum Dc_n$	$Rc = \sum Rc_n$	$O\&Mc = \sum O\&Mc_n$

LCCA scope

Equation 22 based on Fuller (2016) and Marszal & Heiselberg (2011), shows which costs are relevant in the LCCA. Not all costs are taken into account during in the construction costs database (IGG, 2021). As shown in Table 13, the construction costs software (IGG, 2021) only takes the construction costs, demolition costs, replacement costs and operation & maintenance costs into account. In addition to these costs, 'other costs' (Oc) are taken into account in the calculation software. Oc reflect general construction site costs (IGG, 2021). General construction site costs concern amongst others, management costs, material storage, design costs and surveillance of the production site. Based on the analysis of realized projects, IGG (2021) estimates these to be 10,8% of the total construction costs and O&M costs. Therefore, all costs of construction, demolition, replacement and O&M costs are multiplied by 1,108.

[Eq 22] $$LCC_{FV} = Invst + Rc - Rv + Ec + Wc + O\&Mc + Dc + Oc$$

LCC = total life cycle costs in FV (Future Value) [€]; Invst = FV of construction costs and land costs [€]; Rc = FV of replacement costs [€]; Rv = FV of Residual Value [€]; Ec = FV of energy costs [€]; Wc = FV of water costs [€]; O&Mc = FV of operational and maintenance costs [€]; Dc = FV of demolition costs [€]; Oc = FV of other costs [€];

Costs outside system boundaries

The costs that are not taken into account in the cost calculation software are the residual value (IGG, personal communication, 2021), land costs, energy costs and water costs as shown in Figure 21. Residual value reflects the remaining value of a building or replaced construction products. These costs occur at the EoL of construction products and at the EoL of a building. The residual value of products largely depends on the type of waste material (Veras, personal communication, 2021). All construction waste costs money to process but differ in product specific costs based on utilization in secondary products. Due to the time scope of this study, processing construction waste is not taken into account in the LCC.

The residual value of a building, is a fraction of the original value and occurs decades in the future (Copper8, 2017). Due to discounting future costs to a present value, the residual value is expected to be negligible. Therefore, in the demolition phase, the costs reflect the process of demolishing the building till the waste ends up in the waste containers.

In the cost comparison between both case houses the same installations, built-ins and soil replenishment is assumed. Therefore, the expected water and energy demand is the same as well as the related costs. Similarly to the environmental impact comparison, the water costs and energy costs are not taken into account, see Figure 21. The same thought process applies to the land costs. Acquiring land to build on is the same for a traditional house as a mass timber house. Hence, land costs are also not taken into account in the LCC. Installations, built-ins and soil replenishment are also assumed to be the same and left out of the LCC. Figure 21 shows a visualisation of the system boundaries used in this LCCA. A larger version is depicted in appendix IX. Note that the costs during the production process of various construction products is reflected in the material price and hence within the system boundaries. With the above mentioned system boundaries taken into account, the LCC_{FV} equation (equation 22) becomes the following:

[Eq 23] $$LCC_{FV} = Invst^{*} + Rc + O\&Mc + Dc + Oc^{**}$$

LCC = total life cycle costs of case house in FV (Present Value) [€]; Invst = FV of construction costs (no land costs) [€]; Rc = FV of replacement costs [€];O&Mc = FV of operational and maintenance costs [€]; Dc = FV of demolition costs [€]; Oc = FV of general construction site costs (10,8% of all future value costs) [€].*

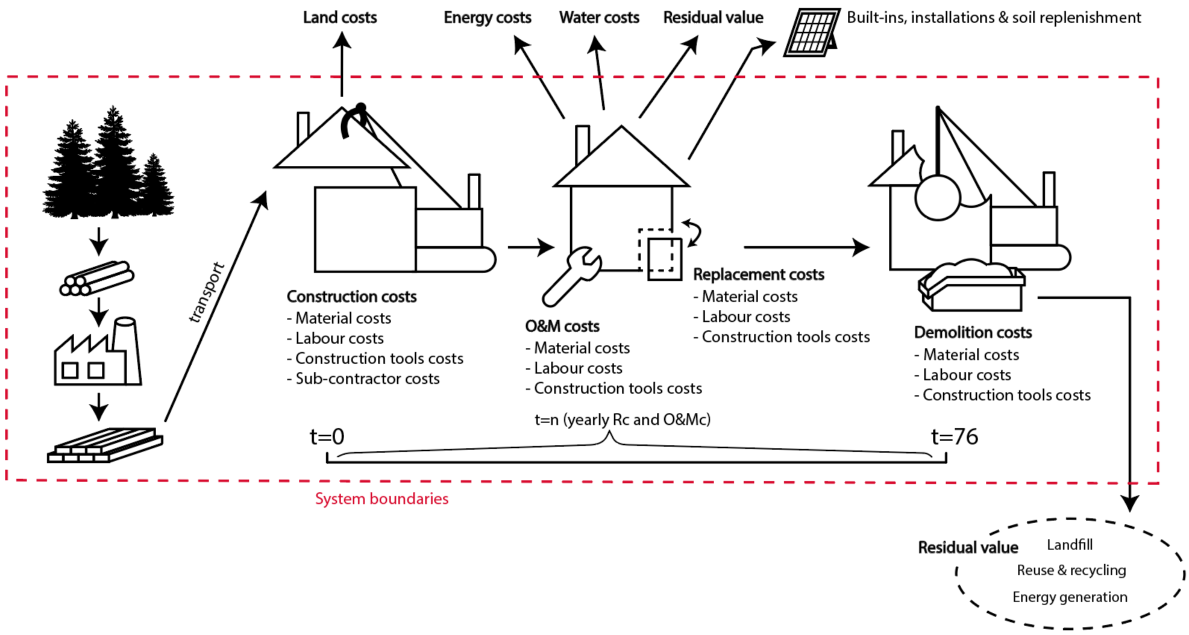


Figure 21: LCCA spatial and temporal scope

Discounting costs

The cost calculation software calculates all costs in future values. Equation 24 (from Petersen & Fuller (1995)) is used to convert future values to present values, using a discount factor. A discount factor of 2,25% is recommend by Werkgroep Discontovoet (2020). This factor is based, among other things, on the Dutch inflation and average project risks.

$$[\text{Eq } 24] \qquad LCC_{PV} = \sum_{t=0}^{N} \frac{C_t}{(1+d)^t}$$

LCC_{PV} = Life Cycle Costs per case house in Present Value (PV) [€]; C_t = future value of costs in year t; N = project time period [years]; d = discount rate.

The LCC_{PV} is calculated based on the discounted annual costs per m^2GFA. Both the discounted costs over time of the mass timber house and traditional house will be expressed by using a house with 143 m^2 GFA. According to Ministerie van Algemene Zaken (2019), this is de average GFA of a Dutch terraced house. As shown in , the LCC_{PV} is calculated over a time period of 75 years. The investment in construction costs occurs in base year 0. Following up, 75 year of replacement and O&M costs are explored. Lastly, the building is demolished at the end of year 75. In addition to the LCC_{PV} per case house, the LCC_{PV} is also expressed per functional unit. The LCC_{PV} per functional unit is calculated via equation 25.

$$[\text{Eq } 25] \qquad LCC_{PV,norm} = \frac{LCC_{PV}}{143*75}$$

LCC_{PV} = Life Cycle Costs per case house in Present Value (PV) [€]; C_t = future value of costs in year t; N = project time period [years]; d = discount rate.

Material costs and construction methods

All materials and costs of the traditional house are present in the cost calculation database (IGG, 2021). The traditional house is constructed of prefabricated (reinforce) concrete walls and floors. These wall- and floor elements are hoisted with a crane and mounted on site. The mass timber house on the other hand consists of individual modules which are mounted on site. In order to protect comparability between both case houses, it is assumed that the mass timber house is also made up of individual prefabricated floor, wall and roof elements. Similarly as to the traditional house, these are hoisted into position and mounted on site.

Prefabricated building elements

The specified prefabricated concrete building elements are already available in the construction costs database (IGG, 2021). The mass timber elements however, are not fully available. The database does feature timber construction wall, roof and floor elements though. These construction products from the database differ in structure compared with the walls, roof and floors of the mass timber house. Nevertheless, the product cards can be modified to reflect the mass timber house. The structure of various mass timber house elements is assessed via the Bill Of Material (BOM) (Sustainer Homes, 2020a), MPG (Sustainer Homes, 2020c), and input is taken from a document that shows the average timber constructions in the Netherlands (NBvT, 2020). Using this information, outside walls, inside walls, ground floor, storey floors and the roof are constructed according to the cost framework shown in Table 13. Reference costs of conventional wall and floor constructions in IGG (2021) are used for cost comparison.

Material costs

Most materials shown in the BOM (Sustainer Homes, 2020a), MPG (Sustainer Homes, 2020c) and average timber construction document (NBvT, 2020) are available in the construction costs database (IGG, 2021). Hence, the respective costs and labour costs are also available to use in the cost framework. Differences in material quantities are adjusted for in the costs framework. Only the LVL beams used in the floors, walls and roof of the mass timber house are not available in the costs database. The prefab wooden elements in the database are made up of solid wood beams instead of LVL beams. The labour and labour costs of tailoring and assembling the solid or LVL beams is expected to be the same. Therefore only the materials prices of the wooden beams are different. A LVL price of 800 €/m^3 is used in the cost framework (DERIX & METSÄ wood, personal communication, n.d.). The construction costs, demolition costs as well as the replacement costs and O&M costs are calculated. Worth noting is that only the finishing layers of the prefab wooden building elements needs replacement and maintenance. The structural LVL beams are packed in an air-tight foil which eliminates erosion and product damage.

Sensitivity LCCA

Uncertainty in the LCC results originates from uncertainties in the discount factor and LVL material costs. Werkgroep Discontovoet (2020) suggests to use three different discount scenarios to assess the sensitivity of the results due to the discount factor. The first scenario will feature the average discount factor of 2,25%. In addition a 'low discount scenario' with a discount factor of 1,85% and a 'high discount scenario' with a discount factor of 2,65% is used.

Material prices in the costs database are updated and should therefore reflect the current prices. For several products the price is compared with an online commercial available version which showed prices are indeed the similar. Material costs have seen significant fluctuations due to the COVID-19 pandemic at the time of writing. Almost all construction prices have seen price increases, but especially lumber has seen big fluctuations (NBC News, 2021). According to Unilin & Martens hout (personal communication, 2021) the prices in LVL have generally seen an increase of 30-40%. Therefore, the difference in the mass timber building costs due to changes in the LVL wood price will be explored. In the increased price scenario a price of 1.080 €/m3 is used. In the decreased price scenario a price of 520 €/m^3 is used.

Scenario analysis

The difference in CO_2 emissions and Life-cycle-costs between both case houses is explored via a scenario analysis. In one period all newly constructed terraced houses between 2020 and 2030 in the Dutch built environment will conceptually be constructed in mass timber. This scenario is dubbed ‘Mass timber scenario’. In the other scenario all newly constructed terraced houses are built in traditional style, which is denoted as ‘Traditional scenario’. The difference in CO_2 emissions between both scenarios is assessed via the MPG method and the modified MPG method. The latter takes temporary biogenic carbon storage and carbonation into account. In addition to the CO_2 emissions, the difference in life-cycle-costs is explored. Comparing the difference in CO_2 emissions with the difference in costs shows the cost effectiveness of building with mass timber. Note that the cost effectiveness is strongly dependent on the case house design though.

Newly constructed houses

The amount of newly constructed houses between 2020 and 2030 is based on the Vesta Maïs model (PBL, 2021). This model shows two scenarios of the expected newly constructed Dutch houses. One scenario that reflects big expansion of the built environment and one that reflects a conservative scenario. The average of both scenario is used to represent the expected addition in terraced houses. The yearly amount of new constructed terraced houses is multiplied with the average terraced house GFA from Ministerie van Algemene Zaken (2019). Hence, the yearly added amount of terraced houses is expressed in m^2 GFA via equation 26.

$$\text{[Eq 26]} \qquad GFA_t = Q_t * 143$$

GFA_t = annually additional new constructed terraced house [m^2]; Q_t = number of terraced houses constructed in year ‘t’ [units]; 143 = average GFA of terraced house.

GWP reduction

The CO_2-emissions in the traditional scenario and mass timber scenario are based on the normalized material related GWP (GWP_{norm}). This is the GWP per functional unit (kg CO_2-eq/m^2GFA*year), which is calculated in the environmental impact assessment. Both the GWP calculated via the MPG and modified MPG method are taken into account in the scenario analysis. Note that the modified MPG method takes temporary biogenic storage and carbonation into account. The GWP calculated via the modified MPG method is expressed as $GWP_{m,norm}$. Hence, four scenarios are constructed, shown in Table 14. The total emission over 2020-2030 is calculated via equation 27 and equation 28.

*Table 14: Fours analysed scenarios. GWP_{norm} = global warming potential expressed per functional unit [kg CO_2-eq/m^2GFA*year]; $GWP_{m,norm}$ = global warming potential that takes temporary storage and carbonation into account, expressed per functional unit [kg CO_2-eq/m^2GFA*year].*

Scenario	All houses constructed in:	GWP expressed in:	Total scenario GWP
Traditional scenario	Traditional house	GWP_{norm}	$Total\_GWP_{traditional}$
Mass timber scenario	Mass timber house	GWP_{norm}	$Total\_GWP_{mass\ timber}$
Traditional scenario$_m$	Traditional house	$GWP_{m,norm}$	$Total\_GWPm_{traditional}$
Mass timber scenario$_m$	Mass timber house	$GWP_{m,norm}$	$Total\_GWPm_{mass\ timber}$

$$\text{[Eq 27]} \qquad Total\_GWP_i = \sum_{t=2020}^{2030} GWP_{norm,i} * GFA_t * (2030 - t)$$

*$Total\_GWP_i$ = Cumulative amount of CO_2-eq emissions over 2020-2030 per scenario ‘i’ [kg CO_2-eq]; $GWP_{norm,i}$ = yearly CO_2-eq emissions of case house ‘i’ according to the material related MPG-score [kg CO_2-eq/m^2GFA*year]; GFA_t = annually additional new constructed terraced house [m^2].*

$$[\text{Eq } 28] \qquad Total\_GWPm_i = \sum_{t=2020}^{2030} GWP_{m,norm,i} * GFA_t * (2030 - t)$$

*$Total\_GWP_i$ = Cumulative amount of CO_2-eq emissions over 2020-2030 per scenario 'i', calculated via modified MPG-score [kg CO_2-eq]; $GWP_{m,norm,i}$ = yearly CO_2-eq emissions of case house 'i' according to the material related modified MPG-score [kg CO_2-eq/m^2GFA*year]; GFA_t = annually additional new constructed terraced house [m^2].*

The reduction in GWP between the two case houses is calculated via equation 29 and 30.

$$[\text{Eq } 29] \qquad Total\_GWP_{red} = Total\_GWP_{traditional} - Total\_GWP_{mass\ timber}$$

$Total\_GWP_{red}$ = reduction in GWP between the traditional scenario and mass timber scenario calculated via the MPG-score [kg CO_2-eq]; $Total\_GWP_{traditional}$ = Cumulative amount of CO_2-eq emissions over 2020-2030 in traditional scenario [kg CO_2-eq]; $Total\_GWP_{mass\ timber}$ = Cumulative amount of CO_2-eq emissions over 2020-2030 in mass timber scenario [kg CO_2-eq];

$$[\text{Eq } 30] \qquad Total\_GWPm_{red} = Total\_GWPm_{traditional} - Total\_GWPm_{mass\ timber}$$

$Total\_GWPm_{red}$ = reduction in GWP between the traditional scenario and mass timber scenario calculated via the modified MPG-score [kg CO_2-eq]; $Total\_GWPm_{traditional}$ = Cumulative amount of CO_2-eq emissions over 2020-2030 in traditional scenario calculated via modified MPG-score [kg CO_2-eq]; $Total\_GWPm_{mass\ timber}$ = Cumulative amount of CO_2-eq emissions over 2020-2030 in mass timber scenario calculated via modified MPG-score [kg CO_2-eq];

Policy goals

The reduction in CO_2-eq emissions of the Dutch construction sector by building in mass timber is compared against the Dutch climate goals (Rijksoverheid, 2013). According to PBL et al. (2020), the Dutch government aims to reduce annual CO_2-eq emissions with 49% compared to the annual emission in base year 1990. With the current sustainability policies taken into account, the annual emission in 2030 is expected to be 150,2 Mton CO_2-eq per year (PBL et al., 2020). This is 33,9 Mton CO_2-eq per year short of the climate goal. Mitigating emissions by constructing in mass timber is currently not part of the sustainability policies (PBL et al., 2020). Therefore, it can aid in reducing the remaining annual CO_2-eq emissions needed to reach the climate goals.

The additional annual CO_2-eq emissions reduction that is needed to reach the climate goals is assumed to follow a linear pattern in this study. Hence, every year an additional annual reduction of 6,6 Mton CO_2-eq is needed to reach the 49% reduction of the annual emissions from 1990. Via this assumption the cumulative reduction in annual emissions over 2020-2030 years is expected to be 427,6 Mton CO_2-eq. Therefore, the attribution of emission reduction by building all terraced houses in 2020-2030 in mass timber is calculated via equation 31 and 32.

$$[\text{Eq } 31] \qquad Mass\ timber\ attribution = \frac{427{,}6\ Mton\ CO_2{-}eq}{Total\_GWP_{red}}$$

Mass timber attribution = attribution of building mass timber houses instead of traditional houses in reaching the climate goal in 2030 [%]; 427,6 = cumulative additional amount of reduction needed over 2020-2030 in order to reach climate goals in 2030 [Mton CO_2-eq]; $Total\_GWP_{red}$ = reduction in GWP between the traditional scenario and mass timber scenario calculated via the MPG-score [kg CO_2-eq].

$$[\text{Eq } 32] \qquad Mass\ timber\ attribution_m = \frac{427{,}6\ Mton\ CO_2{-}eq}{Total\_GWP_{red}}$$

$Mass\ timber\ attribution_m$ = attribution of building mass timber houses instead of traditional houses in reaching the climate goal in 2030, scenario reduction calculated via modified MPG-score [%]; 427,6 = cumulative additional amount of reduction needed over 2020-2030 in order to reach climate goals in 2030 [Mton CO_2-eq]; $Total\_GWPm_{red}$ = reduction in GWP between the traditional scenario and mass timber scenario calculated via the modified MPG-score [kg CO_2-eq].

Difference in costs

In order to measure the costs effectiveness of reducing CO_2-eq emission via mass timber construction, the costs of all scenario in Table 14 are calculated. The Life-Cycle-Costs in present value per functional unit ($LCC_{PV,norm}$) from the LCC comparison is used for the scenario cost calculation. These costs represent all life cycle costs of the specific case houses normalized to

€/m^{2}GFA*year. Via the annual new additional terraced houses, the total costs over 2020-2030 are calculated. Equation 33 shows the equation to calculate the cumulative costs over the 2020-2030 time period. The future annual costs are discounted to the base year of 2020. A discount costs of 2,25% from Werkgroep Discontovoet (2020) is used.

[Eq 33] $$Total\_LCC_i = \sum_{t=2020}^{2030} \frac{LCC_{PV,norm,i} * GFA_t * (2030-t)}{(1+d)^t}$$

*$Total\_LCC_i$ = Total discounted life cycle costs per scenario 'i' [€]; $LCC_{PV,norm,i}$ = life cycle costs in present value of single case house 'i' [€/m^{2}GFA*year]; d = discount factor of 2,25%; t = time [years].*

The difference in costs between the traditional and mass timber scenario is calculated via equation 34.

[Eq 34] $$Total\_LCC_{diff} = Total\_LCC_{traditional} - Total\_LCC_{mass\ timber}$$

$Total\_LCC_{diff}$ = Difference in total discounted life cycle costs between traditional and mass timber scenario [€]; $Total\_LCC_{traditional}$ = Total discounted life cycle costs in present value of Traditional scenario [€]; $Total\_LCC_{mass\ timber}$ = Total discounted life cycle costs in present value of Mass timber scenario [€].

Carbon costs

According to NEA (2021) a carbon tax will be introduced in 2021 in the Netherlands. This carbon tax starts with €30,48 in 2021 and increases with €10,73 each year (NEA, 2021). The effect of the introduction of the carbon tax on the scenario costs is included in a separate scenario calculation. In addition to the difference in total discounted life cycle costs in equation 34, the costs difference is calculated with a carbon tax included. Equation 35 and 36 show the incorporation of the carbon tax. Note that the costs due to the carbon tax are also discounted.

[Eq 35] $$Total\_LCC_i(CT) = \sum_{t=2020}^{2030} \frac{\left(LCC_{PV,norm,i} * GFA_t * (2030-t)\right) + \left(GWP_{norm,i} * GFA_t * (2030-t) * CT_t\right)}{(1+d)^t}$$

*$Total\_LCC_i(CT)$ = Total discounted life cycle costs per scenario 'i', with carbon tax included [€]; $LCC_{PV,norm,i}$ = life cycle costs in present value of single case house 'i' [€/m^{2}GFA*year]; d = discount factor of 2,25%; t = time [years]; GFA_t = annually additional new constructed terraced house [m^2]; $GWP_{norm,i}$ = yearly CO_2-eq emissions of case house 'i' according to the material related MPG-score [kg CO_2-eq/m^{2}GFA*year]; CT_t = carbon tax in year 't' [€/kg CO_2-eq].*

[Eq 36] $$Total\_LCC_{diff}(CT) = Total\_LCC_{traditional}(CT) - Total\_LCC_{mass\ timber}(CT)$$

$Total\_LCC_{diff}(CT)$ = Difference in total discounted life cycle costs between traditional and mass timber scenario, with carbon tax included [€]; $Total\_LCC_{traditional}(CT)$ = Total discounted life cycle costs in present value of Traditional scenario, with carbon tax included [€]; $Total\_LCC_{mass\ timber}(CT)$ = Total discounted life cycle costs in present value of Mass timber scenario, with carbon tax included [€].

The total discounted life cycle costs and differences between scenarios are calculated as well for the scenarios in which the GWP is calculated via the modified MPG method. The difference in total discounted life cycle costs between the two scenario is denoted as '$Total\_LCC_{diff}m(CT)$' in €. In the scenario with the modified MPG, the mass timber house can have a net negative emission. Mitigating emission however will not generate an income. Therefore the carbon tax is 0 if negative CO_2-eq emissions occur.

Cost effectiveness

The cost effectiveness of mitigating CO_2-eq emission by constructing mass timber houses instead of traditional houses is calculated for both the scenarios with and without carbon tax. Table 15 shows the equations used to calculate cost effectiveness of all different scenario comparisons. The cost effectiveness or 'mitigation costs' of mass timber is compared with alternatives found in (Ritchie, 2017).

Table 15: Cost effectiveness equations of various scenario comparisons.

Scenario comparison	Cost effectiveness equation
Mass timber versus traditional timber	$\frac{Total\_GWP_{red}}{Total\_LCC_{diff}}$
Mass timber versus traditional timber (CT) - Taking carbon tax into account - GWP calculated via original MPG method	$\frac{Total\_GWP_{red}}{Total\_LCC_{diff}(CT)}$
Mass timber versus traditional timber$_m$ (CT) - Taking carbon tax into account - GWP calculated via modified MPG method	$\frac{Total\_GWPm_{red}}{Total\_LCC_{diff}m(CT)}$

Results

Material comparison

The material division of both buildings is shown in Figure 22. A detailed breakdown of material weights per building element or type of material is shown in Table 30 and Table 31 in appendix VII. Note that the building weights do not include built-ins, installations and soil replenishment.

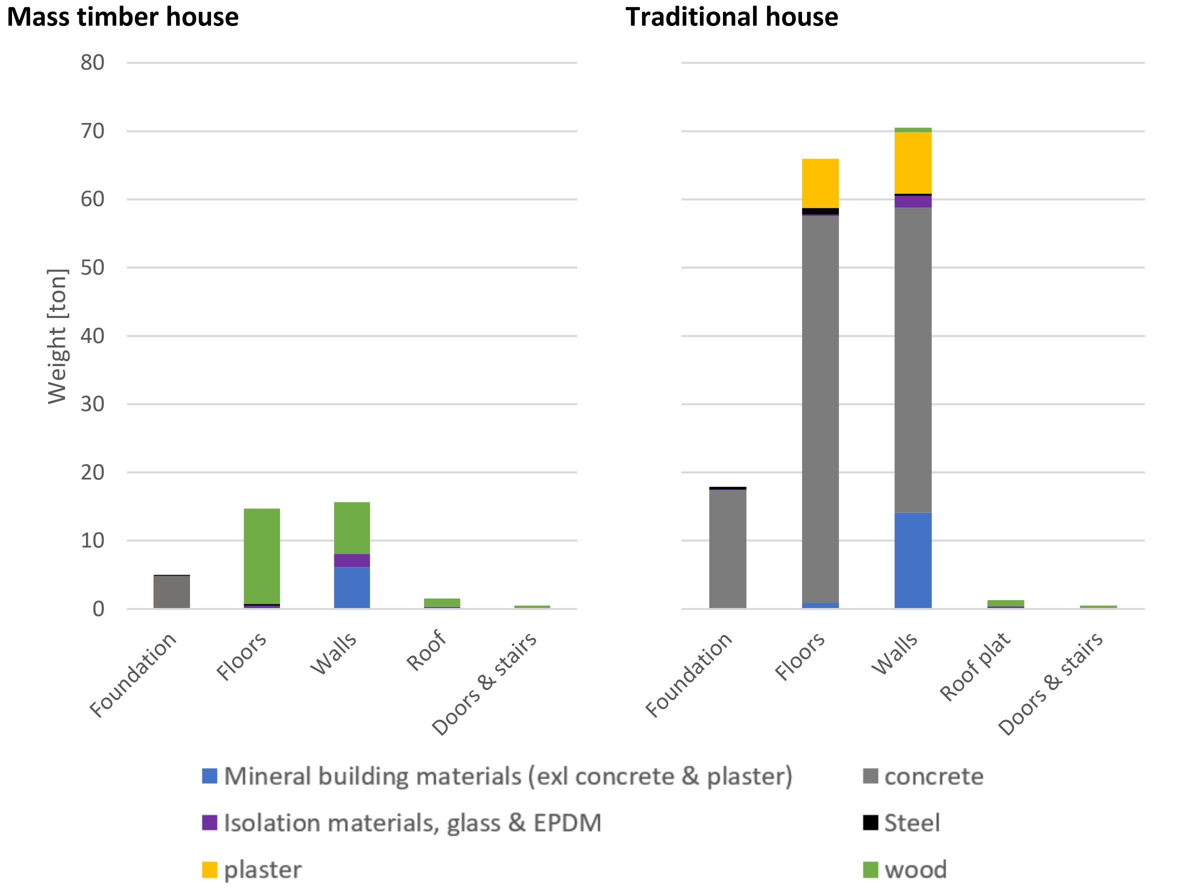


Figure 22: Material division of mass timber house and traditional house based on weight. Materials divided based on framework in appendix III.

Material division – mass timber house

In the mass timber house, wood contributes to 62% of the total building weight and is used in all parts of the building except for the foundation. The foundation is completely made out of concrete and steel and is responsible for 13% of the total body weight. The attribution of the masonry façade (part of 'mineral building materials' in Figure 22) is 15% of the total building weight. Furthermore, insulation is responsible for only 4% of the building weight, due to its low density. In total the building weighs 37,3 ton which refers to 228 kg/m^{2}GFA.

Material division – traditional house

The weight of the traditional house is dominated by the usage of concrete. Concrete is responsible for 73% of the total body weight. This is similar to concrete weight share of the terraced house in EIB et al. (2020), which is 75%. 15% of the concrete is used for the foundation. The weight of the foundation is 11% of the total building weight. This is slightly more than the 8% weight contribution of the foundation in EIB et al. (2020). The share of insulation in the total building weight of the traditional house is 1%. EIB et al. (2020) shows that the average terraced house has 2%

insulation based on the total building weight. Furthermore the attribution of 22 ton of plaster is noticeable in Figure 22. This differs from EIB et al. (2020), where only 8 ton of plaster is used. The material type 'plaster' in Figure 22 contains both plaster wall finish, gypsum creed and plaster blocks as shown in appendix III. The difference in plaster usage between EIB et al. (2020) and the traditional case house originates from the gypsum creed in the traditional house. The reference house from EIB et al. (2020) uses cement creed instead of gypsum. The amount of plaster finish and plaster blocks is similar in both the traditional house and EIB et al. (2020). Masonry (6%) and cement (3%) are the biggest contributor of weight from 'mineral building materials' in Figure 22. In total the traditional house weighs 162 ton and 1.108 kg/m^{2}GFA. Which is relatively light compared to the 1.552 kg/m^{2}GFA from EIB et al. (2020). This can be explained due to more wood and cement usage per m^{2}GFA in the EIB et al. (2020) terraced house.

Material and weight differences

The mass timber house is 76% lighter than the traditional house. This is similar to the weight reduction of 74% found in Švajlenka et al. (2017). The weight reduction can be accounted to the wood usage, which prevents the usage of heavy concrete. The mass timber house uses 910% more wood per GFA than the traditional house. Furthermore, the structural parts (floors and walls) of the mass timber house are only 21% of the weight of the traditional floors and walls. Similar ratios are found in Centrum Hout (2021b). Due to the lightweight materials in the mass timber frame, the foundation is only 5 ton, compared to 18 ton in the traditional house. Therefore, the foundation of the traditional house is 256% heavier. Both buildings use similar amounts of insulation material. 1.358 kg in the mass timber house and 1.533 kg in the traditional house. Per m^{2}GFA this results in 21% more insulation material in the traditional house. The attribution of steel in the total building weight is 1% in both houses as well as in EIB et al. (2020). However, per m^{2}GFA the mass timber houses uses significantly less steel (2,8 kg/m^{2}GFA) compared to the traditional house (11,6 kg/m^2).

Environmental impact comparison

MPG score

The MPG scores of the mass timber house and traditional house are shown in Figure 23. The mass timber house and original traditional house feature the original input from the MPG reports (Centrum Hout, 2020; Sustainer Homes, 2020c). A second version of the traditional house is added which shows the MPG score of the traditional house with the modifications mentioned in the paragraph 'Case house comparability'. These modifications include a flat roof (instead of a sloped roof), one mutual wall (instead of two) and the same built-ins and installations as the mass timber house (see Table 7).

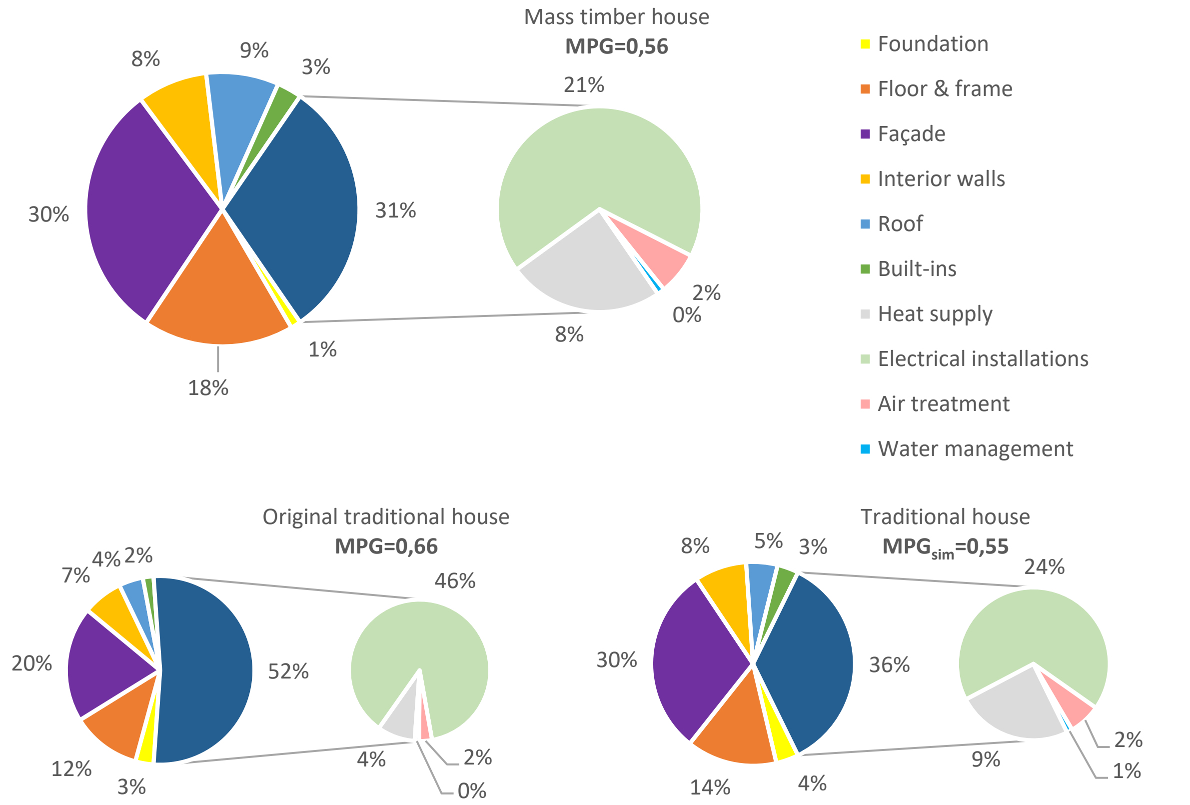
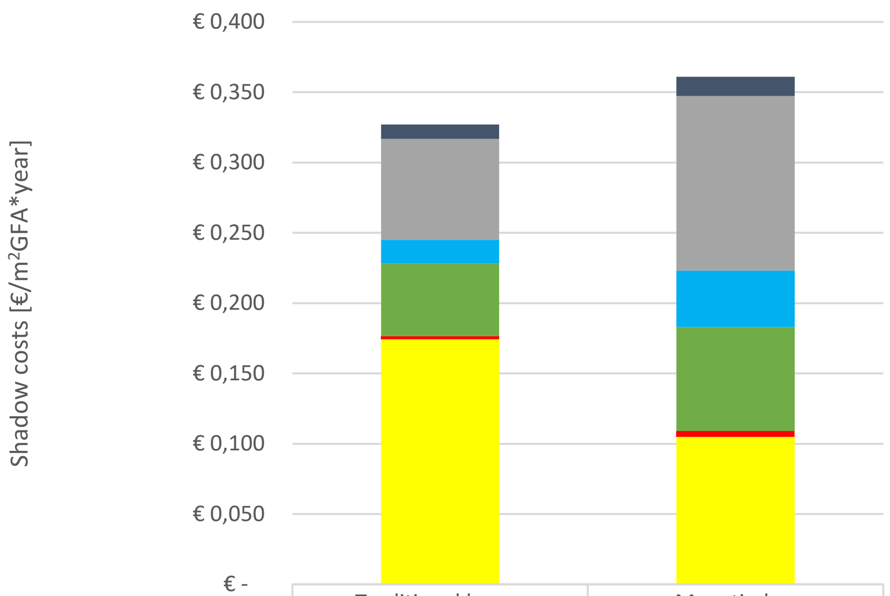


Figure 23: Division of MPG-scores to building elements. MPG_{sim} shows the MPG-score of the case houses with same installations & built-ins shown in appendix V. The traditional house_original shows the MPG-score of the traditional house with original installations & built-ins.

The MPG-scores of the mass timber house and original traditional house differ from their original MPG reports (Centrum Hout, 2020; Sustainer Homes, 2020c). Both MPG-scores are decreased due to updates in the Dutch determination method (Nationale Milieudatabase, 2021c). The mass timber MPG-score decreased from 0,59 to 0,56 €/m^2GFA*year. The traditional house MPG-score decreased from 0,68 to 0,66 €/m^2GFA*year.

Differences MPG score mass timber versus traditional house

Contrary to the claims in Pajchrowski et al. (2014), Figure 23 shows that the mass timber house has a slightly higher environmental impact than the traditional house, despite the buildings having the same installations, built-ins and absence of soil replenishment. This difference can be attributed to the construction material related impacts. Figure 24 shows the shadow costs of the most significant construction material related environmental impacts. Table 32 in appendix VIII shows the environmental impacts of all 11 impact categories before conversion to shadow costs. The MPG_{mat} (summation of all construction material related impacts) is shown in Table 16.



	Traditional house	Mass timber
Marine ecotoxicity	€ 0,010	€ 0,014
human toxicity	€ 0,072	€ 0,124
Eutrophication	€ 0,017	€ 0,040
Acidification	€ 0,052	€ 0,074
Photo-oxidant creation	€ 0,002	€ 0,004
Global warming 100 year	€ 0,175	€ 0,105

Figure 24: Construction material related shadow costs of most significant impact categories in of both case houses.

Table 16: Construction material related MPG-score of both case houses.

	Traditional house	Mass timber house
MPG_{mat} [€/m^{2}GFA*yr]	0,33	0,37

The difference in MPG_{mat} between the mass timber house and traditional house is 0,05 €/m^{2}GFA*year. The biggest difference between the two case houses originates in the GWP impact category. This category is significantly lower in the mass timber house. An analysis of the GWP of both case houses can be found in the paragraph 'GWP score'. Despite the reduced GWP, three other impact categories result in the higher MPG_{mat} score of the mass timber house: human toxicity, acidification and eutrophication. The traditional house scores 0,10 €/m^{2}GFA*year lower due to lower impacts in these three categories. Human toxicity is the biggest contributor to the MPG_{mat} of the mass timber house. This impact category accounts for 34% of the total impacts. In the traditional house human toxicity is responsible for 22% of the total impacts. An analysis of the contribution of different construction materials to the MPG_{mat} will highlight environmental impact causes.

Attribution of construction products

The environmental impacts shown in Figure 24 (and Table 32 in appendix VIII) are the summation of the impacts of all construction materials. Reinforced concrete accounts for 50% of all material related impacts of the traditional house. This is expected since concrete is responsible for 73% of the total building weight. Plaster has the second largest environmental impact in the total building and accounts for 15% of all material related impacts. Furthermore, glass (11%) and isolation (10%) are third and fourth largest contributor of material related impacts. Worth mentioning is that part of the EPS isolation is integrated in the prefabricated concrete floors. This isolation is accounted for in the concrete material impact instead of the insulation material.

Remarkable is that the majority of material related impacts of the mass timber house originate from the Medium-Density-Fibreboard (MDF) usage. MDF accounts for 46% of all material related impacts, even though it is only 11% of the total body weight. Chipboard on the other hand, accounts for 14% of total body weight but 14% of all material related impacts. The majority of the wood is used for the LVL frame (26%). LVL is only responsible for 5%. Lastly, the attribution of insulation is 7% to the material related impacts.

Replacing MDF

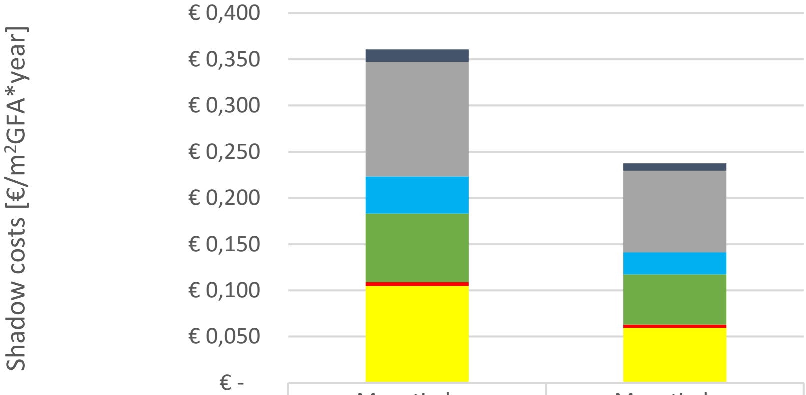
The high environmental impact of MDF is attributed for 64% due to GWP and human toxicity (Nationale Milieudatabase, 2021b). According to Rivela et al. (2006), 91% of the human toxicity impact is a result of energy usage for fibre dryers and press vents during wood preparation. Furthermore, formaldehyde is released during the pressing which contributes to human toxicity. These findings are supported by Piekarski et al. (2017), who claims that power production (32%) and transport (23%) are big contributors to human toxicity. Power production (29%) and transport (18%) are also related to the large GWP emission of MDF (Piekarski et al., 2017).

The MDF construction product in the NMD database is based on EcoInvent (Nationale Milieudatabase, 2020a, 2021b), since there are no validated Dutch MDF EPDs available. Furthermore comparison of the environmental impacts with international EPDs is difficult since countries use different PCRs. Some take biogenic storage into account for example, which limits comparability (Wood Solutions, 2020). The NMD viewer (Nationale Milieudatabase, 2021b) allows comparison of MDF as wooden sheet materials with other sheet materials. Comparable wooden sheet materials are chipboard and Oriented-Strand-Board (OSB), which are also based on EcoInvent. Table 17 shows the shadow costs of 1 m^2 sheet material of MDF, chipboard and OSB. In addition, the MPG-score of the relevant sheet material in the mass timber house is shown.

Table 17: Shadow costs of different wooden sheet materials according to (Nationale Milieudatabase, 2021b) and their MPG-score in the mass timber house.

	Shadow costs [€/m^2]	MPG score
MDF	1,0495	0,1693
Chipboard	0,3448	0,0417
OSB	0,2948	0,0428

Table 17 shows that chipboard and OSB have roughly 60% lower impact per m^2 and a 75% reduction in MPG-score when utilized in the mass timber house. Furthermore, (NBvT, 2020) shows that wooden construction elements (e.g. prefab wooden wall elements) are often made with OSB instead of MDF. In order to assure comparability and avoid distortion of the results due to significant attribution of MDF in impact, the MDF in the mass timber house is replaced with OSB. Figure 25 and Table 18 shows the climate related environmental impacts of the timber house with MDF and OSB. Replacing MDF with OSB results in a MPG_{mat} reduction of 0,13 €/m^2GFA*year. The material related impact of the mass timber house with OSB instead of MDF is 27% lower than the traditional house (0,33 €/m^2GFA). As shown in Figure 25, all impacts are decreased substantially. Human toxicity remains the largest impact category with a contribution of 37% to the total impact score, after weighting factors.



	Mass timber house [MDF]	Mass timber house [OSB]
Marine ecotoxicity	€ 0,014	€ 0,008
human toxicity	€ 0,124	€ 0,089
Eutrophication	€ 0,040	€ 0,024
Acidification	€ 0,074	€ 0,054
Photo-oxidant creation	€ 0,004	€ 0,004
Global warming 100 year	€ 0,105	€ 0,060

Figure 25: Construction material related shadow costs of most significant impact categories of mass timber house with MDF and OSB.

Table 18: Construction material related MPG-score of mass timber house with MDF and OSB.

	Mass timber house with MDF	Mass timber house with OSB
MPG_{mat} [€/m^{2}GFA*yr]	0,37	0,24

Human Toxicity Potential (HTP)

The human toxicity in EN 15804 is expressed in in 1.4 DCB-eq kg. This is a toxic substance prescribed by the CML-2, which provides a framework to compare environmental impacts of products (TNO, 2004). The shadow costs in the Dutch determination method are developed by TNO (2004). This report shows that the majority of the toxicity impacts are linked to atmospheric emissions, such as particulate matter, heavy metals and Volatile-Organic-Compounds. Shadow costs of human toxicity are calculated by exploring the effects of various toxic substances on human health and the method to mitigate or undo relevant emissions (TNO, 2004). Furthermore, weighting factor are applied to reflect severity and governmental policy goals. Due to the amount of toxic substances and the uncertainty in linking a value of toxicity for human health each substance, these shadow costs are highly debatable.

An analysis of numerous wood-based product EPDs by NBvT (2021) shows that HTP is the largest or second largest impact category in all EPDs. These EPDs consist of construction product assemblies (e.g. wooden roof element). The impacts of the underlying products used in the assemblies are taken from EcoInvent, which is prescribed by Nationale Milieudatabase (2020a). Among these products roughly 75% of the HTP impact is linked to gypsum fiber board, glass wool, OSB and steel. On the other hand the attribution of spruce wood (for structural beams and columns) and other materials are responsible for the remaining 25% impact. Furthermore, assumptions, uncertainties and representation for Dutch construction products of the EcoInvent products are debatable. Due to the uncertainty of the HTP shadow costs and the significant contribution of HTP in EcoInvent products, the representation of impacts of wood-based products in the NMD is questionable.

Differences MPG score traditional house versus original traditional house

The effects of the modification to the original traditional house are shown in Figure 26. The largest difference in MPG-score occurs due replacing the installations of the original traditional house with the mass timber installations. In addition, Figure 23 and Figure 26 show that the MPG-score of the original traditional house decreased from 0,66 to 0,55 €/m^{2}GFA*year. Differences in MPG due to changing the pitched roof to a flat roof or changing the built-ins are negligible. In addition the increase in MPG due simulating one mutual wall instead of two is explainable. More insulation, masonry, window frames and glass are needed which increases the material related impact. The biggest difference in MPG-score due to the modifications is the reduction in impact of electrical installations. Figure 23 shows that the share of electrical installations decreased from 46% (original traditional house) to 24% (traditional house). The MPG calculation software (W/E adviseurs, 2021) shows that this reduction in MPG-score is a result of decreased usage of PV panels. More specifically, the 16,5 m^2 solar panels in the original traditional house result in an impact of 0,248 €/m^{2}GFA*year. This is 37,4% of the entire MPG-score of the original traditional house. The impact of the PV panels halves when the 8 m^2 solar panels are used from the mass timber house. This emphasizes the trade-off between the EPG and the MPG.

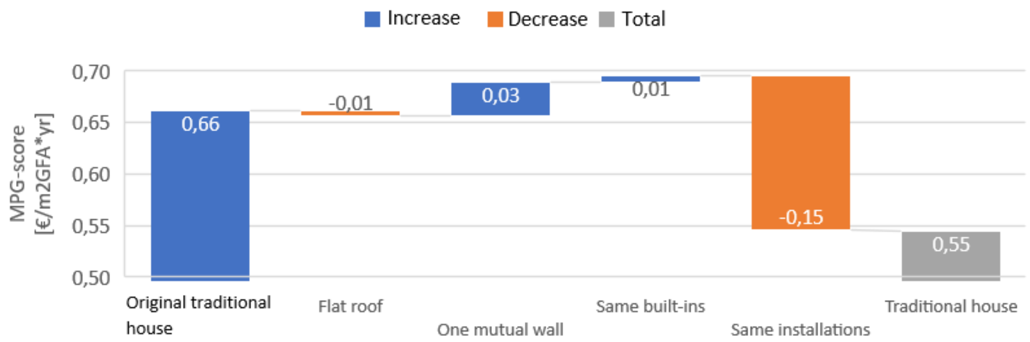


Figure 26: Effect of modifications on MPG-score of the traditional house.

GWP score

Figure 27 shows the constructiona material related GWP_{100} (GWP_{mat}) of the traditional house and the mass timber house with OSB instead of MDF. The traditional house emits 38,2 ton CO_2-eq over the builing lifespan. The mass timber house emits 66% less CO_2-eq over the builing lifespan, namely 14,6 ton. This reduction is more than the 22% decrease between timber frame constructions and traditional building found in Centrum Hout (2021b). The mass timber house uses more wood compared to the timber frame construction, which explains the difference in GWP reduction (Centrum Hout, 2020, 2021b). The GWP reduction in this study is also bigger compared to the reduction of 41% found in W/E adviseurs (2016). W/E adviseurs (2016) found a CO_2-eq of 39,8 ton per traditional house and 23,3 ton per timber frame constructino with extra wood usage in the façade. (NBvT, 2021)

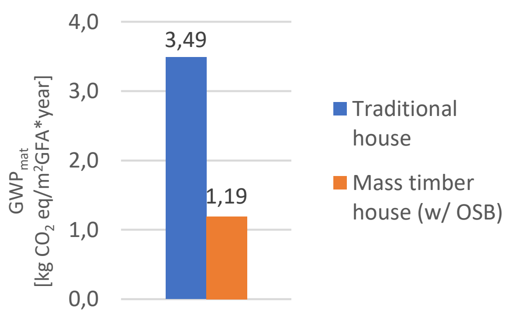


Figure 27: GWP_{mat} score per m2GFA.

Attribution of construction products

Nationale Milieudatabase (2021b) and NBvT (2021) shows that the majority of construction product related environmental impacts happen in the production phase. This applies to both (reinforced) concrete, insulation and wooden products. In the traditional house 50% of the environmental impacts are linked (reinforced) concrete construction products, as shown in Figure 28. Note that these percentages are based on the shadow costs. 35% of environmental impacts are attributed to the combination of plaster, glass and insulation. The biggest impact category of concrete is GWP, which accounts for 49% of all environmental impacts (Nationale Milieudatabase, 2021b). Hence a quarter of all environmental impacts of the traditional house are related to the GWP of concrete production. This is in line with the findings in (IEA, 2019). Furthermore, GWP in the production phase accounts for 84% of the environmental impact of plaster, 42% of glass and 60% of PIR/PUR insulation (Nationale Milieudatabase, 2021b). Majority of GWP impact originates in reinforced concrete and plaster production since they are responsible for 87% of the total building weight.

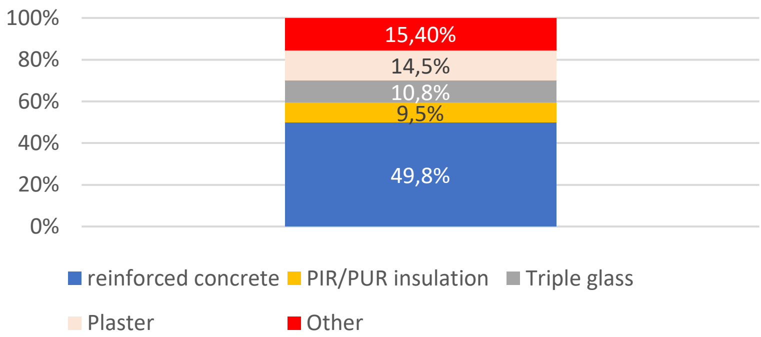


Figure 28: Traditional house MPG_{mat} division over construction products.

The significant reduction in concrete usage in the mass timber house is a big contributor to the lower GWP score. In addition, CO_2 intensive materials such as plaster are avoided since wood-based products are used as wall and ceiling finishes (Sustainer Homes, 2020c). The biggest contributor to GWP are the OSB and chipboard, as shown in Figure 29. Both materials have 38% of their environmental impact due to GWP in the production phase (Nationale Milieudatabase, 2021b). Glass is accountable for 24% of the environmental impact and finds 11% of its impact due to production related CO_2-eq emissions. Noteworthy is that the mass timber house uses glass wool insulation instead of PIR/PUR, which results in lower GWP. The glass wool from manufacturer KNAUF produces insulation with a shadow cost of 0,488 €/m^2 compared with 1,981 €/m^2 of PIR/PUR insulation. Interestingly, the shadow costs of KNAUF's glass wool have 27% lower shadow costs compared to the EcoInvent glass wool in the NMD viewer (Nationale Milieudatabase, 2021b). This indicates a difference between EPD input and EcoInvent input in the NMD database.

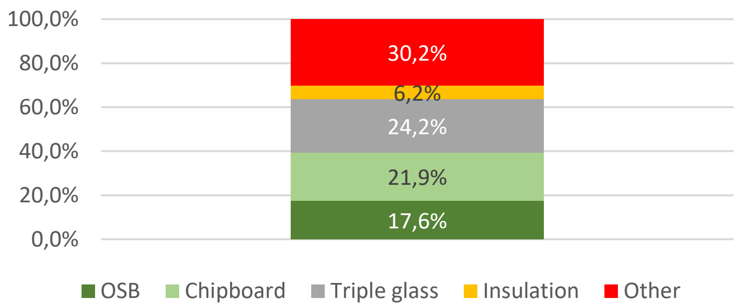


Figure 29: Mass timber house MPG_{mat} division over construction products.

Modified GWP

The modified GWP 'GWP_m' shows the global warming potential over 100 years when CO_2 sequestration due to temporary biogenic carbon storage (*$GWP_{bio,red}$*) and carbonation (*$GWP_{carb,red}$*) are taken into account. Figure 30 and Table 19 shows the impact of temporary carbon storage and carbonation on the construction material related GWP of both case buildings. The massive reduction in GWP of the mass timber house, results in a net storage of CO_2 in the building. A negative GWP value is reached since the amount of sequestered carbon is higher than the CO_2-eq emitted during the production phase.

Per functional unit the traditional house emits 3,13 kg CO_2-eq/m^2GFA*year, which is 10% less compared to the original GWP value (see Figure 27). The mass timber house emits -0,24 kg CO_2-eq/m^2GFA*year. This is 120% less than the original value. By using the 'delayed emission method' and valuating carbonation, the mass timber house emits 108% less CO_2 per m^2GFA over the building lifespan compared to the traditional house. This difference is less than the 157% found in (Švajlenka et al., 2017). However, Švajlenka et al. (2017) only look at the production phase and hence count all biogenic carbon as negative emission.

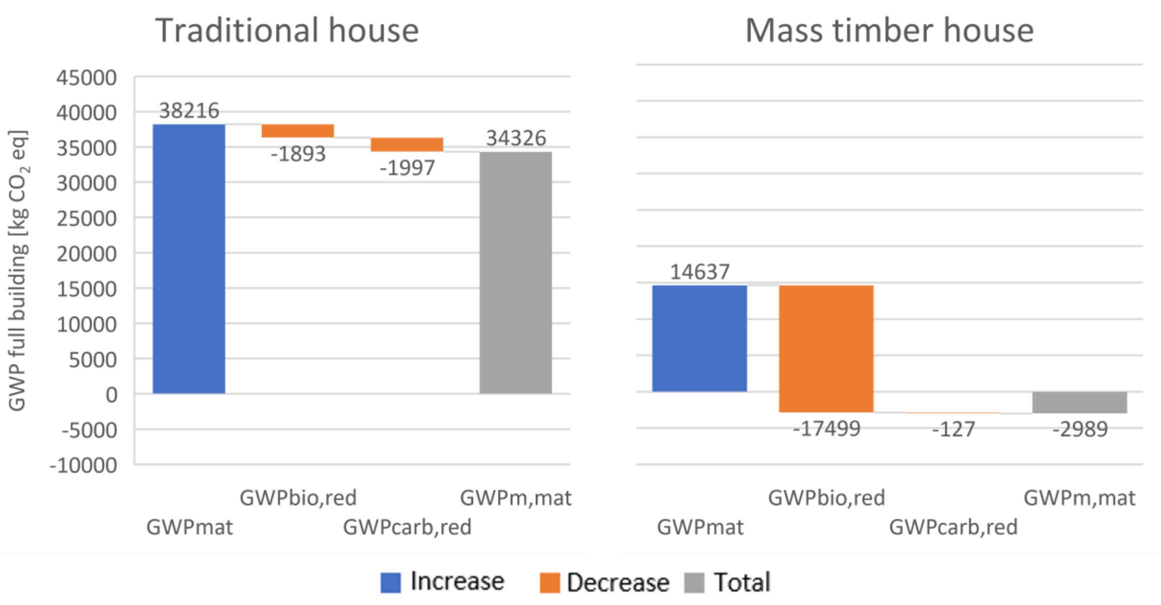


Figure 30: Effect of taking temporary biogenic carbon storage ($GWP_{bio,red}$) and carbonation ($GWP_{carb,red}$) into account. GWP_{mat} = construction material related global warming potential (without installations, built-ins and soil replenishment); $GWP_{m,mat}$ = construction material related global warming, taking temporary carbon storage and carbonation into account.

Table 19: Material related GWP of both case houses determined via the modified MPG calculation.

	Traditional house	Mass timber house
$GWP_{m,norm}$ [kg CO_2-eq/m^2GFA*year]	3,13	-0,24

Traditional house

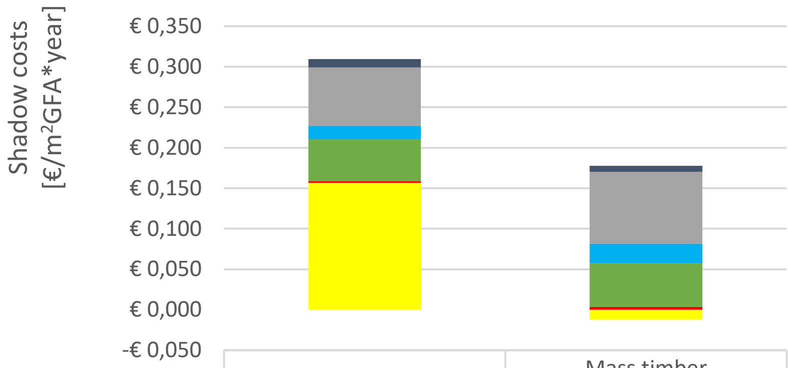
The biggest decrease in GWP in the traditional house is due to carbonation. This explainable since 73% of the traditional house's weight is from (reinforced) concrete. Carbonation of the sheltered CEMIII concrete during the 75 year lifespan of the building is responsible for 71% of CO_2 sequestration in concrete. This is a result of the high carbonation rate constant due to the sheltered condition of the concrete walls and floors. CO_2 sequestration per type of concrete per exposure condition is shown in Table 26 in appendix I. Furthermore, the limited wood usage in the traditional house results in a low decrease in GWP due to temporary biogenic carbon storage. Nevertheless results the incorporation of temporary storage and carbonation in a 10% decrease of biogenic emissions.

Mass timber house

Figure 30 shows that over 100 years 2.989 kg CO_2 is sequestered in wood-based products in the mass timber building. The net negative emissions are a result of the low emissions during the production phase, large biogenic carbon content and permanent carbon storage in reused and recycled wood-based products. The emissions during production and biogenic emissions at EoL are lower than the amount of CO_2 sequestrated in the wood-based products over the building lifespan. 50% of the $GWP_{bio,red}$ is from the delay in biogenic emissions of the wooden sheet material (chipboard and OSB) and 27% due to the LVL frame. Only 127 kg CO_2 is sequestrated in the concrete foundation. CO_2 sequestration per type of concrete per exposure condition is shown in Table 27 in appendix I. In total the GWP of the mass timber house is reduced with 120% in the modified MPG method compared to the original MPG method.

Modified MPG

The effect of the reduced GWP is taken into account in the modified MPG ($MPG_{m,mat}$) shown in Figure 31. Emissions of all 11 impact categories of the full building are shown in Table 34 in appendix VIII. Table 20 shows that the $MPG_{m,mat}$ has been reduced significantly. The material related MPG_{mat} of the mass timber house has been decreased with 29% due to valuation of temporary carbon storage and carbonation. The MPG_{mat} of the traditional house decreased with 6%. When taking temporary storage and carbonation into account, the $MPG_{m,mat}$ of the mass timber house is 45% lower compared to the traditional house. In the original MPG_{mat} the mass timber house scored 12% higher on the MPG_{mat} compared to the traditional house.



	Traditional house	Mass timber house
Marine ecotoxicity	€ 0,0103	€ 0,0077
human toxicity	€ 0,0718	€ 0,0886
Eutrophication	€ 0,0168	€ 0,0237
Acidification	€ 0,0516	€ 0,0544
Photo-oxidant creation	€ 0,0020	€ 0,0035
Global warming 100 year	€ 0,1567	-€ 0,0121

Figure 31: Modified construction material related shadow costs of most significant impact categories in of both case houses.

Table 20: Modified construction material related MPG-score of mass timber house with MDF and OSB.

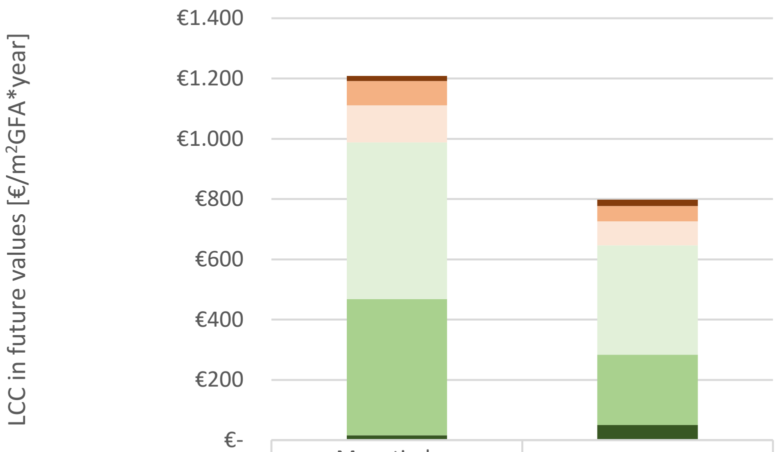
	Traditional house	Mass timber house
$MPG_{m,mat}$ [€/m²GFA*yr]	0,31	0,17

Life cycle cost comparison

Future value

All building costs in future value are shown in Figure 32. The Investment costs at the start of the construction project are significantly higher in the mass timber house. The investment in construction costs is 35% lower in the traditional house compared to the mass timber house. A similar value of 34% is found in Centrum Hout (2021b) concerning a mass timber house with CLT frame. Differences in costs are highest between the structural frames (structural walls and floors) in the mass timber and traditional house. The LVL frame of the mass timber house is 313 €/m^{2}GFA. Which is 88% more expensive than the concrete frame, which costs 210 €/m^{2}GFA.

This increase in costs is partially countered by the lower foundation costs in the mass timber house. The foundation of the mass timber building is 70% cheaper than the traditional house. This difference is much lower compared to the 30% found in Švajlenka et al. (2017). Furthermore, different material usage in finishing layers results in 40% higher costs per m^2 GFA in the mass timber house. Demolition costs of both buildings also differ with 57% higher costs in the mass timber house. The concrete foundation piles are often left in the ground, hence the demolition costs of the foundation are 0. Lastly, annual replacement and O&M costs are 22% lower in the mass timber house. These costs are recurrent during the building lifespan. Detailed evaluation of these costs show where cost differences originate from.



	Mass timber house	Traditional house
Rc, O&Mc	€16,56	€21,34
Dc - Finishing layers	€80,53	€50,20
Dc - Structural frame	€123,50	€79,36
Dc - Foundation	€-	€-
Invst - Finishing layers	€519,37	€363,74
Invst - Structural frame	€452,60	€233,05
Invst - Foundation	€15,68	€49,97

*Figure 32: Life Cycle Costs of all costs over the building lifecycle in future values [€/m^{2}GFA*year].*

Construction costs

As shown in Figure 33 and Figure 33, the highest differences in construction costs originate in the façade finish, inside walls and structural frames. Cost differences in the façade are a result of a bigger masonry surface in the mass timber building and the usage of wooden window and doorframes. The lower masonry surface in the traditional house results in roughly 50% lower façade costs. These costs however, are related to specific design choices and do not originate in a structural material difference. The remaining difference in façade costs is due to the wooden window frames in the mass timber house. In the traditional house the window and doorframes are already integrated in the prefabricated concrete walls. Therefore, the related costs are denoted in the structural frame costs of the traditional house.

The majority of the higher construction costs of the mass timber house are caused by the LVL frame. 57% of the LVL costs originate from the outer walls, in which the support columns are taken into account. Figure 34 shows that the costs are divided roughly 50/50 by material and sub-contractor costs and labour costs. The LVL material costs are 7% of the total outer wall frame costs. The labour costs of setting the LVL beams and applying the chipboard batten are responsible for 27% of the outer wall frame costs. In the storey floors the setting, chipboard batten and applying notches is 30% of the storey floor costs. 40% of the costs in the storey floors are caused by the LVL material costs. In addition, part of the cost difference in the structural frame is a result of the mass timber ceiling. The mass timber house is originally made up of several wooden modules, which feature both a bottom and a top layer. When two modules are stacked, the floor of the upper module consist of a bottom layer and the top layer of the module underneath. This results in extra material and labour costs. Furthermore, it is assumed that all building elements are hoisted in place with a crane. The attribution of hoisting costs is significant in the LVL frame. Approximately 29% of the total frame costs are attributed to hoisting. The attribution of hoisting costs in the prefabricated concrete frame is taken into account in the costs but not available for further detailed exploration in the cost calculation software (IGG, 2021).

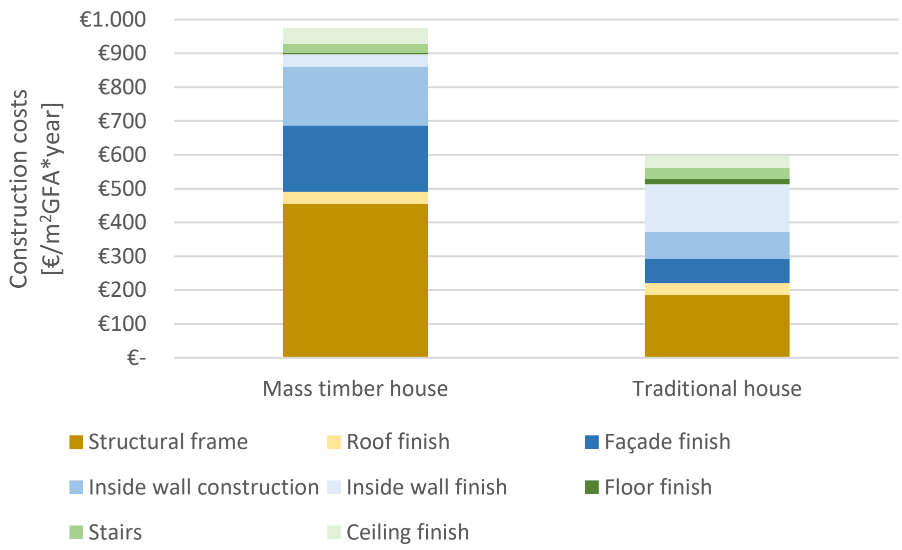


*Figure 33: Construction costs [€/m^{2}GFA*year].*

Cost differences in inside walls and the structural frame are a result of more expensive prefabricated mass timber wall and floor elements as shown in Figure 34. Costs are expressed per wall area or floor area depending on the building element. The wooden roof used in the mass timber house can also be used in traditional houses, therefore no cost alternative is shown. In addition, only the walls feature sub-contractors. The cost calculations software (IGG, 2021) assumes that the plasterboard wall finish is delivered and installed by sub-contractors. All mass timber building elements are more expensive than the traditional alternative. Since these differences are per m^2 floor or wall area, the differences in total building increase significantly. Worth mentioning is the ratio between material and labour. These ratios match the ratios mentioned by Wonen in hout (personal communication, 2021). Due to increases in wood prices, material labour ratios are increasing toward 50%. In addition, manually assembling the wooden framework and finishing layers result in high labour costs.

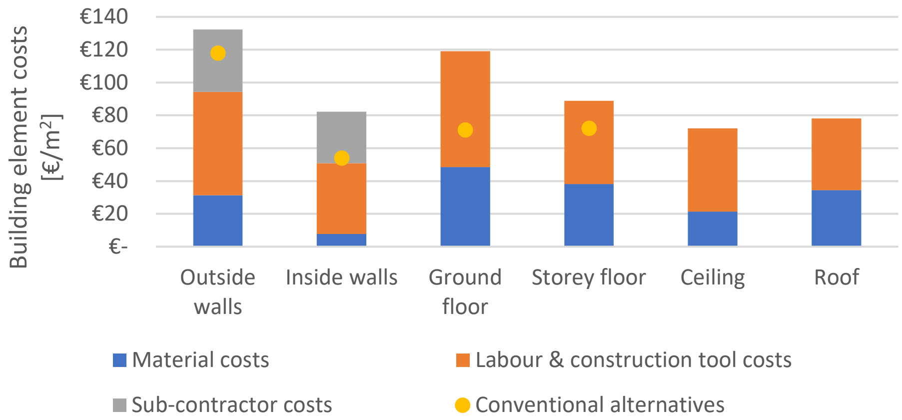


Figure 34: Cost differences between prefab mass timber building elements and conventional alternatives.

Replacement and Operation & Management costs

Figure 35 shows the annual operation & management costs in future values. The most significant differences in O&M costs is a result of the plaster wall finish. Plaster in maintenance intensive and needs to be replaced several times. The mass timber house uses plasterboards as finish which are low in maintenance. According to IGG (2021) the plasterboard ceiling finish on the other hand is more maintenance intensive than plaster finish. This results in higher ceiling O&M costs in the mass timber house.

The structural frame of both houses does not require maintenance. In the traditional house the concrete walls and floors are protected by a masonry layer from the outside and plaster finish from the inside. The LVL frame in the mass timber house is also protected by a masonry layer from the outside and plasterboards from the inside. In addition, the LVL frame is covered by air tight tape and foil. Hence, the LVL frames experience little to no degradation due to weathering.

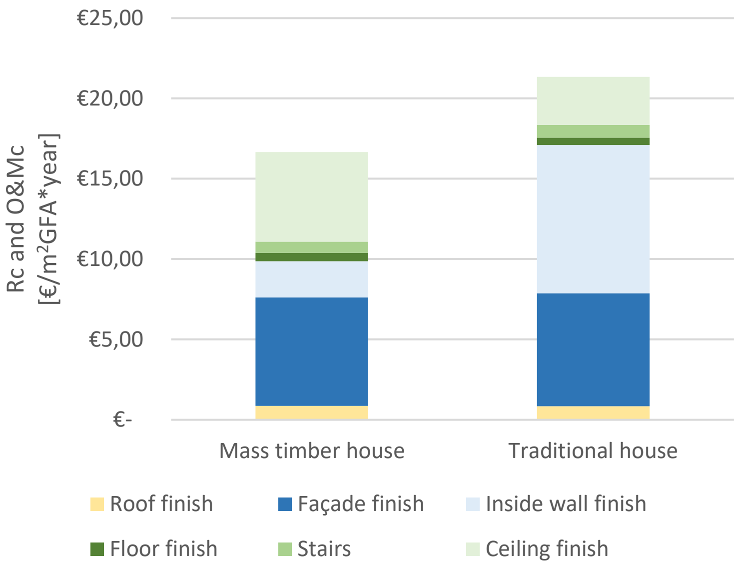


*Figure 35: Operation & management costs in future values [€/m²GFA*year].*

Demolition costs

The demolition costs are calculated per building element and shown in Figure 36. This means the façade finish and inside walls are removed before the prefabricated frame in the case houses is demolished. Most of the difference in demolishing costs occurs in the demolition of the structural frame. In the demolition of the concrete frame it is assumed that the building elements are made of a homogeneous material, which does not need separation. Separation of reinforced steel within the concrete is assumed to happen at waste management facilities. Hence, during the demolition no labour is spent on disassembling various prefabricated building elements. Furthermore, the masonry façade finish and façade insulation are removed separately before the frame is demolished.

In the mass timber house, the building is rather deconstructed instead of demolished. Wooden sheet material is removed first from walls and floors before the LVL beams are deconstructed. This demolition process requires more labour and results in 66% higher demolition costs. Lastly, the difference in façade demolition costs is a result of the larger masonry surface in the mass timber house.

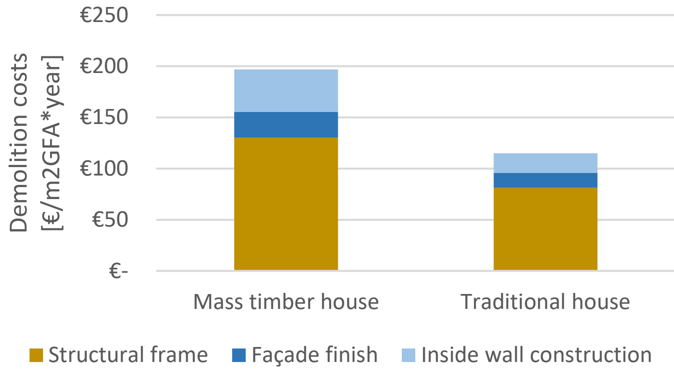


*Figure 36: Future value of the demolition costs [€/m²GFA*year].*

Present value

Figure 37 shows the LCC of the mass timber and traditional building with both a GFA of 143 m². The total discounted Life-cycle-costs with average discount factor are €206K for the traditional house and €232K for the mass timber house. This shows that the costs of the mass timber house are 13% higher over the full building life cycle. Due to the lower replacement and O&M costs, the difference in initial construction costs are slowly countered over time. Table 21 shows the present value of the life cycle costs expressed per functional unit. Even though the difference in LCC_{PV} per functional unit seems small, the difference results in a €26K difference in the average terraced building over its full lifespan.

The traditional house features higher annual maintenance costs, which increases the impact of the discount factor. LCC costs of the traditional house become 7% higher when the discount factor is decreased with 0,4 percentile points. On the other hand, the LCC of the mass timber house increases with 5%. A 6% lower LCC score of the traditional house is shown when the discount factor is increased with 0,4 percentile points. The mass timber house LCC decreases with 4%. Hence, the difference in LCC between the two case houses decreases when a lower discount factor is applicable. In none of the scenarios the LCC of the mass timber house are lower than the traditional house.

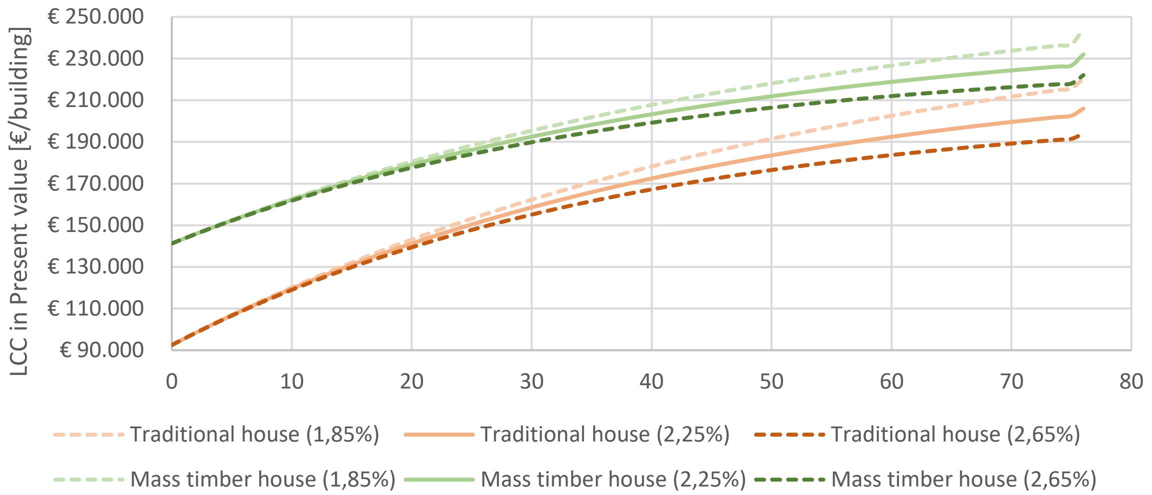


Figure 37: Life Cycle Costs in present value, with different discount factors [€/building]. The solid lines represent the average discount factor from Werkgroep Discontovoet (2020). The dotted lines represent high and low discount scenarios.

Table 21: Life cycle costs of both case houses in present value expressed per the functional unit.

	Traditional house	Mass timber house
LCC_{PV} [€/m^{2}GFA*year]	19,20	21,63

LVL price impact

The LVL price has little effect on the price of the mass timber house as shown in Figure 38. An increase in LVL price of 35% results in a 1,5% increase in the present value LCC. A reduction in LVL price of 35% results in a 1,5% lower LCC. A mass timber house is still 11% more expensive compared to a traditional house at a LVL price of 520 €/m^3. This shows that despite LVL accounting for 21% of the total body weight, the fluctuations in LVL price do not result in significant change in LCC.

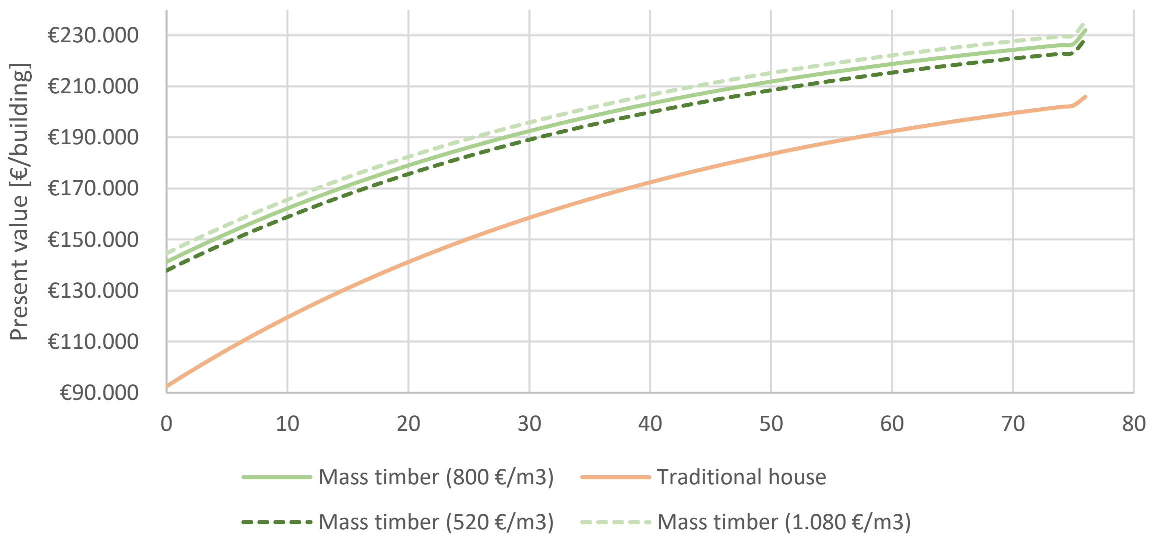


Figure 38: Effect of LVL price fluctuations on present value LCC [€/building].

The difference in LVL price has more effect on specific LVL building elements. Figure 39 shows the sensitivity of the six building elements and the total LVL frame. The roof and storey floors are most sensitive to changes in the LVL price. In these building elements LVL has the biggest share in material costs. Building elements which feature more volume of other materials and more labour are less prone to changes in LVL price. These building elements are outside and inside walls. The attribution of sub-contractor costs also decreases the sensitivity to LVL-prices.

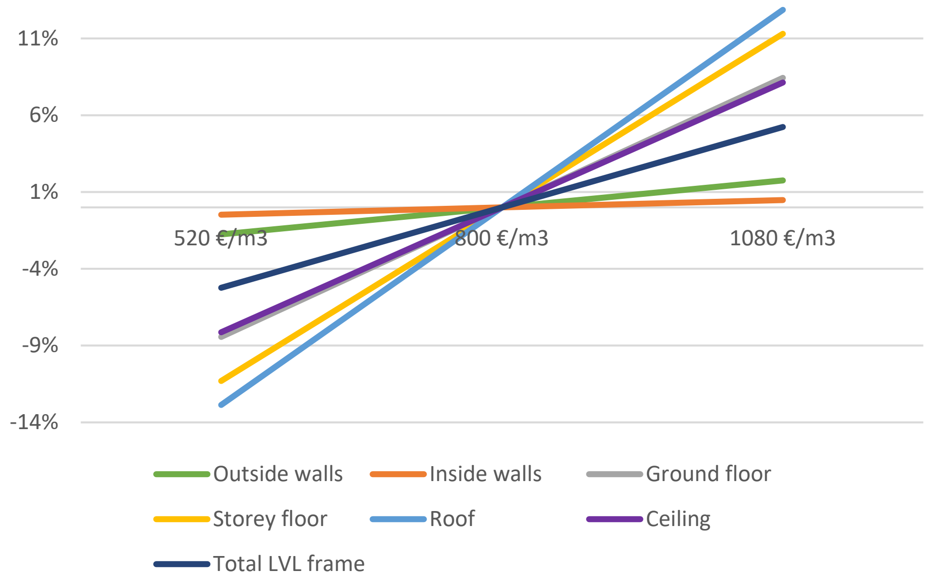


Figure 39: Effect of LVL price on costs of LVL building elements and total LVL frame [%].

Scenario analysis

Scenario GWP reduction

According to PBL (2021) approximately 26.800 new houses are constructed every year between 2020 and 2030. Therefore every year 383 ha GFA of terraced house is added to the Dutch built environment. Figure 40 shows the related amount of CO_2-eq emissions related to the construction materials in four different scenarios. The difference in cumulative emissions between both case houses is 66% when GWP is calculated via the MPG method. This difference increases to 108% when temporary storage and carbonation are taken into account in the modified MPG calculation.

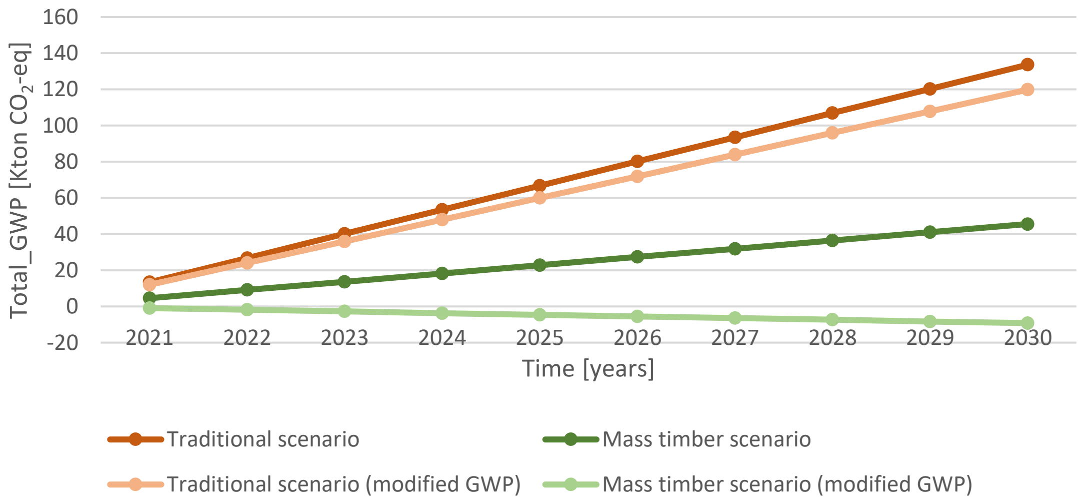


Figure 40: Total material related CO2-eq emission four scenarios.

Difference in scenario costs

Figure 41 shows the difference between the mass timber scenario and traditional scenario. with and without carbon tax and in a scenario in which the emission are calculated via the modified MPG-score. In the scenario with no carbon tax and emissions calculated via the MPG method, the mass timber house is 12,6% more expensive compared to the traditional house. The carbon tax reduced the difference in scenario costs with 2,3 percentile points. Assessing the GWP of the scenarios via the modified MPG-score further decreases the difference in costs with 0,3 percentile points to 10%. In the scenario with no carbon tax and in which the GWP is assessed via the MPG-score, the scenario cost difference is roughly 500 million euro. This cost difference is decreased to 388 million €, when a carbon tax is taken into account and temporary carbon storage and carbonation integrated in the MPG calculation.

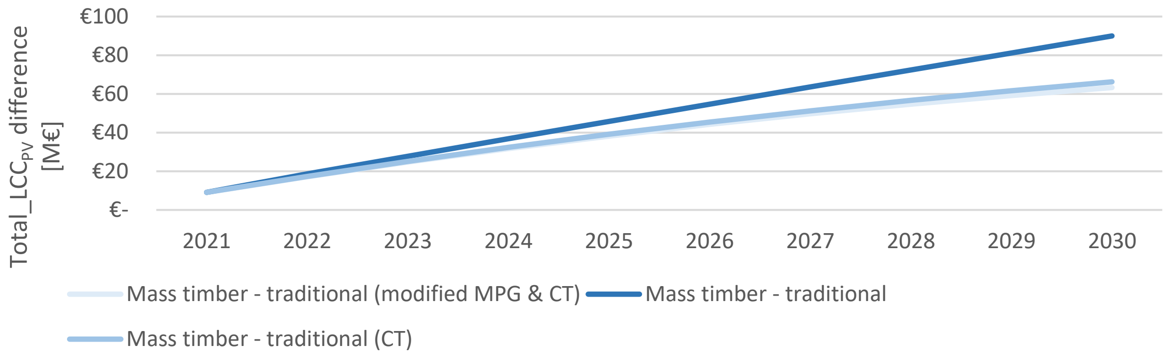


Figure 41: Difference in scenario life cycle costs comparison; CT = carbon tax.

Climate goal and mitigation cost

According to PBL et al. (2020) the current Dutch sustainable policies are not enough to lower the annual emissions to the climate goals. The CO_2-eq emissions mitigated through constructing mass timber terraced houses instead of traditional versions in 2020-2030 aids in reducing the additional annual emissions. The contribution varies between 0,11-0,17% as shown in Table 22 based on the method of accounting for temporary biogenic storage and carbonation. By using the modified MPG method the attribution increases with 0,06 percentile points.

The costs of mitigating CO_2-eq emissions through constructing in mass timber instead of traditional houses are shown in Table 22. The inclusion of a carbon tax and valuating temporary biogenic carbon storage and carbonation results in a halving of mitigation costs. In both cases, mitigation costs are significantly higher than the most expensive mitigation costs shown in Ritchie (2017). A gas plant with Carbon Capture Storage has a mitigation cost of approximately 0,057 €/ton CO_2-eq.

Table 22: Mass timber attribution to 2030 climate goal and mitigation costs.

	Attribution to 2030 climate goal [%]	Mitigation costs [K€/ton CO_2-eq]
Mass timber - traditional	0,11	€ 1,03
Mass timber - traditional (CT)	0,11	€ 0,83
Mass timber - traditional (modified MPG & CT)	0,17	€ 0,55

Discussion

Research limitations

The results in this study are based on the comparison between a mass timber and traditional case house. Furthermore, the methods used for assessing costs and environmental impact have their limitations and impact on comparability, validity and reliability of the results.

Case houses

Due to the novelty and rarity of mass timber construction (Ministerie van Binnenlandse Zaken, 2020), not a lot of mass timber constructions in the Netherlands are available for academic studies. Therefore, the mass timber case house selection prioritised technical and financial data availability. Although detailed technical and financial data is collected, it is still specific to one particular mass timber construction method. Not all mass timber constructions are made up of LVL or constructed in modules, which limits the comparability of the mass timber related findings in this study.

The environmental impact and costs of traditional buildings, on the other hand, are already well known. According to Moussard et al. (2018), reinforced concrete has been around for approximately 150 years. Therefore, the costs and environmental impact related to traditional buildings has been explored in detail already. Therefore, the traditional terraced case house better represents the average of the related costs and environmental impacts compared to the findings of the mass timber house. However, due to the novelty and actuality of mass timber, this study provides a first step in exploring the costs and potential of CO_2 emission mitigation via LVL-based mass timber constructions compared to the traditional alternative.

Similar energy installations

In the costs and environmental impact comparison it is assumed that the buildings feature the same energy performance. Underlaying differences in energy usage and energy generation are however possible. The MPG reports (Centrum Hout, 2020; Sustainer Homes, 2020c) show that in contrast to the mass timber house, the traditional house requires electricity from the grid even though it features double the size of the solar panel area. This leads to believe that the mass timber house is actually better insulated. Since the energy installations are eliminated in the comparison in this study, the remaining case houses do feature a difference in the degree of insulation. The material comparison however shows that the traditional house already uses 21% more insulation per GFA. Nevertheless, different insulation materials differ in insulation value when the same volume is applied. Therefore, it can be assumed that the traditional house would have higher environmental impact and costs when similar insulation is guaranteed. However, due to the unavailability of energy performance data regarding the traditional house, assumptions had to be made. Even though the case house might differ in insulation, the energy performance of the whole building (taking energy installations into account) is expected to be similar. Therefore, contractors that need to build a A+++ house according to the Dutch energy performance rules, can realistically choose the mass timber or traditional house. Therefore the comparison in costs and environmental impact is still valid.

Cost validity and reliability

The costs of the case houses calculated via the IGG construction costs software (IGG, 2021) provide significant validity and reliability. Costs are frequently updated and based on realized construction projects (IGG, personal communication, 2021). However, due to the unavailability of financial data from the mass timber house, the validity of the mass timber costs are debatable.

Nevertheless, the method applied in this study to estimate the costs of LVL prefabricated building elements suggests that an accurate cost representation is made.

Prefabrication

Construction and demolition costs of the mass timber case house are expected to be lower when the original method of prefabricated modules is used instead of prefabricated building elements. Although the cost comparison is benefitted by the assumption that both buildings are constructed in a similar way, differences in construction method can result in significant cost differences. McKinsey & Company (2019) shows that up to 20% of the construction cost can be reduced by modular constructions. Construction times can furthermore be decreased to roughly 50% if the prefabricated modules only need to be installed and assembled on-site (McKinsey & Company, 2019). Modular constructions can be made both from mass timber constructions as traditional construction. Hence, these cost reductions would not result in significant differences between the two case houses. Nevertheless, it can be argued that due to the weight reduction in mass timber, less transport and heavy construction tools are needed. This results in faster construction times compared to a modular construction made of traditional construction materials. Future study focussed on modular mass timber and modular traditional houses can explore potential cost difference. When comparing the construction costs in this study with future studies, it must be taken into consideration that costs are not calculated based on modular constructions.

Residual value

The LCC method used in this study does not taken residual value into account. However, whereas the traditional house is assumed to be reduced to demolition rubble. The mass timber house is not demolished via e.g. a wrecking ball, since that would seem excessive and unlikely. Hence, the mass timber building is manually deconstructed using scaffolding. Therefore it can be assumed that specific building elements (e.g. timber slats and beams) remain more intact compared to the traditional house. In case of the mass timber house, design for disassembly has been taken into account according to Sustainer Homes (personal communication, 2021). This significantly increases the circularity, which is reflected in the residual value of construction materials and the building. According to Copper8 (2017), residual value can be 10 to 20% higher compared to a traditional building with low circularity. Though, since these costs are relevant after several decades, differences in residual value remain uncertain. When mass timber constructions will be deconstructed after their lifespan, more valid claims regarding differences in residual value compared to a traditional house can be made.

MPG methodology

The EN 15804 (European Standardization, 2019) in combination with the Dutch determination (Nationale Milieudatabase, 2020a) method provide excellent reliability of the results. Due to detailed description of calculation rules and tracking methodological changes in amendment sheets, the environmental impact assessment via the MPG-score is transparent. Nevertheless the uncertainty of toxicity shadow costs (TNO et al., 2004) and the substitution benefits of wood-based construction materials in module D (NIBE, 2019b) are debatable. Furthermore, significant differences in shadow costs between EcoInvent products and EPDs is witnessed in the NMD (Nationale Milieudatabase, 2021b), see Table 23. In addition, EPDs are based on product data from EcoInvent, which has shown to have a significant attribution in the EPD's product related environmental impact (NBvT, 2021).

Table 23: Differences in EPD and EcoInvent shadow costs. From Nationale Milieudatabase (2021b).

	Product related shadow costs		
	Glass wool	Concrete rib floor	Spruce timber columns
Manufacturer	KNAUF	Betonhuis	Centrum Hout
	0,488 €/m2	4,484 €/m2	0,100 €/m
EcoInvent	1,981 €/m2	10,360 €/m2	0,6551 €/m

Validity of the environmental impact results in this study are therefore strongly tied to the validity of the product data in EcoInvent and the assumptions in the Dutch determination method (Nationale Milieudatabase, 2020a). Furthermore, differences in determination methods between European Union member states limit comparability of environmental impact results. However, due to the transparency of the methodology, the assumptions on which the results are based on are clearly shown. Therefore, the environmental impact comparison results are reliable and can be used for comparison with other LCA studies.

MPG discussions

The introduction of the MPG has sparked numerous discussions regarding the calculations rules in the Dutch determination method (Nationale Milieudatabase, 2020a) concerning wood-based products. For instance the discussion concerning the decision to compare the incineration of wooden products in module D with the substitution of wooden pellets for energy generation instead of the Dutch fuel mix. NIBE (2019b) has shown that with every release of new PCR the shadow costs of wooden products have become higher. The last update had the most impact, in which the substitution of energy generation by wooden product incineration is compared with wooden pellets. Wooden pellets have significantly lower emissions compared to the average Dutch fuel mix, thus creating less substitution benefits. On the contrary, other European countries do compare the substitution of wood for energy generation with their average fuel mix. NIBE (2019b) states that the Dutch methodology might lead to less comparability of LCA results with studies from other European countries. Furthermore they argue the incentive to use biobased materials with generally lower emissions is decreased since EWP have become less attractive compared to the old method.

Incineration versus recycling and reusage

More contradictory results concerning module D for EWP have been found in a study by CE Delft (2021). They show that incineration of wooden products results in higher substitution benefits compared to recycling, even though biomass incineration generally has very low emissions. This is explained due to the fact that the production of wood-based products generally has an even lower environmental impact, hence why the mitigated impacts in module D are lower. CE Delft (2021) claim that studies have shown that the low emissions attributed to biomass are debatable and that the general consensus is that cascading wood products allows for postponing carbon emissions for a longer time. In reality recycling of EWP might thus be favoured over incineration, although this is not the case in the EN 15804. Furthermore the default scenarios developed by Nationale Milieudatabase (2021d) also indicate a high amount of incineration compared to reusage and recycling. For instance, in Table 24 the default EoL of a wooden beam (uncontaminated) and wooden sheet material (uncontaminated) according to the PCR can be seen.

Table 24: Default EoL scenarios according to (Nationale Milieudatabase, 2021d)

	landfill	incineration	Recycling	Reusage
Wood ‘clean’ (beams, planks)	5%	80%	10%	5%
Sheet material ‘clean’ (cladding)	5%	85%	10%	0%

Theoretical implications

The assessment of temporary biogenic storage in this study is based on the method constructed by (TNO, 2021b). Whereas TNO (2021b) only focussed on the production stage, this study constructed a method that takes the whole building life cycle into account. The Impulse Response Function (IRF) from Joos et al. (2013) is put to practice in a framework that allows temporary carbon storage to be taken into account in the MPG calculations. In addition, the framework used in this study shows how to take carbonation into account based on academic findings and recommendations. The British PCR already take carbonation into consideration and the framework in this study provides a way for the Dutch determination method to do the same.

Dynamic LCA approach

The method constructed in this study to take temporary biogenic storage into consideration is a dynamic LCA approach. The method assumes all carbon sequestration occurs before wood harvesting. However, Hoxha et al. (2020) also shows an alternative DLCA that assumes biogenic carbon is sequestrated in new tree growth during the building life cycle. Via this approach the reduced logging scenario from Ouden et al. (2020) can be integrated in the GWP assessment. When traditional construction products are used instead of wood-based products, logging can theoretically be assumed to be postponed. This would result in additional carbon storage in existing trees and lower the impact of concrete products. Wood-based products on the other hand would result in more carbon sequestration due to faster sequestration rates in the early growth phases (Broadmeadow & Matthews, 2003). This approach could be a more uniform approach that takes biogenic storage into account for both traditional and wood-based products.

Policy implications

This study shows that a carbon tax has little effect on the difference in costs between a mass timber house and a traditional house. If the reduction potential that mass timber constructions offer were to be utilized, the difference in costs needs to be compensated. Although global warming effects are becoming more urgent, costs still play a major role in building projects. In order to make mass timber more economically favourable, the difference in costs will need to be compensates for via subsidies.

Furthermore, biogenic carbon storage is currently not assigned a value in the MPG even though TNO (2021a) and this study indicate the potential of GWP reduction. In addition, PBL et al. (2020) show that additional CO_2 reduction is needed to reach the Dutch climate goals. This study shows that mass timber offers significant GWP reduction compared to a traditional building. Valuing carbon storage in wood-based construction products in the MPG increases the incentive for construction companies to choose mass timber instead of traditional houses. This would require an adjustment in the Dutch determination method which needs to be discussed by policy makers.

The carbonation of concrete on the other hand has less impact on the GWP reduction. In addition, carbonation is regarded as a negative effect in the built environment due to reinforced steel corrosion (Galan et al., 2010). Therefore, stimulating carbonation in the MPG-score is not desirable.

Conclusion

This study aims to provide a comparison of the economic costs and environmental benefits of a mainstream mass timber house compared to a traditional house. The material comparison shows that the high attribution of wood (63%) in the mass timber house results in a significant decrease of 76% in total building weight.

A big share of the environmental impact in both case houses are the energy installations. In the traditional house 37% of the full MPG score originates in PV panel usage. The MPG-score of the PV panels reduces with roughly 50% when the PV surface is halved. This shows a trade-off between the EPG-score and MPG-score in nZEB buildings. A better EPG-score is reached by incorporating more PV panels, while the MPG-score significantly worsens.

The environmental impact assessment also shows the significant attribution in impact due to MDF usage. Despite being only 11% of the building weight, MDF is responsible for 46% of the MPG score of the mass timber house. The construction related material impact of the mass timber house with MDF is even higher than the traditional house, which contradicts the findings in academic literature. After replacing MDF with OSB however, the MPG score of the mass timber house is reduced with 35% and becomes 27% lower than the traditional house. Worth noting is that the biggest impact category in both houses are human toxicity potential and global warming potential.

The global warming potential of the mass timber house is significantly reduced when temporary carbon storage and carbonation are taken into account. The negative MPG_{mat} score of -0,24 €/m^2GFA*year shows that the mass timber house has the potential to reduce GWP in a 100 year time period. In a scenario in which all terraced houses in 2020-2030 are built in mass timber instead of traditional houses this would result in 108% reduction in CO_2-eq emissions. Despite contributing only 0,11% to achieving the 2030 climate goal, it indicates the potential of actively decreasing GWP via building construction instead of increasing GWP. Postponing emissions further via cascading increases the permanent carbon storage potential in the built environment. By incorporating biogenic storage in the MPG-score, this reduction potential can be reflected via significantly lower MPG-scores of mass timber buildings. Incorporating carbonation also lowers the MPG-score of both case houses, but significantly less than biogenic storage.

This GWP reduction potential in mass timber houses comes at a price though. The LVL frame of the mass timber house is almost 100% more expensive than the concrete frame due to high material costs and large contribution of labour in LVL building elements. On the other hand this study found that replacement and O&M costs were lower in the this specific mass timber house. The air tight sealing of the structural LVL elements results in no maintenance. In addition, the OSB wall finish also significantly reduced costs. As a result the difference in LCC in the 2020-2030 scenario decrease over time but still result in the mass timber scenario being 500 M€ more expensive than the traditional scenario. A carbon tax and incorporating biogenic storage and carbonation would decrease this difference with 22%.

Despite these reductions, the mitigation costs of reducing emissions via mass timber are still significant, with 550 €/ton CO_2-eq. Mitigation costs however can be decreased by increasing wood cascading, which should therefore be reflected in the MPG via the suggested 'modified MPG method'. Furthermore, prefabrication and residual value are not taken into account in this study. Therefore future studies could explore the mitigation costs with these aspects taken into account. Regardless of the costs, the effects of global warming are becoming more clear (IPCC, 2021), whilst projections show that climate goals are not expected to be reached with the current policies (PBL et al., 2020). Mass timber offers a way of actively reducing emissions due to carbon storage, while mitigating CO_2-eq emission of concrete and steel production.

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Appendix I - Carbonation of concrete

Theory – carbonation process

The absorption of CO_2 by more precisely 'Portland cement' (most frequently used cement) is called carbonation. During the production of concrete from Portland cement, CO_2 is emitted due to fossil fuel burning and the calcination of limestone. The ration of emission originating from fossil fuels and calcination is roughly 50/50% (Pade & Guimaraes, 2007). A substantial part of these calcination emissions can be absorbed via carbonation. According to Galan et al. (2010), carbonation is the formation of calcium carbonate ($CaCO_3$) from calcium oxide (CaO) and CO_2, due to alkaline components in concrete reacting with CO_2 in the atmosphere. CO_2 diffuses at the surface and diffuses into concrete, lowering the pH value (making it less alkaline). Usually, carbonation is seen as a deterioration of concrete since it leads to the corrosion of steel reinforcements embedded in reinforced concrete (Galan et al., 2010). But in a CO_2 balance comparison it is a beneficial characteristic. Noteworthy is that carbonation keeps on happening even after demolition (Pade & Guimaraes, 2007).

Theory – carbonation in the Dutch PCR and EN 15804

Carbon storage via carbonation has so far not been introduced in the Dutch PCR. On the other hand, in the English PCR (BRE, 2014), which is also based on EN 15804, carbonation is taken into account. In the English PCR carbonation is divided over two types of concrete. Firstly, concrete surfaces that are made of pure limestone are assumed to carbonate for 100% within a short time of the installation (BRE, 2014). The amount of carbon that the concrete stores is noted in construction phase [A5] (see Table 2). All carbon that has been taken up during calcination is assumed to be stored in A5.

A different approach has been taken for cementitious products that contains fractions of limestone. In this case the English PCR prescribes that the amount of carbon storage depends on the strength of the concrete product. Carbon storage for these products is noted in the use stage B1. Precast concrete is assumed to carbonate after production, hence why carbonation is assumed to happen in the manufacturing stage A3, construction stage A5 and use stage B1). At the EoL (C4) concrete carbonates as well when it is crushed and partially landfilled, which is also taken into account in BRE (2014).

Method – carbonation process

The amount of carbon that is stored in concrete products via carbonation, depends on the degree and depth of carbonation and on the geometry of the concrete product. In turn, the degree and depth of carbonation depends on the period of time various concrete material surfaces are exposed to a certain environment (Dodoo et al., 2019).

Method – degree of carbonation

The degree of carbonation (DoC) shows the share of CO_2 fixed compared to the maximum amount that could be fixed by reaction with carbon oxide (Andrade & Sanjuán, 2018). This depends on the type of concrete that is used. The types of concrete in the buildings focussed on in this study are mainly CEM I and CEM III (which stand for different types of concrete mixes). It is assumed the subtype of CEM I is CEM I 42,5N which is frequently used for concrete screed and simple concrete structures that don't have to meet special demands (Betonhuis, 2020). The type of CEM III concrete is assumed to be CEMIII/A 42,5N, a slag-based concrete which features roughly 40% slag (slag is a side product in the production of pig iron) (VVM cement, 2019). According to a seller of concrete (Drogemortel.nl, n.d.), CEMIII 42,5N is used for foundation, floors and reinforced walls. In comparison to CEM I, slag-based concrete like CEM III has a higher degree of carbonation (Andrade & Sanjuán, 2018). The division in types of concrete of concrete products used in the mass timber and traditional houses is based on whether or not the concrete type is specified in the NMD and the area of application. The wooden house for instance only has concrete foundation, which is often made entirely out of CEM III.

Method – carbonation depth

The carbonation depth shows the depth that carbonation process in the material happens. This depth depends on the carbonation rate constant 'k'. Pade & Guimaraes (2007) show different carbonation rate constants for CEM I in various exposure conditions in table 2 in their study. These constants can be converted to carbonation rate constants for CEM III by applying a correction factor shown in table 3 in Pade & Guimaraes (2007). As previously mentioned CEM III 42,5N features roughly 40% slag, so a correction factor of 1,2 is applied. Since all concrete elements in the mass timber house and traditional house are either buried (foundation) or covered with a finishing layer, isolation or façade material, carbonation rate constants are chosen from the category buried and sheltered (table 2 in Pade & Guimaraes). However, carbonation still occurs after demolition, which is assumed to happen after a 75 year life time in the MPG. Thus the waste scenario of concrete plays an important role in the amount of CO_2 that can be absorbed. Stichting bouwkwaliteit (2019) show that the MPG calculations assume that 99% of the concrete is recycled and 1% ends up as landfill. Similar to Pade & Guimaraes, 2007 this study assumes the concrete rubble is exposed to the atmosphere for 4 months before being recycled and turned into new concrete. The MPG calculation looks at a period of 100 years, so 1% of the concrete waste is exposed for the remaining 25 years while the other 99% is used again in new concrete. Pade & Guimaraes (2007) argue that if the concrete is reused again, the carbonation rates are negligible. Carbonation depth constants are used in equation 37 to calculate the carbonation depth (Pade & Guimaraes, 2007).

[Eq 37] $$d = k * (Cf) * t^{0,5}$$

d = carbonation depth, Cf = correction factor if applicable, t = time period

The carbonation depth is multiplied by the area of exposed concrete surfaces in order to calculate the carbonated volume in equation 38. Important to note is that carbonation rates of tight covered surfaces are almost negligible (Lagerblad, 2005). In the traditional house, walls and floors are covered with isolation and plaster on the inside. Assumed is that carbonation will only take place on concrete walls covered by façade and floors covered with tiles. Hence why only half of the above ground concrete surfaces is taken into account in the calculation. Furthermore the exposed area of the concrete elements increases significantly when it is crushed to rubble and thus allows for more carbonation. It is estimated that concrete rubble will have an average surface from a 70cm*40cm*40cm block. The amount of concrete rubble blocks is calculated based on the volume of the concrete elements before demolition.

[Eq 38] $$v = d_i * A_i$$

v = carbonated volume, d_i = carbonation depth per cement type and exposure condition, A_i = surface per cement type and exposure condition

In order to calculate the CO_2 uptake per kg carbonated concrete over a specific time period the following equation is used (see equation 39), from Pade & Guimaraes (equation 3). The amount of CO_2 uptake also depends on the material dependent DoC. Andrade & Sanjuán (2018) provide more up to date DoC values, which taken into account in [Eq 3]. Table 25 shows the carbonation rate constants with correction factor, time period of exposure, carbonation depths and CO_2 uptake/m^3 concrete.

[Eq 39] $$M_{co2} = DoC * C * CaO * \frac{M_{co2}}{M_{CaO}}$$

M_{co2}= CO_2 uptake/m^3carbonated concrete, DoC = 60% for CEM I & 100% for CEM III (Andrade & Sanjuán, 2018), C = mass of Portland cement per m3 concrete = ±390 kg, CaO = mass fraction of CaO in Portlandcement = ±65% (Pade & Guimaraes, 2007), $\frac{M_{co2}}{M_{CaO}}$ =molecular mass of CO_2/molecular mass of CaO

Table 25: carbonation rate constants 'k' (from Pade & Guimaraes. 2007)

Exposure condition	*k*	Correction factor	*T [years]*	*d [mm]*	*M_{co2} [kg CO_2/m^3 carbonated volume]*
Buried (CEM III)*	0,75	1,2	75	8	199
Buried CEM III	0,75	1,2	25	4	199
Sheltered CEM III	2,5	1,2	75	26	199
Exposed CEM III	1,0	1,2	0,33	0,69	199
	1,0	1,2	25	6	199
Buried CEM I	0,75	N.A.	25	4	120
Sheltered CEM I	2,5	N.A.	75	22	120
Exposed CEM I**	1,0	N.A.	0,33	0,57	120
	1,0	N.A.	25	5	120

**foundation is only made from CEM III; **100% of concrete is exposed for 4 months (0,33 year) during the demolition phase from which 99% eventually recycled and 1% landfilled for 25 years.*

Results – carbonation in the traditional house

Table 26: CO_2 sequestration in concrete in the traditional house

Exposure condition	*T [years]*	*M_{co2} [kg CO_2/m^3 carbonated volume]*	*Sequestrated CO_2 [kg]*
Buried (CEM III)*	75	199	137
Buried CEM III	25	199	0
Sheltered CEM III	75	199	1.427
Exposed CEM III	0,33	199	71
	25	199	6
Buried CEM I	25	120	0
Sheltered CEM I	75	120	340
Exposed CEM I**	0,33	120	15
	25	120	1
Total			1.997

**foundation is only made from CEM III; **100% of concrete is exposed for 4 months (0,33 year) during the demolition phase from which 99% eventually recycled and 1% landfilled for 25 years.*

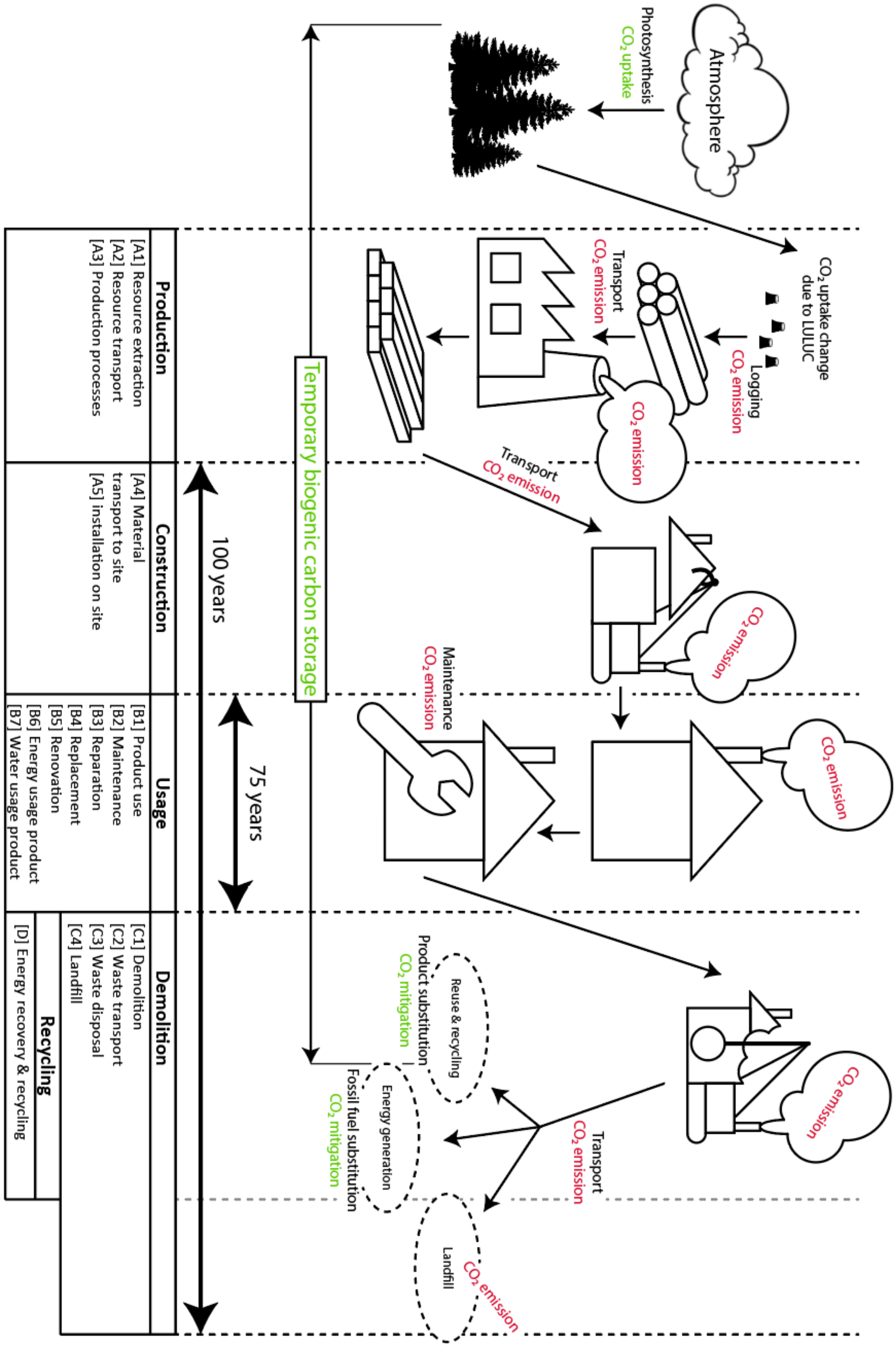
Table 27: CO_2 sequestration in concrete in the mass timber house

Exposure condition	*T [years]*	*M_{co2} [kg CO_2/m^3 carbonated volume]*	*Sequestrated CO_2 [kg]*
Buried (CEM III)*	75	199	122
Buried CEM III	25	199	0
Exposed CEM III	0,33	199	4
	25	199	0,36
Total			127

**foundation is only made from CEM III; **100% of concrete is exposed for 4 months (0,33 year) during the demolition phase from which 99% eventually recycled and 1% landfilled for 25 years.*

Appendix II - Figure 8

CO_2 emissions of wood-based products in the life cycle of a building, based on the EN15804 LCA framework.

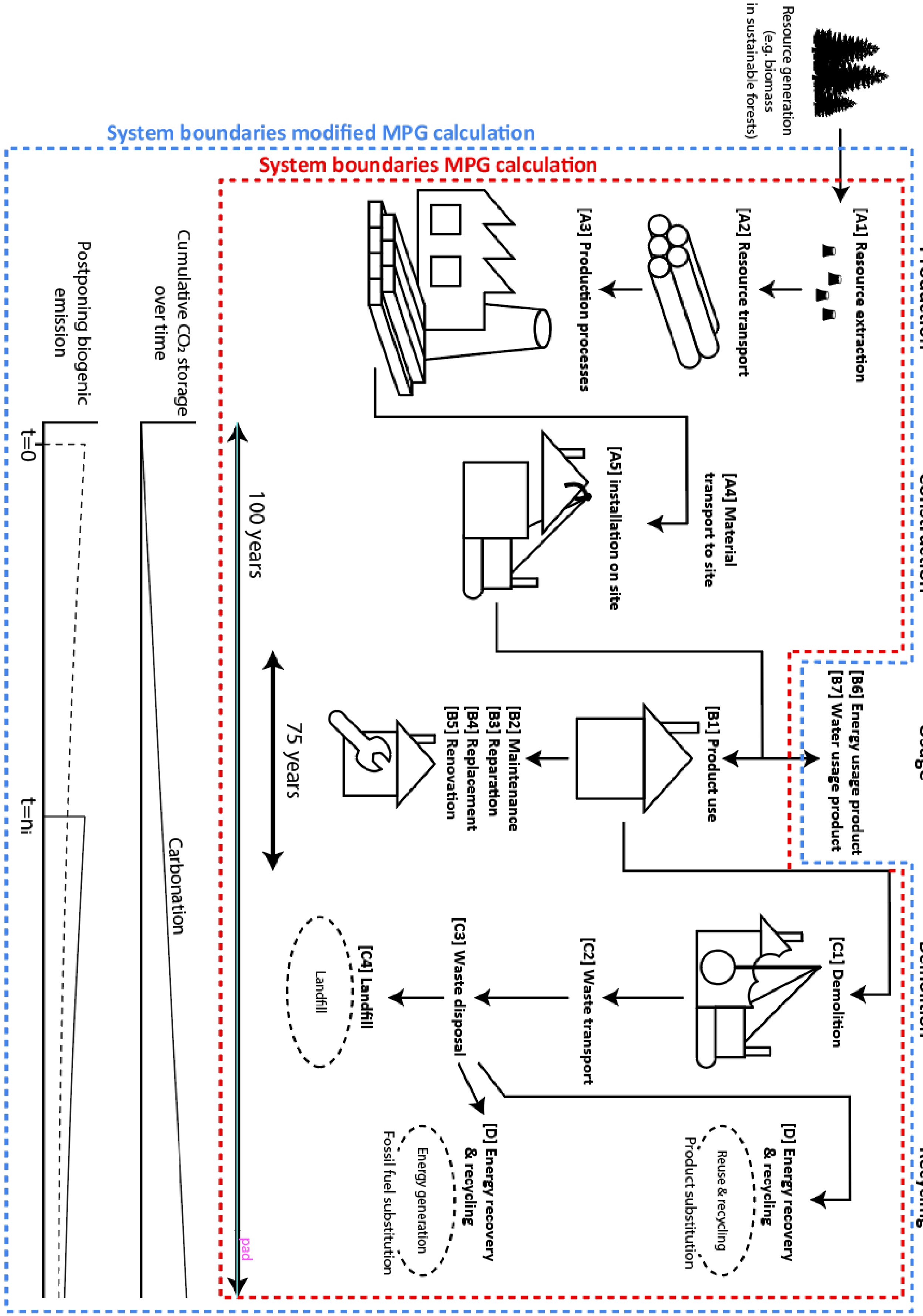


Appendix III - Material division framework

Table 28: base material division

Type of material	**Contains following products:**
Mineral building materials	
Concrete	- Part of reinforced concrete walls, floors, beams and piles
Plaster	- Gypsum creed - Plaster blocks - Part of plaster board - Plaster finish
Ceramics	- Ceramic tiles
Cast stone	- Door sill
Masonry	- Part of masonry wall
Cement	- Part of masonry wall - Part of cement fibre board
Steel	- Part of reinforced concrete walls, floors, beams and piles - Part door joints - Part of window frames - Part of plaster board - Steel guide rails
Isolation materials	
EPS	- Part of wooden roof element - Part of reinforced concrete walls and floors (integrated insulation)
Glass wool	- Part of plaster board - Glass wool insulation
PIR/PUR	- PUR insulation
Wood	- Part of wooden roof element - MDF - Chipboard - Wooden floors - LVL beams & columns - Stairs & doors - Door & window frames - Part of cement fibre board
Glass	- Triple window glass
EPDM	- EPDM roof finish - EPDM foundation protection

Appendix IV - Figure 18



Appendix V - Built-ins, installations, stairs and doors used in comparison for both case houses

Material comparison & environmental impact		**Life cycle costing analysis**	
Component	Characteristic	Component	Characteristic
Soil replenishment	0 m^3	Soil replenishment	0 m^3
Wooden alkyd painted outside doors with glass	2 pieces	Meranti wooden frames with blunt door	10 pieces
Wooden honey comb inside doors	8 pieces		
Painted European wooden stairs	2 pieces	Spruce wooden stairs	2 pieces
Multiplex alkyd painted kitchen cabinets	4,2 m	Simple kitchen 1,8 m	1 piece
Countertops	4,2 m		
Porcelain toilets with wall closet and fountain	2 pieces	White toilet with wall closet and reservoir	2 pieces
Ceramic washbasin	2 pieces	White plastic washbasin	2 pieces
Walk-in shower	1 piece	Douche cabinet with mixer tap	1 piece
Heat pump (air – water) 24 kW	1 piece	Heat pump (air-water)	24 kW
Floor heating 95 W/m^2	94,4 m^2	Floor heating	94,4 m^2
Electric boiler 120 L	1 piece	Electric boiler 80 L 2,5 kW	1 piece
Grounding installations	94,4 m^2	Grounding installations	1 piece
Insulated installation wire	94,4 m^2	-	-
PV, mono Si panels	8 pieces	PV panel (panel sizes differ from MPG, so pieces are based on similar PV surface)	5 pieces
VLA ventilation system type D without heat recovery, individual	94,4 m^2	Mechanical ventilation	262 m^3/h
Polyethene water pipes	94,4 m^2	Plastic water pipes	94,4 m^2
Outdoor sewerage from recycled PVC	94,4 m^2	Outdoor sewerage	9 m
Indoor sewerage from recycled PVC	94,4 m^2	-	-
Rainwater drainage from PVC (18 mm diameter)	13 m	Rainwater drainage from PVC	2

Appendix VI - F_n of different years of biogenic emission '*n*'

Table 29: F_n of different years of biogenic emission 'n'. Calculated via equation 14.

n	F_n
n=25	-16,79%
n=30	-20,47%
n=50	-36,65%
n=55	-41,15%
n=60	-45,88%
n=61	-46,85%
n=75	-61,72%
n=85	-74,13%
n=99	-99,29%

Appendix VII - Detailed material division of case houses

Table 30: Material division of mass timber house based on weights. Weights are in kg.

	Mass timber house					
	Foundation	Floors	Walls	Roof	Doors & stairs	**Total**
Mineral building materials	4.861	111	6.123	0	0	11.095
• *concrete*	4.861					4.861
• *plaster*						0
• *ceramics*			574			574
• *cast stone*						0
• *masonry*			5.549			5.549
• *cement*		111				111
Steel	162	296			7	465
Isolation materials	0	337	783	237	0	1.358
• *EPS*						0
• *glass wool*		337	783			1.120
• *PIR/PUR*				237		237
wood		13.950	7.610	1.206	485	23.251
glass			1.132			1.132
EPDM				73		73
Total	5.023	14.695	15.648	1.516	492	**37.373**

Table 31: Material division of traditional house based on weights. Weights are in kg.

	Traditional house					
	Foundation	Floors	Walls	Roof	Doors & stairs	**Total**
Mineral building materials	17.400	64.766	67.784	0	0	149.951
• *concrete*	*17.400*	*56.657*	*44.678*			118.735
• *plaster*		*7.226*	*8.995*			16.221
• *ceramics*		*174*	*430*			604
• *cast stone*			*46*			46
• *masonry*			*9.658*			9.658
• *cement*		*709*	*3.977*			4.686
Steel	405	960	322	0	7	1.694
Isolation materials	76	213	913	331	0	1.533
• *EPS*	76	213		195		483
• *glass wool*			12			12
• *PIR/PUR*			901	137		1.038
wood			678	886	485	2.050
glass			816			816
EPDM			0,7	66		67
Total	17.881	65.939	70.515	1.284	492	**156.111**

Appendix VIII - Environmental impacts in kg divided over 11 categories

Table 32: Construction material related environmental impacts of the full building over full lifespan.

	Traditional house	Mass timber house
Abiotic resource depletion [kg Sb eq]/building	1,64	0,18
Fossil fuel depletion [kg Sb eq]/building	178,49	186,96
Global warming 100 year [CO_2 eq]/building	38215,50	25830,00
Ozone depletion [kg CFK-11 eq]/building	0,00	0,00
Photo-oxidant creation [kg C_2H_2 eq]/building	22,12	50,68
Acidification [kg SO_2 eq]/building	141,26	227,55
Eutrophication [kg PO_4 eq]/building	20,48	54,74
human toxicity [kg 1,4-DCB eq]/building	8738,10	16974,00
Freshwater ecotoxicity [kg 1,4-DCB eq]/building	294,56	654,36
Marine ecotoxicity [kg 1,4-DCB eq]/building	1127850,00	1660500,00
Terrestrial ecotoxicity [kg 1,4-DCB eq]/building	179,58	132,84

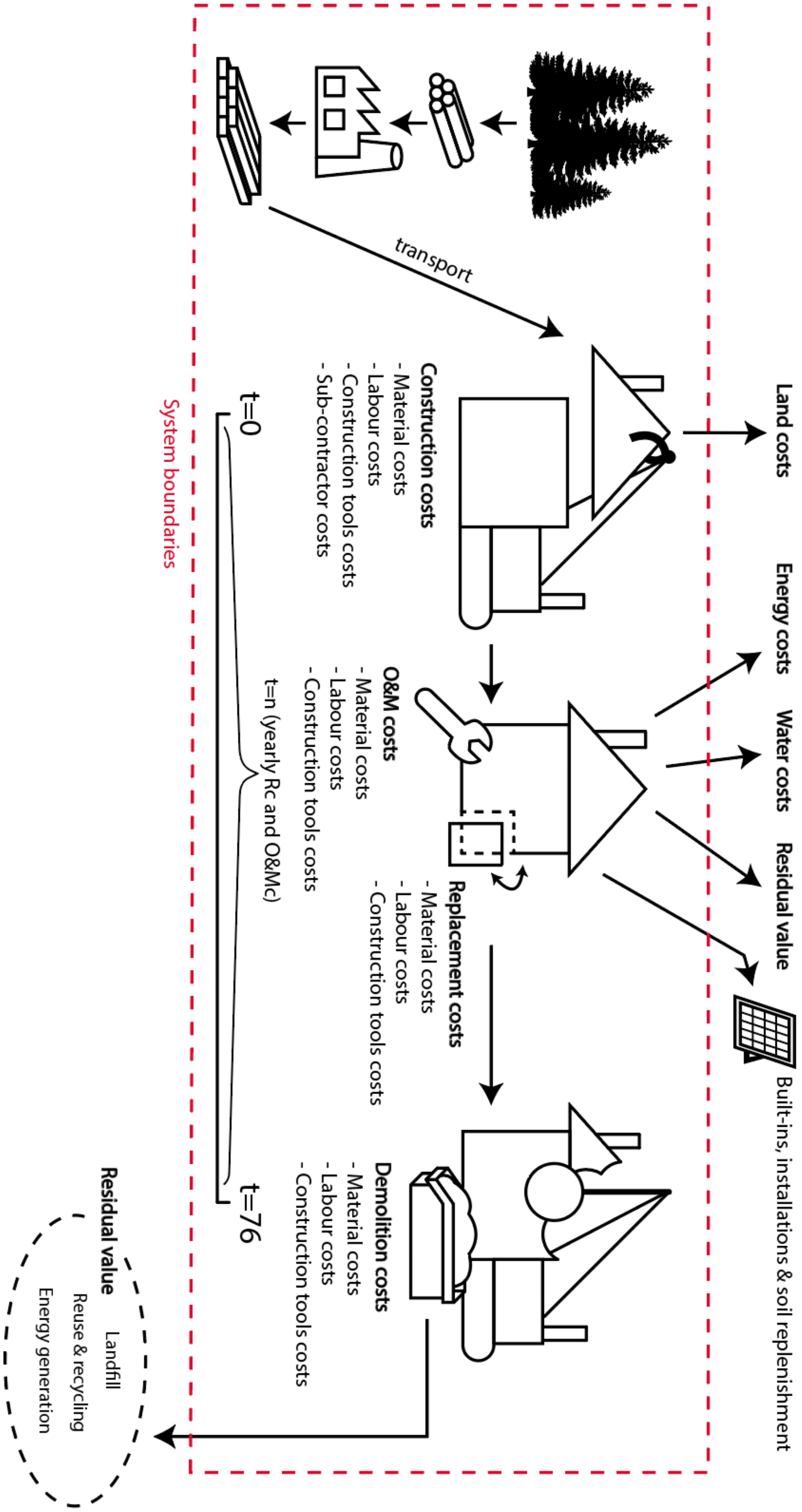
Table 33: Construction material related environmental impacts of the full mass timber building over full lifespan. Two versions of the mass timber house are shown, one with MDF and one with OSB.

	Mass timber with MDF	Mass timber with OSB
Abiotic resource depletion [kg Sb eq]/building	0,18	0,13
Fossil fuel depletion [kg Sb eq]/building	186,96	99,26
Global warming 100 year [CO_2 eq]/building	25830,00	14637,00
Ozone depletion [kg CFK-11 eq]/building	0,00	0,00
Photo-oxidant creation [kg C_2H_2 eq]/building	50,68	43,30
Acidification [kg SO_2 eq]/building	227,55	167,28
Eutrophication [kg PO_4 eq]/building	54,74	32,35
human toxicity [kg 1,4-DCB eq]/building	16974,00	12103,20
Freshwater ecotoxicity [kg 1,4-DCB eq]/building	654,36	435,42
Marine ecotoxicity [kg 1,4-DCB eq]/building	1660500,00	942180,00
Terrestrial ecotoxicity [kg 1,4-DCB eq]/building	132,84	115,37

Table 34: Modified construction material related environmental impacts of the full building over full lifespan.

	Traditional house	Mass timber house
Abiotic resource depletion [kg Sb eq]/building	1,64	0,13
Fossil fuel depletion [kg Sb eq]/building	178,49	99,26
Global warming 100 year [CO_2 eq]/building	34325,81	-2988,65
Ozone depletion [kg CFK-11 eq]/building	0,00	0,00
Photo-oxidant creation [kg C_2H_2 eq]/building	22,12	43,30
Acidification [kg SO_2 eq]/building	141,26	167,28
Eutrophication [kg PO_4 eq]/building	20,48	32,35
human toxicity [kg 1,4-DCB eq]/building	8738,10	12103,20
Freshwater ecotoxicity [kg 1,4-DCB eq]/building	294,56	435,42
Marine ecotoxicity [kg 1,4-DCB eq]/building	1127850,00	942180,00
Terrestrial ecotoxicity [kg 1,4-DCB eq]/building	179,58	115,37

Appendix IX - Figure 21



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