Environmental Impact Reduction Options for Wood Construction Systems in Apartment Buildings

A scenario-based comparative case study

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Abstract

The construction sector is responsible for 39% of the global energy- and process-related CO_2 emissions, of which 11% is due to the production of construction materials. The municipality of the city of Leiden in the Netherlands has set goals to build 17,000 new dwellings between 2020-2030 and to lower its overall carbon footprint. In this study, the environmental impact reduction potential of wood construction systems (WCSs) for the construction of 17,000 mid- and high-rise residential buildings in Leiden was explored. The two WCS alternatives studied are cross-laminated timber (CLT) construction systems built with either the modular or flatpack method. A number of sustainability choices expected to lower the environmental impact of WCSs through prolonged biogenic carbon retention time were quantified in a scenario-based life cycle assessment (LCA). These choices included high-end reuse of WCSs, wood material downcycling into particleboards, extending the building service life (BSL), dwelling size reduction, and wood resource country selection. Results showed a maximum hypothetical impact reduction of 92.3% for modular CLT and 91% for flatpack CLT WCSs. This hypothetical reduction was achieved when all sustainability choices were combined. The selected scenarios used and the level of detail of the LCA model do not fully align with current trends in the construction- and housing sector. Therefore, the actual realization of the impact reductions presented should not be perceived as highly feasible. Two originally included WCS alternatives consisting of CLT and timber frame construction (TFC) hybrids could unfortunately not be quantified due to technical issues with the used LCA modelling software.

List of Abbreviations

BSL = building service life
CLT = cross-laminated timber
EoL = end-of-life
GHG = greenhouse gas
GWP = global warming potential
LCA = life cycle analysis
TFC = timber frame construction
WCS = wood construction system

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I would like to use this opportunity to express my gratitude towards the people (in)directly involved in my thesis project and to share a few thoughts.

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1 Introduction

Humanity faces an important challenge in climate change which requires immediate mitigation measures in virtually all economic sectors, including the construction sector (IPCC, 2014). The global population is projected to grow from 8 billion in 2022 to 10.9 billion in 2100, while the global share of people living in urban areas is expected to increase from 50% to 85% (OECD, 2015; United Nations, 2019). In order to accommodate housing to this growing population in a sustainable way, realization of ample dwellings with minimal climate impact is required, especially in urban areas.

The construction sector highly influences the global resource and energy consumption which relies heavily on fossil and finite resources (Cabeza et al., 2014). The sector is responsible for 39% of the global energy- and process-related CO_2 emissions, of which 11% is due to the production of construction materials (IEA, 2019; UNEP, 2009). In Western Europe, the construction sector accounts for 40% of total primary material (Herczeg et al., 2014). This is in part due to the use of energy- and carbon-intensive material utilization in buildings.

In order to disrupt the unsustainable status quo, current mainstream construction practices need to be revised and adjusted when possible. Incorporation of sustainable construction principles in new buildings can aid in minimizing the environmental impact of the built environment. One of these principles is to make an appropriate selection of building materials.

For the Netherlands, a sustainable construction sector is of interest as the Dutch government has set the goal to build 845,000 new dwellings between 2020 and 2030 (Ministry of the Interior and Kingdom Relations, 2020). This is due to an increase in housing shortage in the Netherlands over the last decades (Lucassen, 2020). Simultaneously, the Dutch government has the ambition to make the switch to a circular economy by 2050 (Ministry of Infrastructure and the Environment, 2016). However, the urbanization goal and circular economy ambition are currently incompatible with one another, as bridging the housing shortage with finite carbon-intensive construction materials is in conflict with circular economy principles. Selecting bio-based building materials can help to overcome this mismatch (IRP, 2020; Kovacic et al., 2018).

In recent years, biomass is increasingly thought of as a promising provider of building materials that can aid in lowering the environmental impact of the construction sector. Biomass such as wood can accommodate many of the functions of conventional construction materials, whilst having a lower impact on the environment. Through material substitution, wood can mitigate environmental impacts by reducing greenhouse gas (GHG) emissions and (fossil) energy demand (Suter et al., 2017). Consequently, increased use of biomass in the form of engineered wood products can contribute to leveraging the shift towards a low-emission construction sector (Hildebrandt et al., 2017). This is especially important during periods where construction activities are being scaled up (Centrum Hout, 2021).

Wood construction systems (WCSs) can replace conventional construction systems, thereby limiting the use of carbon-intensive construction materials. There are different WCSs available, each consisting of different technologies, components, production processes, characteristics and end-of-life recycling options. Most studies on WCSs do not compare WCSs with one another, but rather compare them with conventional construction systems. The question whether wood as a construction material has a lower environmental impact than its fossil-based counterparts such as concrete, steel and bricks has therefore been researched and answered extensively in the recent past.

At the time of writing, a societal debate is taking place in the Dutch construction sector on whether or not biomass, in particular wood, would be a fitting solution in overcoming the massive urbanization task in a more sustainable way. A central topic in this discussion is the lack of consensus in the LCA community on a standard method for determining the environmental impact of bio-based buildings. In addition, there is the question on how to properly incorporate and score the effect of the timing of emissions and carbon sequestration by biomass. Currently, the choice lies with the researcher conducting the assessment on how to include this, if it is even included at all.

The debate on the methodological choices for scoring the environmental impact of bio-based products has a far-reaching impact. Circularity and renewability of bio-based products in buildings are not properly scored yet: because of this, studies often have to include the assumption that wood products are incinerated after their initial use, even though these products have a high potential for repairability and reusability (Centrum Hout, 2021).

Now that the construction sector is expected to transition towards a circular economy, new scenarios are being investigated that explore the effects of high-end wood product reuse (Fraanje & Nijman, 2021; TNO, 2021). In this context, there is a need for research on the effect reusability and prolonged use phases can have on the life cycle environmental impact of wood construction systems. This could show the difference in environmental impact reduction potential between different WCS alternatives and aid local governments, such as the municipality of Leiden, in selecting sustainability choices and sustainable alternatives to conventional construction methods. With this in mind, this study's main research question and sub-questions were formulated:

What effect do additional sustainability choices have on the life cycle environmental impact of two wood construction system alternatives, and on the total wood material requirement for 17,000 residential dwellings?

Sub-question 1: What is the effect of wood material cascading on the environmental impact?
Scoring the environmental impact of WCSs for four recycling pathways: (1) single use; (2) single use & downcycling; (3) reuse; and (4) reuse & downcycling.

Sub-question 2: What is the effect of the building service life on the environmental impact?
Showcase the influence carbon storage time periods have on the WCS environmental impact.

Sub-question 3: What is the influence of the choice in wood sourcing country on the environmental impact?
Comparing the shares of environmental impact caused by electricity use and truck transportation distance for five potential wood sourcing countries.

Sub-question 4: What is the effect of dwelling size on the environmental impact per dwelling and building?
Showcase the influence of dwelling size on the environmental impact of social and private dwellings.

Sub-question 5: What would be the total wood material requirement for the mid- and high-rise residential dwellings planned for the city of Leiden for 2020-2030?
Estimation of the wood material required for the construction of 17,000 social housing and private rent dwellings.

The aim of this study is to determine how certain parameters and sustainability choices influence the life cycle environmental impact of apartment buildings utilizing WCSs. The objective is to gain insight in best practices and to underline the importance of a well-considered use of wood in buildings. The

WCS alternatives were selected based on findings in literature and on interviews with wood construction practitioners active in the Netherlands. The environmental impact from cradle to grave of these WCS alternatives was assessed through life cycle assessment (LCA). Additional sustainability choices such as reuse, downcycling and prolonging the building service life (BSL) were included to showcase the effect of prolonged carbon retention time on the environmental score of the buildings.

Although the author set out with four different WCS alternatives at the start of this study, this number ultimately had to be reduced to two due to LCA modelling issues.

2 Background Information

This chapter gives an overview of concepts and definitions relevant to this study.

2.1 Bio-based Materials

There are a number of advantages to bio-based materials compared to the materials they could substitute. A main asset is their capability of atmospheric carbon sequestration (Hoxha et al., 2020). During growth, atmospheric carbon is bound and stored within the biomass through the process of photosynthesis (Kovacic et al., 2018; Peñaloza, 2017). In wood, carbon accounts for about 50% of its dry mass (Pittau et al., 2018). This biogenic carbon is released back into the atmosphere during natural degradation of the biomass or upon incineration. Another advantage of bio-based materials is that they are regenerative, making their availability theoretically limitless in the future under the right circumstances.

Contrary to conventional building materials, bio-based materials are regenerative and do not require carbon-intensive industrial processes or mining and extraction activities for production (Sathre & González-García, 2013). The carbon sequestration and binding capacity creates an opportunity to store atmospheric carbon in bio-based goods over longer periods of time (Churkina et al., 2020). Given the longevity and volume of buildings in comparison to that of any other man-made good or product, buildings are ideal structures for long-time storage of sequestered carbon. In addition, when biomass is discarded, it can be incinerated for energy recovery which may substitute fossil fuels in energy generation (Petersen & Solberg, 2005). The combination of these factors makes bio-based materials often less energy- and emissions-intensive than conventional materials with similar functions (Guest et al., 2013).

Utilization of bio-based materials in buildings contributes to a healthy indoor living environment for inhabitants. This is in part because bio-based materials are capable of regulating air humidity by extracting water vapor from humid air and releasing it when the air is dry. This prohibits mold formation and enhances air quality (Centrum Hout, 2021). In addition, emissions of volatile organic compounds hazardous to humans is lower in bio-based materials compared to abiotic construction materials (van de Groep, 2021). Radon radiation that originates from concrete and stony materials is also avoided when building with bio-based materials (Centrum Hout, 2021). Of the wood used in buildings, massive timber has the lowest human health impact although health effects further depend on the level of wood treatment, its age, the time spent indoors by inhabitants, and building ventilation rate (Steubing et al., 2015). There is evidence that indoor application of wood elements also has a positive influence on the level of well-being of inhabitants through stress reduction, and that wooden buildings can improve attention and focus while reducing pain perception (Fell, 2010).

A number of European countries have formulated goals for a bio-based economy (Nabuurs et al., 2016). The Dutch government acknowledged the importance of biomass utilization in a circular economy and declared that bio-based materials play a significant role in achieving a more climate-neutral, circular economy (Strengers & Elzenga, 2020). This statement corresponds with the national intermediate goal of a 50% primary abiotic material demand reduction by 2030. An increased utilization of secondary and renewable materials could help in achieving this (Ministry of Infrastructure and the Environment, 2016). A transition towards a more bio-based economy over the long term is expected to happen as the general consensus is that the level of abiotic material substitution with biomass will likely continue to grow beyond 2030 (Strengers & Elzenga, 2020). Studies have shown that the environmental impact of the construction sector decreases with increased use of bio-based materials (Peñaloza, 2017).

2.2 Wood Construction Systems

Wooden buildings consist of wood construction systems (WCSs). In these construction systems, the load-bearing structure is made predominantly or completely out of wood (Centrum Hout, 2021). Additionally, other building components such as facades may also consist of either wood or other bio-based products.

From an environmental perspective, WCSs have the potential to store atmospheric carbon for long periods of time. The longer the wood remains in use and is not incinerated, the longer the release of carbon is delayed (Hoxha et al., 2020). Storing wood in buildings is a promising option for effective atmospheric carbon capture and storage because of the long lifetime of buildings generally have a longer lifetime than other wood products. In addition, WCSs can substitute for conventional construction systems utilizing carbon-intensive materials such as concrete and steel.

For abiotic building materials used in conventional construction systems, resource extraction and production processes are more invasive to the environment and more energy and GHG intensive than for WCSs (Guest et al., 2013). WCSs have a relatively low carbon footprint in comparison to abiotic construction systems because they utilize primarily bio-based materials. Next to the benefit of low-carbon materials utilization, other strengths of WCSs are the central production of prefabricated products and the level of material efficiency (Hildebrandt et al., 2017). In addition, wood material is lighter to transport and easy to process into building components (Centrum Hout, 2021). Cross-laminated timber (CLT) was developed in the early 1990s and has made the utilization of WCSs in high-rise buildings a reality, expanding the material substitution potential for a larger share of the built environment (IRP, 2020).

By utilizing timber instead of concrete in buildings, embodied building emissions as well as transportation emissions can be reduced (Sandanayake et al., 2017). WCSs are about 80% less heavy in weight than concrete or masonry structures, allowing for lighter albeit sometimes bulkier building foundations (Lehmann, 2012). It also allows for optional utilization of electric construction cranes, potentially reducing a building's environmental impact even further (Centrum Hout, 2021). Because of the light weight and prefabrication, the number of transport movements to the construction site can be reduced to one fifth of that of conventional construction (Ramage et al., 2017). Rapid on-site assembly allows for a drastic reduction in the costs, time spent on the construction site, construction activity impacts, and waste (Lehmann, 2012). In addition, constructing with WCSs may lead to healthier working conditions at the construction site as well as in the WCS factory (Studio Marco Vermeulen, 2020).

2.3 Reuse and Cascading

In addition to material substitution, it is important to optimize bio-based building usage to further mitigate the environmental impact of the construction sector. One way of doing so is by prolonging the time bio-based materials remain within the built environment by means of reuse and cascading (Steubing et al., 2015). The environmental impact of bio-based products can be significantly reduced if the products are reused rather than disposed of through landfill (Chen, 2019). Through reuse and cascading, the release of carbon emissions upon end-of-life disposal is postponed (TNO, 2021). The choice in management of post-use, decommissioned wood products can be seen as the most significant source of variability in environmental impact in the product life cycle (Sathre & O'Connor, 2010).

A sustainability measure that can enhance the time period in which WCSs reside in the built environment is design for disassembly and reuse. Design for disassembly would allow for the building components to be taken out of the first building intact so they can be reused in a second building after the first building is decommissioned (John et al., 2009). The combination of high level of workability of wood, the option for dry connections between wooden construction elements, and the relatively light material weight make design for disassembly highly applicable in WCSs (Centrum Hout, 2021).

When high-end reuse of the bio-based construction product is not an option any more due to e.g. irreversible damage, the product can serve as a wood resource for secondary industries such as furniture production or the biochemical industry (Centrum Hout, 2021). This method of levelling-down is known as cascading. A study from as early as 1997 showed that extending the lifespan of pinewood material and cascading resulted in a reduction of virgin pinewood demand and GHG emissions (Fraanje, 1997).

Prerequisites for enhanced environmental performance through cascading are efficient final energy recovery and low material losses during recycling (Steubing et al., 2015). By recovering energy from wood products during end-of-life incineration, fossil energy carriers can be substituted. It is also relevant what other products are substituted through the cascaded use of wood (Suter et al., 2017). Through the combination of substituting carbon-intensive materials by bio-based materials and cascaded use, a higher level of environmental impact mitigation can be achieved (Suter et al., 2017).

2.4 Biogenic Carbon Accounting in Buildings

Over the last decade, academic research on life cycle impacts of the built environment has increased (Pomponi & Moncaster, 2016; Röck et al., 2020). For bio-based building components, carbon storage is an important factor in determining their environmental impact. Carbon capture and storage is the sequestration and retention of atmospheric carbon in products for a certain time period and may lead to a reduction in atmospheric CO_2 concentration (Hoxha et al., 2020). Given that buildings can have a long service life and consist of considerable material volumes, there is great potential for storing carbon in the built environment. By increasing the lifespan of bio-based structures, the carbon storage potential and therewith the environmental performance of buildings can be improved (Nakano et al., 2020). Because of the carbon sequestration capacity, wood-based construction materials often show negative carbon emission values (Kovacic et al., 2018).

In past environmental impact assessments, the assumption was often made that wood-based building materials are climate neutral, i.e. they have net zero carbon emissions. However, this assumption is an oversimplification because the environmental impact is dependent on case-specific factors (Peñaloza, 2017). These factors depend on the one hand on the modelling of the forest system, for example the timing of carbon flows associated with tree growth and the forest land use baseline, and on the other hand on LCA modelling parameters - in particular the time horizon for impact calculation, the end-of-life assumptions, and the time period for biogenic carbon storage (Peñaloza, 2017). When these factors are addressed, study results generally display negative carbon emissions rather than net zero emissions.

Until recent years, it was common for LCA practitioners to assume that biogenic carbon stored in bio-based materials is released back into the atmosphere within 100 years after building construction. However, as the construction sector develops towards a circular economy, the number of investigative studies that include scenarios wherein construction wood is given a second or third life upon primary building decommission have increased (Fraanje & Nijman, 2021; TNO, 2021). An example study on the reuse of CLT panels showed that the total global warming potential decreases as the rate of reused panels increases (Passarelli, 2018). When cascading and substitution effects for bio-based materials are quantified, it involves longer timespans where effects of biogenic carbon sequestration become increasingly influential on their environmental performance (Suter et al., 2017).

The methodological choices for the assessment of biogenic carbon are becoming more important as the trend of environmental impact reduction of buildings continues (Hoxha et al., 2020; Röck et al., 2020). When evaluated with different methods, the environmental impact of building components diverges significantly. At the building level, this variation in biogenic carbon calculations could even lead to misleading information (Hoxha et al., 2020). It is therefore necessary that the assessments of biogenic carbon storage and the environmental impact are conducted in a transparent way.

2.5 LCA Methods for Biogenic Carbon Accounting

In LCA, there are several methods for biogenic carbon accounting in bio-based materials. There is no consensus among practitioners on which method is the preferred choice, as this usually depends on the outline of the study. However, in a recent critical review of LCA methods for scoring biogenic carbon in buildings, the so-called dynamic approach came out best due to its level of robustness and transparency (Hoxha et al., 2020). In this sub-chapter, three common LCA methods for biogenic carbon accounting are described: The 0/0 approach also known as carbon neutrality, the -1/+1 approach, and the dynamic approach.

Until recently, the impacts associated with biogenic carbon were largely neglected in LCA studies. It was assumed that the amount of CO_2 released from biogenic materials during their end-of-life phase is equally absorbed during biomass regrowth, bringing the net sum of carbon emissions to zero (Guest et al., 2013; Pittau et al., 2018). The main criticism on this approach as well as on the -1/+1 approach described below is that the impact of timing of carbon emissions and the influence of rotation periods of biomass growth are not considered. In the 0/0 approach, the benefits of carbon uptake (the first 0) and storage as well as the burdens of carbon release (the other 0) upon incineration or degradation are not considered as an impact (Guest et al., 2013; Hoxha et al., 2020). This is an oversimplification of the situation and leads to issues in environmental impact calculations.

In the -1/+1 approach, both biogenic carbon uptake (-1) during biomass growth and carbon release (+1) upon end-of-life incineration are considered. In addition, the transfers of biogenic carbon between different systems are accounted for. The advantage of this approach is that it gives an overview of all biogenic carbon in the product system. Benefits of sequestered biogenic carbon are taken into account within the product stages, which causes the carbon emissions of these life cycle stages to be lower (Hoxha et al., 2020). In order to avoid misleading environmental impact results, the release of carbon emissions (+1) during the end-of-life stage must be reported as well.

The dynamic biogenic carbon accounting approach is the most robust and transparent and is therefore recommended to LCA practitioners (Hoxha et al., 2020; Levasseur et al., 2010, 2012). Because time parameters such as carbon storage and biomass rotation time (i.e. the timespan between biomass inception and biomass harvest) are taken into account, this approach can be considered the most comprehensive for assessing the environmental impact of biomass products. The timing of carbon uptake and emission is particularly relevant for bio-based products that store carbon on any time horizon. The addition of these time parameters to the calculations has a significant influence on the results (Levasseur et al., 2013).

Within the dynamic approach, the choice has to be made between two assumptions for timing the biogenic carbon sequestration by biomass: (1) assuming that the biomass absorbs carbon before the use of the harvested bio-based products, representing the actual stored carbon and following the natural carbon cycle, or (2) assuming that an equal amount as the harvested biomass starts regrowing after the production process, replacing the biomass used for production (Peñaloza et al., 2016; Pittau et al., 2018). Because there is a considerable variation in results between the two assumptions, the selection needs to be justified and clearly stated (Peñaloza et al., 2016). The second assumption is considered the most transparent and reliable approach for calculating the environmental impact of wood-based buildings (Hoxha et al., 2020).

In order to get representative environmental impact results for bio-based products, all life cycle stages of a bio-based product should be examined rather than limiting the assessment to solely the product stage. If only the product stage is examined, results can be significantly different from a full LCA, resulting in a misleading environmental impact score (Fouquet et al., 2015; Sandin et al., 2014). The end-of-life stage as well as biomass growth therefore need to be addressed. Attention should also be given to specifying the temporal boundaries of the system. If the parameter for forest rotation time period is included (as it is done in this study), the tree species should be taken into account as well, as the rotation time period may differ per species (Hoxha et al., 2020). Disregarding this parameter may lead to errors in determining the global warming score of the product.

An integral part of life cycle assessment is the allocation of burdens and benefits throughout the studied system. The choice of how benefits are allocated can affect the environmental impact score significantly (Hoxha et al., 2020). There is a risk of double-counting when multiple sectors or products claim the same benefits, for example when the same matter is produced and used in multiple technical systems through cascading (Mehr et al., 2018). To avoid this, practitioners need to clearly define the allocation of benefits and burdens to the different technical systems (Hoxha et al., 2020). It is also recommended to clearly state if, how and where carbon content and environmental impact score calculations are conducted in the system to avoid misleading information (Peñaloza, 2017).

In this study, the LCA is carried out with the dynamic approach. The method proposed by Guest et al (2013) was chosen after recommendations from other researchers in the field of biogenic carbon LCAs. This method includes the parameter of tree species-specific forest rotation time. The exact methodology for this study can be found under *Biogenic Carbon Accounting* in chapter 3.3.2.

2.6 Scenario Modelling

Scenario modelling is a method of exploring an uncertain future and is a first step in charting out possible development trajectories (Fishman et al., 2021). Scenario-based assessments of sustainable development strategies help inform decision makers as well as the public about impacts, consequences and overall potential of a given strategy (Fishman et al., 2021). Many LCA studies employ scenario modelling to see what effect certain design or policy choices may have on the life cycle impacts of a given product or material. These prospective what-if scenarios are often applied to give insights into future developments towards sustainable production and consumption, such as the introduction of technologies on a national or global level (Pauliuk & Hertwich, 2015). The influence of material efficiency strategies on future resource use and emission reductions can also be explored through scenario modelling (Deetman et al., 2018).

Various research questions can be answered through scenario assessments. There is a wide variability of scenario premises, often tailored to answer a particular research question. This leads to scenarios being formulated on a case-specific basis with little overlap with other studied scenarios. Consequently, this limits comparability between study results and the potential for follow-up studies, which are crucial for informing policy (Fishman et al., 2021).

3 Methodology

In order to determine which combination of WCS and sustainability measures has the least environmental impact in mid- and high-rise residential buildings, this study was divided into two research steps. In Step one the scenarios were defined and the data necessary for the life cycle assessment was collected. In Step two the actual environmental impact assessment was carried out through LCA.

In this chapter, the research goal and scope are described first followed by the two research steps.

3.1 Goal and Scope

3.1.1 Goal Definition

The goal of the study is to assess the life cycle environmental impact of WCS alternatives in both mid- and high-rise residential buildings in the Dutch context, specifically for the city of Leiden.

A number of sustainability choices were scored that may reduce the environmental impacts of these WCS alternatives. These choices include WCS recycling, cascading of WCS wood material in particleboards, extending the BSL and reducing the dwelling size. Five optional wood resource countries were chosen based on interview outcomes to showcase to what extent the choice of the country influences the environmental impact.

Currently, there is a range of WCS alternatives available. It is in the interest of city planners to have an overview of the environmental performance of alternatives before deciding on a WCS to utilize in residential buildings. This study aims to provide local governments with recommendations on how to limit the environmental impact of planned residential buildings through the utilization of WCSs and aforementioned additional sustainability measures. The outcome of this study may be helpful in making informed decisions on which WCS to choose for mid- or high-rise residential buildings. In addition, policy makers may refer to this study when drafting requirements for planned wood building such as design factors and a minimum BSL time period.

The data and results of this study are case-specific for the city of Leiden. However, the results and recommendations could be of useful to other cities in the Netherlands or abroad.

3.1.2 Scope and System Boundaries

3.1.2.1 Scope

Case Study: City of Leiden

This study was performed in collaboration with the municipality of Leiden. Leiden is a medium-sized city with 124,000 inhabitants as of 2021 in the western part of the Netherlands. As is the case for other cities in the Netherlands, Leiden faces a housing shortage and therefore urgently needs to create additional dwellings. The planned 17,000 dwellings to be built in Leiden between 2020-2030 are multifamily dwellings in high- and mid-rise apartment buildings, which this study focussed on (Lucassen, 2020).

Product Scope

The focus of this study is on wood material and the effect of using wood as a carbon store in the built environment. The material scope of this study was limited to the wood material utilized in a number of products. The first products are wood construction systems that are integrated in the residential buildings. The second product is particleboard, also known as chipboard or fibreboard. The wood material is transferred from one product to the next, thereby serving multiple functions in its life. These functions are described in more detail in chapter 3.3.

Below, the building scope is explained first. Afterwards, the WCS alternatives are described.

Building types and dwelling distribution

The building scope consists of mid- and high-rise residential buildings which both contain either social housing or private rent dwellings. Other dwelling types such as student housing were not included. All 17,000 planned dwellings were assumed to be either social or private dwellings. In addition, it was assumed that the distribution of social and private dwellings is fifty-fifty.

Of the 17,000 dwellings planned, 75% (12,750 dwellings) will be in high-rise buildings and 25% (4,250 dwellings) in mid-rise buildings (Lucassen, 2020). In the case of Leiden, high-rise buildings are up to nine stories high whereas mid-rise buildings up to 5 stories.

Table 1 shows the dimensions of each dwelling type, as well as the number of dwellings in mid- and high-rise buildings. The regular and small dwelling sizes are based on data retrieved from the previous study in Leiden (Lucassen, 2020). The large dwelling sizes are based on the assumption that the dimensions for larger dwellings are 1.5 times that of the regular sized dwellings.

Table 1: Building- and dwelling types and their dimensions. The buildings consist of either social housing or private rent dwellings (UFA = usable floor area; GFA = gross floor area).

Building type & number of dwellings	**mid-rise 48**						**high-rise 124**					
Dwelling type	**social**			**private**			**social**			**private**		
Dwelling size	small	regular	large	small	regular	large	small	regular	large	small	regular	large
UFA per dwelling (m^2)	40	60	90	40	70	105	40	60	90	40	70	105
GFA per dwelling (m^2)	61	91	137	61	106	159	83	125	188	83	146	219

Concept of floor area: UFA and GFA

There are multiple ways in which building floorspace can be expressed that include or exclude certain building components. Two expressions commonly used are usable floor area (UFA) and gross floor area (GFA). UFA consists of the usable floorspace within a dwelling, whereas GFA covers almost the entire building including hallways and escape routes (Lucassen, 2020). In this study, both UFA and GFA per building type were included in the calculations.

Wood Construction System Alternatives

At the start of this study, four WCS alternatives were included in this study. Unfortunately, due to modeling issues, only two WCSs could be assessed. In this sub-chapter the distinction between flatpack and modular construction is explained first. Afterwards, the WCS alternatives are described in more detail.

Flatpack and modular construction methods

A main distinction between WCSs is the flatpack or modular construction methods. In the flatpack method, the wooden plates are stacked during transportation to the construction site. At the site, the plates are put upright and assembled to form the structure. With the modular construction method, building modules are assembled in the factory before being transported to the construction site. There, the modules are joined together to form the structure.

It was assumed that more truck transport movements are needed for modular WCSs due to the empty space within the modules, resulting in less m^3 of WCS per truckload. Therefore, modular WCS alternatives were assumed to be transported from the factory to the construction site less efficiently than flatpack WCSs: the modular buildings would require more truckloads.

Included elements in wood construction systems

It was assumed that the WCSs consist only of the wood material used in the floors, walls and ceilings of the structure. Other building materials or components used for insulation, windows and doors, electronic appliances and piping were left out of this study. Building foundations were also excluded, even though wooden buildings would likely require less material for foundations because they weigh less than conventional buildings (de Jong, 2021; Friederichs, 2021; van Lith, 2021).

The wood type species used in all WCSs in this study were the softwoods spruce and pine. Both wood types are used for wood construction in Europe and CLT production (de Jong, 2021; Lootens, 2021; van Lith, 2021).

Material intensity levels

Data found on CLT wood material intensity ranged significantly. Because of this, the choice was made to include three material intensity levels in the LCA as shown in Table 2.

The high CLT flatpack material intensity level of 0.75 m^3 per m^2 originated from a paper by Lehmann (2012). The low and medium CLT flatpack material intensity levels of 0.27 and 0.37 m^3 per m^2 were derived from assumptions made in a study by TNO, a non-governmental research organisation (TNO, 2021).

The three material intensity levels of CLT served as the starting point for calculating the material intensities of the remaining WCS alternatives. Wood material intensity levels were therefore in part obtained from literature and in part from own calculations. The calculation steps can be found in *Appendix 1A*.

Table 2: Material intensity levels in m^3 material per m^2 floor space for all four WCS alternatives. Modular WCS alternative intensity level values were rounded upwards. Note: both hybrid alternatives were not assessed due to modelling issues (WCS = wood construction system).

WCS alternative	Low	Medium	High
CLT flatpack	0.27	0.37	0.75
CLT modular	0.33	0.45	0.90
Hybrid flatpack	0.22	0.31	0.64
Hybrid modular	0.27	0.38	0.77

In modular construction, stacking of modules on top of each other results in a double layer of floor and ceiling as well as double layers of walls between dwellings (van Lith, 2021). In order to take this into account, the assumption was made that the modular alternatives require a factor 1.2 of the amount of wood that flatpack alternatives would require (rounded upwards). For flatpack construction, it was assumed that the floors and ceilings as well as the walls between dwellings consisted of single layers.

For the two hybrid WCS alternatives that utilize both timber frame construction (TFC) and CLT, the WCS composition was assumed to be 75% CLT and 25% TFC.

As can be seen in Table 2, TFC requires less wood material per m^2 than CLT. Contrary to massive wood plates in CLT, TFC in the Netherlands usually consists of frames of thin timber columns and beams that are reenforced with plating on both sides and are then filled with insulation material (TNO, 2021).

3.1.2.2 System Boundaries

Economy-environment system boundary

The system boundaries separate the product systems from the rest of the world. All background processes were derived from the Ecoinvent 3.7.1 cut-off database for LCA. The products of these background processes served as inputs for the foreground processes, and the waste flow outputs from foreground processes were linked to background waste management processes.

For our softwood spruce and pine wood resource, only the beams and boards used in CLT and TFC production were part of the product system: tree bark, branches and wood chips as well as the forest soil were considered part of the environment. Potential by-products of softwood harvest were assumed not to be harvested for economic purposes and are therefore not included in the economic system.

Emissions originated from unit processes in the product systems are crossing the economy-environment system boundary.

Cut-offs

Products and activities that were left out of the scope but are expected to be part of the product system in the real world are called cut-offs. These were left out of the study because they were deemed to be of little relevance or due to time constraints.

Building construction and dismantling process stage

Due to unavailable data on the building construction and dismantling processes, the machinery and energy required for these processes were left out. The process inputs were expected to differ between the WCS alternatives, which unfortunately could not be scored in this study.

Use stage

The WCS or particleboard maintenance, repair and replacement were cut off. Operational energy- and water use in the building were left out as well.

End of life stage

In the waste management processes, embodied energy in the wood products was not utilized for electricity generation upon incineration and therefore was cut off.

3.2 Step 1 – Scenario Definition & Life Cycle Inventory

3.2.1 Scenario Definition

In order to quantify the environmental impact of WCSs, a number of scenarios was formulated in which four WCS alternatives were applied in mid- and high-rise multifamily dwellings in Leiden. The notion of biogenic carbon retention in the built environment, the concept of cascading and information on the types of dwellings served as the starting point for scenario formulation. The scenario definition is in part based on information obtained from interviews with a number of Dutch wood construction companies and on literature searches. The scenarios defined below allowed the author to investigate the effect of a number of sustainability choices on the environmental impact of WCS alternatives.

The scenarios were formulated and selected with the exploration of maximum hypothetical impact reduction in mind, in order to indicate what magnitude of WCS environmental impact reduction would theoretically achievable. As such, it should be noted that the selected scenarios, however impactful on environmental impact reduction they may be, differ greatly from the more likely, real-world scenarios. It is therefore imperative to assess the outcome of this scenario-based LCA study in light of the real-world context.

The scenarios were grouped according to one of four recycling pathways, shown in Table 3. These are single building use; single building use with subsequent downcycling of the WCS elements into particleboards; WCS reuse by erecting a second building after the end of service life of the initial building; and WCS reuse with subsequent downcycling of the WCS elements into particleboards. As such, the scenarios and LCA model cover up to three product use layers: one or two subsequent building uses and particleboard use. In all scenarios, final disposal of the wood elements was in the form of municipal incineration in the vicinity of Leiden.

Table 3: Overview of the four recycling pathways run for each wood construction system, wood resource country, and building- or dwelling type (WCS = wood construction system).

Recycling pathway	Pathway description	WCS element reuse rate	kg WCS per 1 kg particleboard
1	WCS single use	-	-
2	WCS single use & downcycling	-	1.36
3	WCS reuse	90%	-
4	WCS reuse & downcycling	90%	1.36

Recycling pathway 1: WCS single use

The WCSs are in use during one BSL after which the WCS wood products are disposed of through waste management in the form of municipal incineration. As a result, this scenario has the shortest carbon retention timespan.

Recycling pathway 2: WCS single use & downcycling

When the building is dismantled after the use phase, the WCS elements are processed into particleboards in the vicinity of Leiden. The particleboards are assumed to remain in the Netherlands. At the end of their assumed service life of 50 years, the particleboards are disposed of through municipal incineration in the vicinity of Leiden.

Recycling pathway 3: WCS reuse

At the end of the initial building use phase, upon building deconstruction, the WCS is dismantled and reused in a secondary building. Consequently, carbon retention in the built environment is prolonged and release of carbon emissions delayed. The assumed rate of WCS reuse is 90%; the remaining 10% is rendered unfit for reuse due to material damage and was disposed of through municipal incineration.

Recycling pathway 4: WCS reuse & downcycling

This pathway is a combination of recycling pathways 2 and 3. Likewise as in recycling pathway 3, 90% of the WCS is reused in a secondary building after the initial building use has ended. And as in recycling pathway 2, the WCS elements are downcycled into particleboards that are assumed to be in use for 50 years before incineration. The downcycling takes place after deconstruction of the secondary building. Reusing the WCS in a secondary building followed by downcycling into particleboards is a form of cascading and prolongs the retention time of biogenic carbon.

Scenario Parameters

Each scenario was subjected to a number of parameters that are shown in Table 4. These parameters were selected to investigate the combined effect of certain sustainability strategies. The parameters and their expected effects are described below.

Table 4: Parameter variations calculated for all scenarios. See Table 2 for material intensities and Table 1 for dwelling sizes per WCS (AT = Austria; SE = Sweden; FI = Finland; CZ = Czech Republic; NL = the Netherlands).

Parameter	Default	Variations
Material intensity	Medium	Low, high
Wood resource country	AT	SE, FI, CZ, NL
Building service life	75 years	50, 100 years
Dwelling size	Regular	Small, large

Material density

Because of the wide variety in material densities found in literature, three material density levels were assessed on the environmental impact of the WCSs.

Building service life (BSL)

The timespan of the BSL directly influences the timespan of biogenic carbon retention in the built environment and the timing of carbon release into the atmosphere upon incineration. Three timespans were assessed.

Wood resource country

This parameter shows the influence of the choice of wood resource country on the overall environmental impact of the alternatives. The difference between countries is mainly apparent in transportation distances and national energy mixes. Road transportation distances between existing locations of production facilities for construction wood and a hypothetical factory for WCS in the Netherlands were obtained using Google Maps. The included wood resource countries were Austria, the Czech Republic, Finland, Sweden, and the Netherlands.

Dwelling size

In previous studies, results hinted toward a significant effect of choosing smaller dwellings on reducing the overall building environmental impact (Lucassen, 2020). Building material demand decreases with dwelling size reduction. In addition to smaller dwelling sizes, larger dwelling sizes were also included in the analysis because of the current trend in the Netherlands to build larger dwellings rather than smaller ones.

3.2.2 Life Cycle Inventory

Semi-structured Interviews

In order to gain information on WCSs currently applied in residential buildings in the Netherlands, four semi-structured interviews with Dutch wood construction practitioners were carried out between April 14th and April 26th 2021. In Table 5, the interviewed wood construction practitioners are listed. The information gathered from the interviews contributed to the WCS selection for this study. In addition, the interviews provided data that could justify some of the assumptions used in scenario definition and LCA modelling. The interview questionnaires and interviewee consent forms can be found in *Appendix 2A-D* and *Appendix 3A-D*, respectfully.

Table 5: Interviewed Dutch wood construction practitioners. Interviews took place between April 14th and 26th 2021.

Interviewee	Company	Date of interview
Teije de Jong	CLT-S	April 14th, 2021
Dennis van Lith	FLETTS	April 16th, 2021
Arthur Friederichs	Sustainer Homes	April 20th, 2021
Ard-Jan Lootens	Solid Timber B.V.	April 26th, 2021

Background Processes and Databases

The basis for this LCA was the datasets of the 'Ecoinvent 3.7.1 cut-off' database. Ecoinvent is a widely accepted LCA database that contains a wide range of life cycle activities, often on a region- or country-specific level. The datasets provided all necessary background processes. The products of these background processes served as inputs for the foreground processes, and outputs of waste flows from foreground processes are linked to background waste management processes.

In addition to the Ecoinvent dataset, the 'biosphere3' dataset was incorporated in the LCA model. This dataset links categorized biosphere compounds to the activities in the Ecoinvent database.

Where available, data representative for conditions in the nations of interest was used or the Ecoinvent data was modified to better meet the study-specific conditions. The main processes to adjust in LCAs are those concerning energy supply, as these usually contribute the most to the overall impact (Reinhard et al., 2019). All modified Ecoinvent activities can be found in *Appendix 1B*.

Life Cycle Stages

In LCA, the life cycle of any given product is divided into life cycle stages. Table 6 shows all life cycle stages of buildings in LCA. The life cycle stages that were included in this study are indicated with checkmarks. These stages include WCS production, transportation, building use, parts of the end-of-life stage, and benefits and loads beyond the system boundary. Each WCS alternative covers the same life cycle stages.

Table 6: Life cycle stages of buildings. The life cycle stages that were included in this study are indicated with checkmarks.

Product stage			**Construction process stage**		**Use stage**							**End of life stage**				**Potential benefits & loads**
A1	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**C1**	**C2**	**C3**	**C4**	**D**
Raw material supply	Transport	Manufacturing	Transport	Construction - installation process	Use, installed products	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction	Transport	Waste processing	Disposal	Recovery, reuse, recycling potential
✓	✓	✓	✓		✓								✓	✓	✓	✓

All life cycle stages were assumed to take place within the Netherlands, except for material sourcing and the first step of WCS production (for any scenario wherein the wood sourcing country is not the Netherlands). The activities starting from building construction until final disposal of WCSs and particleboards were assumed to take place within or in the vicinity of the city of Leiden.

Excluded life cycle stages

Due to a lack of data availability on machinery and energy usage, the construction-installation process stage (A5) as well as the deconstruction stage (C1) were not included in the analysis. Some information was obtained from interviews about differences in building assembly duration time between certain WCS alternatives. However, this information was not substantial enough to be used in the LCA of this study.

The choice was made to exclude the use stages (B2-B7) because wood construction of this kind is relatively new and these building types have not been in existence long enough. Data on maintenance, repair, renovation, replacement, refurbishment, and deconstruction practices for these buildings is scarce or absent.

Below, the included life cycle stages are described in more detail. For all LCA model activities and their exchanges, see *Appendix 1C*.

A1 – Raw material supply

The wood resource for all WCSs in this study was assumed to consist solely of spruce and pine softwood.

The Ecoivent activity adopted as input for TFC production was ‘*beam, softwood, raw, kiln drying to u=10%*’, location ‘*Europe without Switzerland*’. For CLT production, the Ecoinvent activity adopted was ‘*board, softwood, raw, kiln drying to u=10%*’, location ‘*Europe without Switzerland*’. These activities and some of their own input activities were copied and then adjusted to country-specific conditions, in particular the electricity energy mix input.

At the start of the wood resource chain is the Ecoinvent activity ‘*market for sawlog and veneer log, softwood, measured as solid wood under bark*’, location ‘*Europe without Switzerland*’. This activity consists of both spruce and pine from sustainable forest management in both Germany and Sweden, which was considered representative for our study.

For all CLT board and timber beam production factories, it was assumed that the trees were harvested on average 100 km away from the factory. This assumption is based on information from one of the interviewees, who stated that wood is usually harvested within a 100 km radius from the factory (de Jong, 2021). The Ecoinvent activity for sustainable forestry harvesting also applied a wood transport value of approximately 50 ton-kilometer (tkm) by default, which affirmed the assumption of 100 km mentioned earlier.

The CLT boards and timber beams produced in these factories were converted into WCS elements during life cycle stage A3, in the Netherlands (see *A3 – Manufacturing* below).

A2 – Transport

All freight transport in this study is carried out by trucks on roads. All transportation distances in this life cycle stage are shown in Table 7.

Because the manufacturing process of WCSs takes place in two steps at two different locations, two separate transportation movements take place in the product stage. The first movement is of harvested sawlog from the forest resource to the CLT board and TFC beam production plants. The second transportation instance is that of the produced CLT boards and TFC beams from the aforementioned production plants to the WCS production facility in Wehl, the Netherlands.

Transportation from the production plants in the wood resource countries to the WCS production facility in Wehl was assumed to be by truck. Based on general dimensions and loading weights of wood applied by a CLT manufacturer in Austria (KLH Massivholz GmbH, 2020), the Ecoinvent activity '*transport, freight, lorry 16-32 metric ton, EURO6*', location '*Europe*' was chosen for all transport movements to and from the WCS production facility in Wehl, the Netherlands.

For measuring the transportation distance from Austria, Czech Republic, Sweden or Finland to Wehl, locations of existing production plants were used (see Table 7). The distance by road from these plants to the WCS production facility in Wehl was determined using Google Maps. For the Netherlands, the transportation distance from a hypothetical CLT board and TFC beam production plant to the WCS production facility in Wehl was assumed to be 100 km.

Table 7: Road transportation distances in km and tkm per m³ wood material from the wood resource countries to the WCS production facility in Wehl, the Netherlands (tkm = ton-kilometer).

Wood resource country	**Production plant & location**	**Distance to Wehl (km)**	**tkm per m^3 wood material**
Austria	Stora Enso, Ybbs	938	469
Sweden	Stora Enso, Gruvön	1236	618
Finland	METSÄ, Lohja	1786	893
Czech Republic	Stora Enso, Zdírec	909	455
The Netherlands	Hypothetical, 100 km from Wehl	100	50

In LCA, freight transport is expressed in ton-kilometer (tkm). The formula for calculating ton-kilometer is shown in Equation 1, where:

A = weight of the product in kg per m^3.
B = distance in km.
C = transport in tkm.

Equation 1: Formula for ton-kilometer (A = weight in kg/m^3; B = distance in km; C = transportation in tkm).

$$(A / 1000\ kg) * B = C$$

Throughout this study, all wood products were assumed to weigh 500 kg per m^3.

A3 – Manufacturing

The manufacturing process is divided into two steps. The first manufacturing step takes place in one of five wood resourcing countries, and consists of processing harvested sawlogs into CLT boards or timber beams. During the second step, taking place in the Netherlands, the WCS building elements are produced from the boards and beams.

The first step was assumed to take place in existing production plants within the wood resource countries (see *A1 – Raw material supply*). In these plants, the first manufacturing step of processing raw timber into either CLT boards or timber beams takes place. In the scenarios wherein wood resourcing is taking place in the Netherlands, such a plant was assumed to be located 100 km from the WCS production facility in Wehl.

The second manufacturing step consists of producing WCS elements from the incoming CLT boards and timber beams. For all WCS alternatives, this step was assumed to take place at an existing wood housing module production facility in Wehl. Although this facility at the time of writing does not produce the WCS alternatives included in this study and although there are a number of other such production facilities in the Netherlands, this location was assumed to do so and was chosen based on information from the interview with Sustainer Homes (Friederichs, 2021).

A4 – Transport

The produced WCS alternatives were transported from the production plant in Wehl to the building construction site in Leiden. The road distance of 135 km between Wehl and Leiden was determined using Google Maps.

This life cycle stage differs between flatpack and modular WCS alternatives. With transport of flatpack WCSs, the full loading capacity of the truck is utilized. However, with transport of modular WCSs, the empty space within the modules cannot be employed. This means that the maximum truckload capacity for modular WCSs contains less m^3 of wood than for flatpack WCSs, resulting in more truck movements for modular WCS alternatives. In order to address this difference, the number of tkm for modular WCS alternatives was multiplied by a factor 1.5.

For flatpack alternatives, transport from Wehl to Leiden was 68 tkm per m^3. For modular alternatives, this was a factor 1.5 more: 102 tkm per m^3.

B1 – Use, installed products

During this stage, the WCS alternatives serve as floors, walls and ceilings of the buildings. This life cycle stage was included because during this stage, the carbon storage takes place.

C2 – Transport

Upon dismantling of the building at its end-of-life, the WCS elements were transported from the deconstruction site to a hypothetical waste sorting- and processing facility in the vicinity Leiden. The transportation distance was assumed to be 10 km. This translates to 5 tkm per m^3 for flatpack WCS alternatives and 7.5 tkm per m^3 for modular WCSs due to the factor 1.5 (see *A4 – Transport*). The Ecoinvent activity used for this transport movement was '*transport, freight, lorry 16-32 metric ton, EURO6*', location '*Europe*'.

C3 – Waste processing

In this stage, the deconstructed WCS elements are sorted for, depending on the scenario, either reuse, downcycling into particleboards, or disposal.

In case of reuse, it was assumed that 90% of the dismantled WCS elements were fit for a second use as WCSs in a second building. The remaining 10% was assumed to be either damaged or did not meet WCS standards anymore and was disposed of through municipal incineration.

C4 – Disposal

In all scenarios, all WCS elements were eventually disposed of through municipal incineration. At this stage, the biogenic carbon stored in the wood material from both WCS alternatives and particleboards was emitted back into the atmosphere in the form of CO_2.

The facility for municipal incineration was assumed to be 10 km away from the hypothetical waste processing facility. End-of-life particleboards were disposed of at the same facility. The Ecoinvent activity used for this transport movement was '*transport, freight, lorry 7.5-16 metric ton, EURO6*', location '*Europe*'. Following Equation 1, transport to municipal incineration is 0.01 tkm per kg waste wood.

For municipal incineration, the Ecoinvent activity '*treatment of waste wood, untreated, municipal incineration*', location '*rest of world*' was used with adjustments fitting the Dutch energy mix.

D – Potential benefits & loads

After waste processing (C3), the WCS elements were either directly disposed of (C4), reused, or downcycled into particleboards. Here, these pathways are described.

WCS elements were reused for a secondary building in recycling pathway 3 and 4. In recycling pathway 2 and 4, after the primary (recycling pathway 2) or secondary building (recycling pathway 4) is decommissioned, the WCS elements were downcycled into particleboards in the vicinity of Leiden.

For particleboard production, the Ecoinvent activity '*particleboard production, uncoated, average glue mix*', location '*Europe*' was chosen and adjusted to the Dutch energy mix.

The particleboards were assumed to have a service life of 50 years and to have an unspecified use in the vicinity of Leiden. Afterwards, the particleboards were disposed of through municipal incineration.

Particleboard disposal was assumed to take place at the same municipal incineration facility as that of WCS alternatives in the vicinity of Leiden.

3.3 Step 2 – Scenario-based Life Cycle Assessment

The scenarios described in the previous sub-chapter were quantified through scenario-based Life Cycle Assessment (LCA). LCA is a quantitative and objective method and is considered a most adequate tool for assessing environmental impacts associated to a wide range of different product life cycles, including those of buildings (Hoxha et al., 2020).

The outcome of the LCA performed in this study is the environmental impacts associated to the scenarios, expressed in global warming potential (GWP). This allowed for scenario comparison. A contribution analysis of these impact scores revealed the main contributing life cycle activities. This way, the alternatives and scenarios with the lowest environmental impact could be identified.

In this sub-chapter, the properties of the LCA model such as the functional unit and reference flows are described as well as the method chosen for scoring biogenic carbon retention.

3.3.1 LCA Software: Activity Browser

The LCA software chosen for this study is the Activity Browser version 2022.4.29: an open-source software for advanced LCA that builds upon Brightway version 2, which is an open-source Python-based LCA framework (Steubing et al., 2020). Activity Browser provides a graphical user interface to Brightway version 2 that aims to make common tasks such as managing projects and analysing results more intuitive and efficient.

After running the LCA model in Activity Browser, outputs were exported to Microsoft Office Excel for further processing. In Excel, the outputs needed to be adjusted in order to generate representative results. For instance, the effect that biogenic carbon retention has on the overall environmental impacts could not be included prior to running the model in Activity Browser but only afterwards in Excel. The method of taking into account biogenic carbon retention is described under *Carbon Accounting* in chapter 3.3.2.

3.3.2 Functional Unit, Reference Flows, Impact Categories & Biogenic Carbon Accounting

Function

The function of the WCS alternatives is to contribute as building components (floors, walls and ceilings) to a safe and comfortable living space within mid- and high-rise residential buildings. In addition, the wood material of the WCSs enables for biogenic carbon storage in the built environment which is the focus of this study.

In the product system defined in this study, the sole function of particleboards produced from downcycled WCSs is to prolong biogenic carbon retention for an additional 50 years. Any other functional use of these particleboards is not included in the scope of this study and therefore neglected.

Functional Unit

The functional unit is providing 1 m^2 building floor space. The WCS material required for 1 m^2 of floor space is expressed in m^3 WCS per m^2 floor space.

Reference Flows

In LCA modelling, a reference flow is the output flow of an LCA activity chosen by the practitioner. This reference flow is the 'measuring point' in the model.

The four recycling pathways comprise different product systems. Because of the differences, attempts to make direct comparisons between the product systems would be meaningless. It was therefore necessary to create four so-called 'baskets of functions' wherein all recycling pathways generate the same product system (van der Meide, 2022). For this reason, when comparing between the recycling pathways, the reference flows are the baskets of functions 1-4.

However, baskets of functions should not be used when investigating or comparing scenarios solely within one recycling pathway, because the other three recycling pathways are at that point out of scope. To illustrate, when looking into scenarios within recycling pathway 1, no particleboards are produced which means there is no use in drawing comparisons with product systems that do include particleboard production.

When comparing scenarios within one of the recycling pathways, one of two reference flows is used:

- For scenarios *without* particleboard production (recycling pathways 1 & 3), the reference flow is '*C3 – De-construction waste wood processing*'.
- For scenarios *with* particleboard production (recycling pathways 2 & 4), the reference flow is '*D – Particleboard End-of-Life*'.

For answering the third sub-question on the influence of the choice of wood resource country, only the part of the product system up until the arrival of wood in Wehl, the Netherlands is of importance, because after that point the product system is identical for all wood resource country scenarios. Hence, the reference flow for this sub-question is '*A3 – Market for CLT boards*'.

Impact Categories

This study focused on biogenic carbon. Therefore, the impact category '*IPCC 2013, climate change, GWP 100a, with biogenic*' was chosen as it better incorporates biogenic carbon scoring than its impact category family predecessors.

Each impact category has its own characterisation factor which is based on a mathematical model known as a characterization model. The characterization factor in this impact category is global warming potential (GWP). This is based on the category indicator of climate change in terms of radiative forcing of a mass-unit of a greenhouse gas, such as carbon dioxide. GWP is often used by LCA practitioners to express the environmental impact of a given product.

Biogenic Carbon Accounting

As can be read in chapters 2.4 and 2.5, there is no consensus yet in the LCA community on a preferred method for biogenic carbon accounting. In this study, the dynamic approach method proposed by

Guest et al (2013) was used. This method was recommended to the author by other researchers that are also working on LCA studies on biomass.

In order to incorporate the effect of biogenic carbon retention on the global warming potential (GWP), the amount of biogenic carbon needed to be adjusted using GWP_{bio} factor values. These factor values were generated by Guest et al. The GWP_{bio} factor values were used to multiply the amount of biogenic carbon, an output of the LCA model.

For obtaining the factor values, two parameters are needed: biomass rotation period (years) and carbon storage period (years). A biomass rotation period is an average time period in which a given biomass carrier, in our case a tree, lives. The chosen biomass rotation period for tree species used in this study was set on 90 years. This value was set based on rotation periods found in literature ranging from 60 to 110 years (Kellomäki et al., 2021; Penna, 2010). The carbon storage period varied per scenario as shown in Table 8.

Table 8: Carbon retention times (years) for all combinations of building service life with recycling pathways.

building service life	single use	single use & downcycling	reuse	reuse & downcycling
50	50	100	100	150
75	75	125	150	200
100	100	150	200	250

Guest et al (2013) created a table containing GWP_{bio} factor values for a range of carbon retention periods and biomass rotation periods. In this table, the carbon retention time ranges up to only 100 years. However, carbon retention times in our study ranged as far as 250 years. In order to obtain GWP_{bio} factor values for carbon retention periods that exceed 100 years, the factor values from the original table were extrapolated using Excel. The GWP_{bio} factor values for all carbon retention periods used in this study with a rotation period of 90 years are shown in Table 9. The complete extrapolated table can be found in *Appendix 1D*.

Table 9: Carbon storage periods (years) and corresponding GWP_{bio} factor values for a biomass rotation period of 90 years.

Carbon storage period (years)	GWP_{bio} factor value
50	-0.03
75	-0.275
100	-0.62
125	-0.822
150	-1.064
200	-1.55
250	-2.035

The biogenic carbon source used in this LCA is '*carbon dioxide, in air*' which falls under the category 'natural resource, in air'. This compound originates from the 'biosphere3' dataset briefly described in *Background Processes and Databases* in 3.2.2.

The GWP_{bio} factor values were needed to adjust the effect of biogenic carbon storage on the overall environmental impacts for all LCA outcomes. This was done by first multiplying the natural resource biosphere flow 'carbon dioxide, in air' with the appropriate GWP_{bio} factor value. The new value was then subtracted from the overall GWP score resulting in a new, adjusted GWP score.

The method is illustrated here using hypothetical values: for a scenario with a carbon storage period of 75 years, the overall GWP score is 3000 kg CO_2-equivalence and the carbon dioxide natural resource biosphere flow is -2030 kg. The latter value is adjusted by multiplication with the GWP_{bio} factor value -0.275 resulting in 558 kg CO_2. This quantity is then subtracted from the overall GWP score of 3000 kg, resulting in a new score of 2442 kg CO_2-equivalence. The adjusted overall impacts were used for all results in this study.

4 Results

The following sections describe the main LCA outcomes. Each of the sub-questions is answered in individual sub-chapters, followed by an assessment of the combined outcome of sub-questions 1-5 in sub-chapter 4.6.

The goal of this study was to determine how certain parameters and sustainability choices could influence and lower the negative environmental impact of residential buildings utilizing WCSs. In addition, the difference in hypothetical total wood material requirement for realisation of mid- and high-rise residential buildings in the city of Leiden was calculated. The findings of this study can be useful to local policy makers, for example for setting up criteria for wood construction contractors.

Initially, four WCS alternatives were included in this study. However, due to a technical issue with the used Activity Browser LCA software, only two WCS alternatives (CLT flatpack and CLT modular) could be properly examined. This software issue has been identified by other LCA practitioners on earlier occasions (GitHub, 2022). The issue is addressed in more detail in the *Discussion* (chapter 5).

4.1 Effect of Wood Material Cascading on the Environmental Impact

The global warming potential (GWP) per m^2 floor area in each of the four recycling pathways (see Table 3) was scored for the two functioning WCS alternatives using the standard parameter settings (see Table 4). The result is shown in Figure 1.

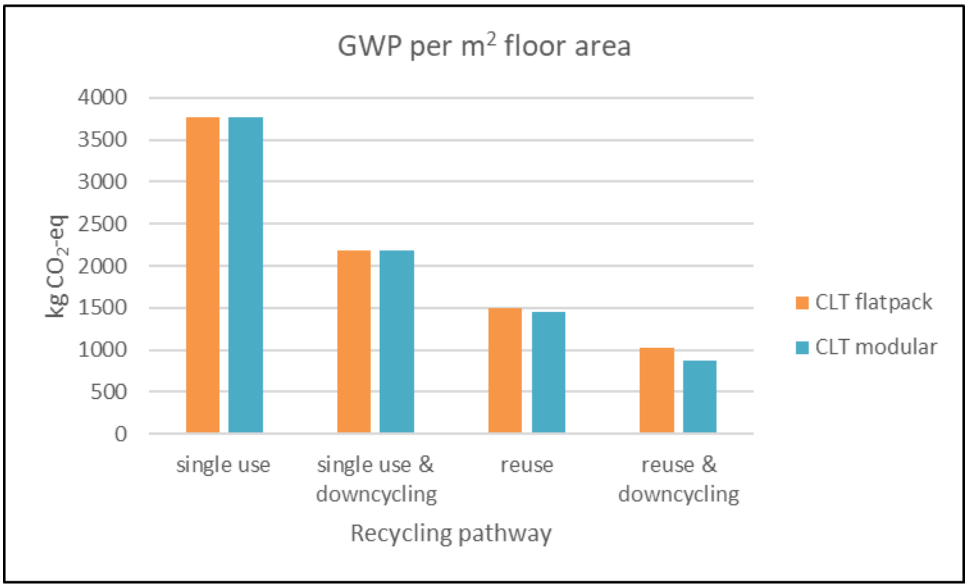

Figure 1: The global warming potential (GWP) of two WCSs (CLT flatpack & CLT modular) expressed in kg CO_2-equivalence per m^2 floor area for all four recycling pathways (GWP = global warming potential (kg CO_2-eq)). The GWP is the same per m^2 usable floor area (UFA) and gross floor area (GFA).

The outcome is generally in line with the expectation that the longer the wood material is kept in the built environment, the lower the environmental impact would be. The choice of downcycling after single use (recycling pathway 2: 'single use & downcycling') results in lowering the environmental impact by 42%. When the WCS is reused in a secondary building (recycling pathway 3: 'reuse') this reduction is 60% for CLT flatpack and 61% for CLT modular. The fourth recycling pathway represents the longest period of biogenic carbon storage, resulting in the lowest environmental impact for both alternatives. Here, the environmental impact is reduced by 73% for flatpack and 77% for modular compared to the single use recycling pathway.

A difference in GWP between the two alternatives becomes apparent in the third and fourth recycling pathways, wherein the modular WCS shows the lower environmental impact. However, for the first two recycling pathways, both alternatives score virtually the same. These findings can be explained by the difference in material intensity per m^2 on the one hand and transportation requirement on the other.

The differences between the CLT flatpack WCS and CLT modular WCS is that the latter was assumed to have a higher material intensity per m^2 and would require more truckloads for transportation than the former (see 3.1.2). The higher wood material intensity would cause the environmental impact to diminish as more biogenic carbon is stored per m^2. However, more transportation movements result in higher emissions which would cause the environmental impact to increase. This may cause the modular WCS environmental impact to level with that of the flatpack WCS in the first two recycling pathways, only to decrease in the last two recycling pathways when the influence of higher material intensity on the GWP outweighs that of higher transportation emissions.

In summary, WCS reuse as well as downcycling both have a significant effect on lowering the overall environmental impact of WCS alternatives. Both sustainability measures combined results in the lowest GWP per m^2.

4.2 Effect of the Building Service Life on the Environmental Impact

The previous section showcased the correlation between the time period of carbon retention and reduction of the environmental impact of wood products. The prolonged time period was achieved through cascading, whilst the BSL time period was fixed on 75 years. However, the BSL may be shorter or longer either by choice or due to unforeseen circumstances. In this sub-question, the effect of having a shorter or longer BSL on the overall environmental impact was examined. The service life of the particleboards remained to be 50 years. The total carbon retention time periods for each combination of BSL and recycling pathway are shown in Table 8 in 3.3.2.

The results for the WCS alternatives CLT flatpack and CLT modular are shown in Figure 2 and Figure 3, respectively. In general, the outcomes were in line with expectation because the environmental impact diminishes as the carbon retention time increases. However, the second and third recycling pathways stand out.

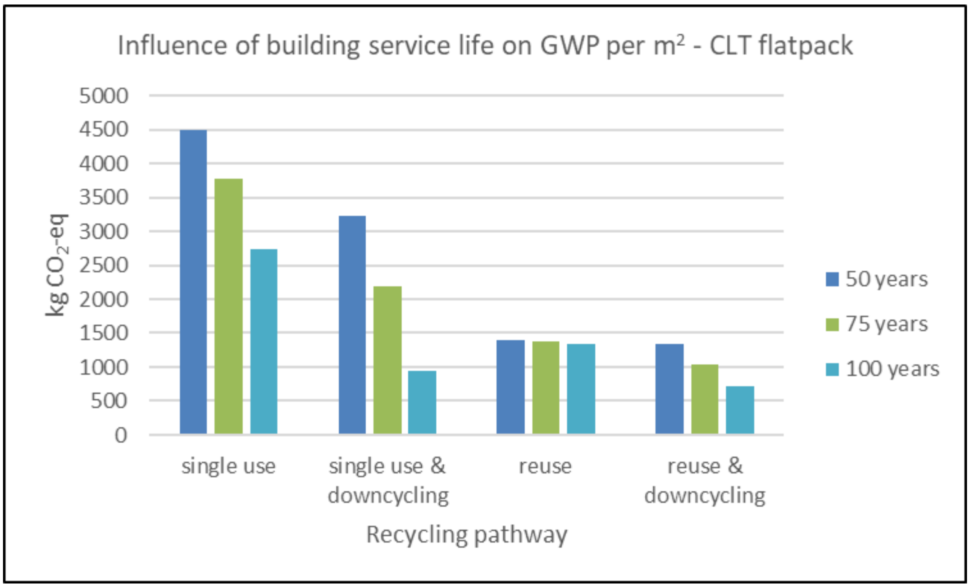

Figure 2: The effect of decreasing or increasing the building service life (years) on the global warming potential expressed in kg CO_2-equivalence per m^2 floor area for all four recycling pathways. WCS alternative: CLT flatpack (GWP = global warming potential (kg CO_2-eq)).

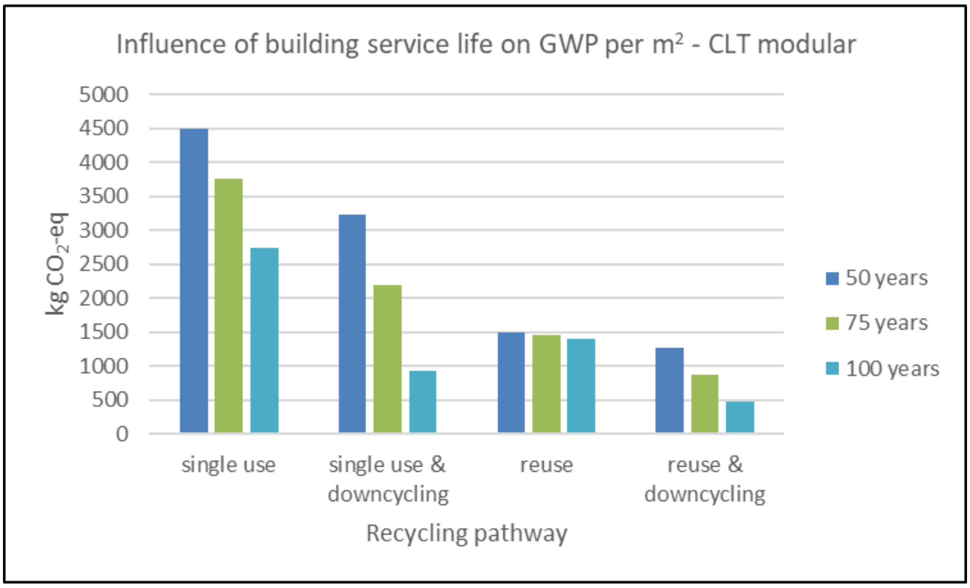

Figure 3: The effect of decreasing or increasing the building service life (years) on the global warming potential expressed in kg CO_2-equivalence per m^2 floor area for all four recycling pathways. WCS alternative: CLT modular (GWP = global warming potential (kg CO_2-eq)).

In the 'reuse' pathway, the difference in GWP between the three BSL scenarios is modest. The cause of this modest difference is a remarkably low value for 'carbon dioxide, natural resource, in air' generated in the LCA model. Using this low biogenic carbon value for calculating the adjusted GWP score resulted in only marginal differences between three BSLs.

The cause of the significantly higher and lower carbon dioxide flows unfortunately could not be determined. One explanation is that the underlying database Ecoinvent is inconsistent which in turn may cause abnormalities in multiple scenarios. In addition, biogenic carbon in Ecoinvent is at the time of writing still a relatively unexplored phenomenon which makes the possibility of inaccuracies high.

4.3 Influence of the Choice in Wood Resource Country on the Environmental Impact

Here, the difference in environmental impact between the five wood resource countries was quantified. In addition, a process contribution analysis was performed in order to identify the main processes contributing to the GWP per country alternative.

For answering this sub-question, only the part of the product system up until the arrival at the WCS plant in Wehl, the Netherlands was assessed. As such, the reference flow of the LCA was changed to the activity ‘A3 – Market for CLT boards’, which is the first activity taking place in the Netherlands.

The negative carbon emissions caused by the wood sourcing from sustainable forestry, which were roughly the same value for all country alternatives, were retracted from the total environmental impact to avoid distorting outcomes. Because carbon storage is not relevant in this sub-question as the wood is not stored (for longer periods of time) and would show the same value for all country alternatives, there was no need to generate the adjusted GWP values. The outcome is shown in Figure 4.

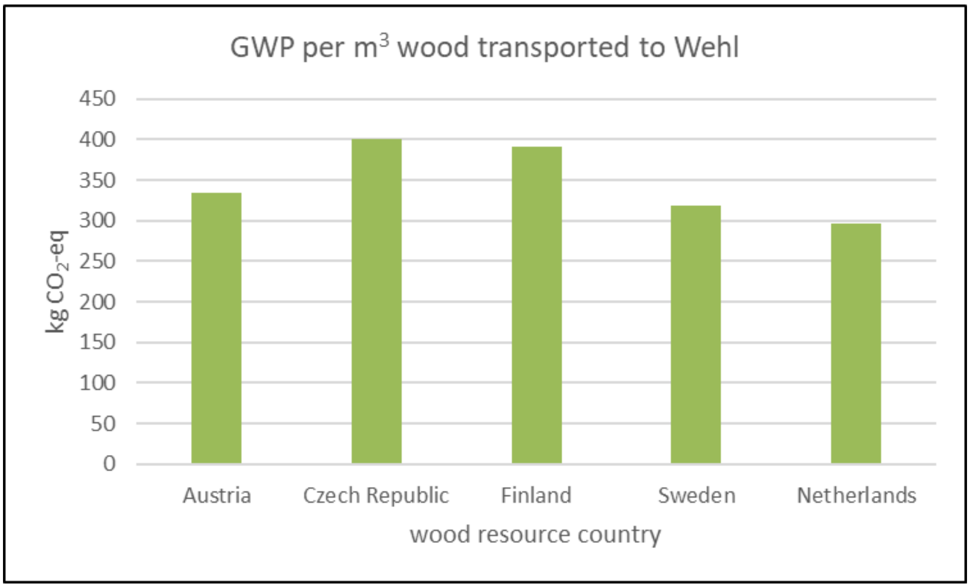

Figure 4: Global warming potential expressed in kg CO_2-equivalence per m^3 wood product for all five wood resource countries (GWP = global warming potential (kg CO_2-eq)).

The result shows that wood sourced from the Netherlands has the lowest GWP. This is logical because the truck transportation distance, responsible for GHG emissions, is the smallest in the Dutch scenario with only 100 km. However, the difference in GWP with Sweden is only marginal even though the transportation distance of 1236 km from Sweden to Wehl is more than 12 times larger. Moreover, the GWP is highest for the Czech Republic although the transportation distance from the Czech Republic to Wehl is smaller than that of the Austrian, Swedish, and Finnish scenarios. Therefore, other processes must be contributing to the GWP in all scenarios. In order to determine which other processes are contributing, a process contribution analysis was performed. The results are shown in Figure 5 and Figure 6.

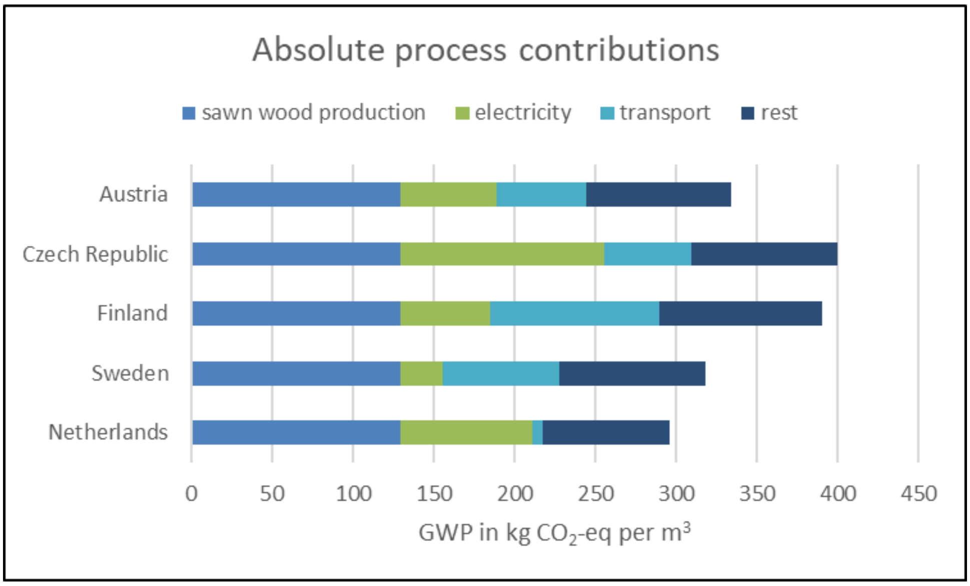

Figure 5: The top processes contributing to the global warming potential expressed in kg CO_2-equivalence per m^3 wood for all five wood resource countries (GWP = global warming potential (kg CO_2-eq)).

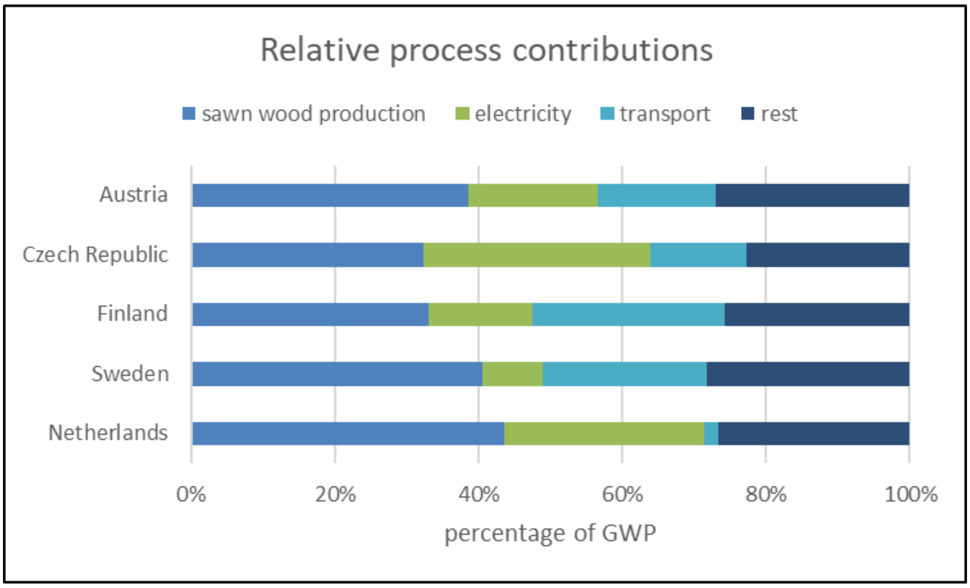

Figure 6: Relative process contributions to the global warming potential expressed in % of total GWP for all five wood resource countries (GWP = global warming potential (kg CO_2-eq)).

As shown in Figure 5, the process of sawn wood production has the same value for GWP per m^3 wood (approximately 130 kg CO_2-equivalence) in all country alternatives. The other main contributors are electricity generation and truck transportation movements. 'Rest' consists of the processes 'diesel, burned in building machine' and 'diesel, low-sulfur'.

The contribution of transport to the GWP was in line with the expectation: the GWP increases linearly with transportation distance.

The Czech Republic showed the largest contribution of electricity generation to the GWP followed by the Netherlands. Sweden showed the smallest contribution of electricity generation followed by

Finland and Austria. The difference between countries in the contribution of electricity is due to variance in the composition of national electricity mixes. A national electricity mix consists of both fossil and renewable energy sources, and the composition of these energy sources varies per country.

The national electricity mixes in the Ecoinvent database used in this LCA were from 2017 and were based on statistics provided by the International Energy Agency for that year. The composition of the national electricity mixes categorized by type of energy source is shown in Table 10. The data in this table was generated from data retrieved from the website of the International Energy Agency (International Energy Agency, 2022). See *Appendix 1E* for the uncategorized data.

Table 10: National energy mix compositions by energy source category in 2017 for all country alternatives according to the International Energy Agency. The energy source group 'Renewable' includes wind, solar PV, hydro, and biofuels. The energy source group 'Fossil' is composed of natural gas, coal, and oil. Values are % of the national electricity mix.

Energy source	Austria	Czech Republic	Finland	Sweden	Netherlands
Renewable	77	12	46	57	13
Nuclear	0	33	33	40	3
Fossil	22	55	19	1	79
Waste & other	1	0-1	2	2	4

The Dutch electricity mix has the largest share of fossil energy sources (79%). However, the contribution of electricity on the GWP is higher for the Czech Republic (Figure 5) even though its share of fossil energy is substantially lower (55%) and the share of renewables is similar for both countries. When nuclear energy is attributed as a renewable energy source, the share of renewables is 26% and 45% for the Netherlands and the Czech Republic, respectively.

The reason for the higher electricity contribution value of the Czech Republic is that coal, which accounts for roughly half of the Czech electricity mix, is a fossil energy source with a higher GWP than natural gas which accounts for almost half of the Dutch electricity mix (see *Appendix 1E*). As such, the Czech electricity mix has a higher GWP than the Dutch electricity mix despite of the Netherlands having the larger share of fossil energy sources and smaller share of nuclear energy source.

When nuclear energy is considered a renewable energy source, the share of renewables for Austria (77%) and Finland (79%) would be similar. The higher value for GWP of Finland compared to Austria (Figure 5) is hence mainly due to the larger transportation distance for Finland.

The electricity mix of Sweden would consist almost exclusively of renewables (97%) when nuclear energy is attributed as renewable. This explains why Sweden shows a lower GWP than Austria despite of the larger transportation distance for Sweden.

4.4 Effect of Dwelling Size on the Environmental Impact

Dwelling size has a direct influence on the amount of wood material required per dwelling as well as for the entire building. In this sub-question, the environmental impact of regular-sized dwellings and buildings was quantified, as well as the effect of smaller or larger dwelling sizes on the environmental impact. In order to do so, the scores of GWP per m^2 from chapter 4.1 of both WCS alternatives were multiplied with the amount of m^2 UFA and GFA per dwelling type. For calculating the GWP of entire buildings, the outcomes were multiplied with the number of dwellings of mid- and high-rise buildings, which are 48 and 124 respectively (see 3.1.2.1).

The UFA and GFA dimensions for all dwelling- and building types and for the three dwelling sizes (small, regular, large) are shown in Table 1 in chapter 3.1.2. The choice was made to multiply these with the GWP scores from the ‘reuse & downcycling’ recycling pathway because the difference in GWP between the two WCS alternatives is the most substantial here. The results are shown in Figure 7.

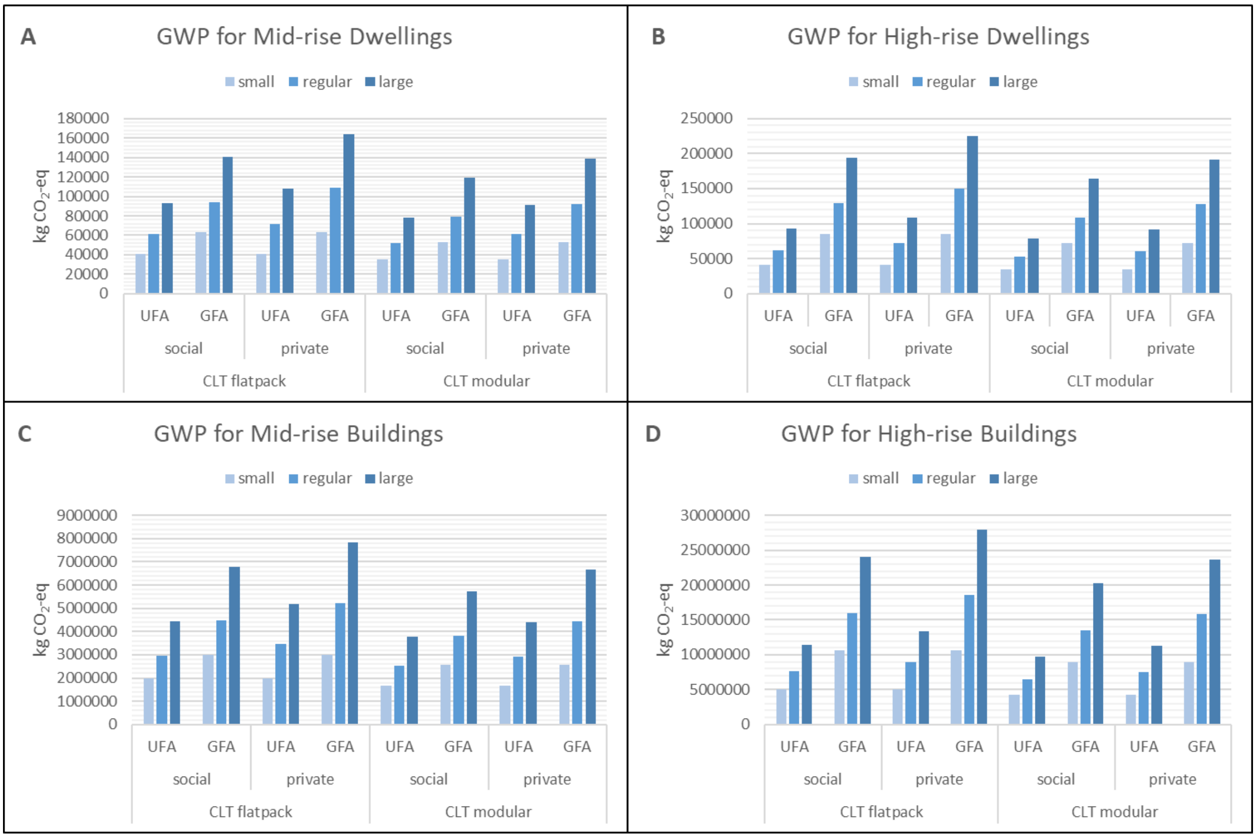

Figure 7 A-D: The effect of dwelling size (small; regular; large) in m^2 UFA and GFA on the global warming potential per dwelling- and building type (social & private; mid- and high-rise) expressed in kg CO$_2$-equivalence for the CLT flatpack and CLT modular WCS alternatives. ***A**-**B**: GWP per dwelling type in (**A**) mid-rise and (**B**) high-rise buildings.* ***C**-**D**: GWP per building type in (**C**) mid-rise and (**D**) high-rise buildings (GWP = global warming potential (kg CO$_2$-eq); UFA = usable floor area (m^2); GFA = gross floor area (m^2)).*

In line with expectation, the GWP per dwelling and building decreased as dwelling dimensions get smaller and increased as they get larger. The GWP per building (Figure 7C-D) is a multitude of the GWP per dwelling (Figure 7A-B).

The GWP scores of the CLT flatpack WCS alternative are higher than those of the CLT modular alternative even though the latter consists of more m^3 wood per m^2. The GWP seems to diminish as the amount of wood used increases, which is in line with the findings of sub-question 1 in chapter 4.1.

In order to determine if this is indeed the cause for the lower GWP scores of the CLT modular alternative, the calculation was carried out with the GWP scores from the ‘single use’ recycling pathway as well in which the effect of biogenic carbon storage is much lower. Because the outcome pattern is the same for all graphs (Figure 7A-D), there was no need to perform the comparison for all four graphs. Therefore, only the GWP per building type in high-rise buildings (see Figure 7D) was calculated. The result is shown in Figure 8.

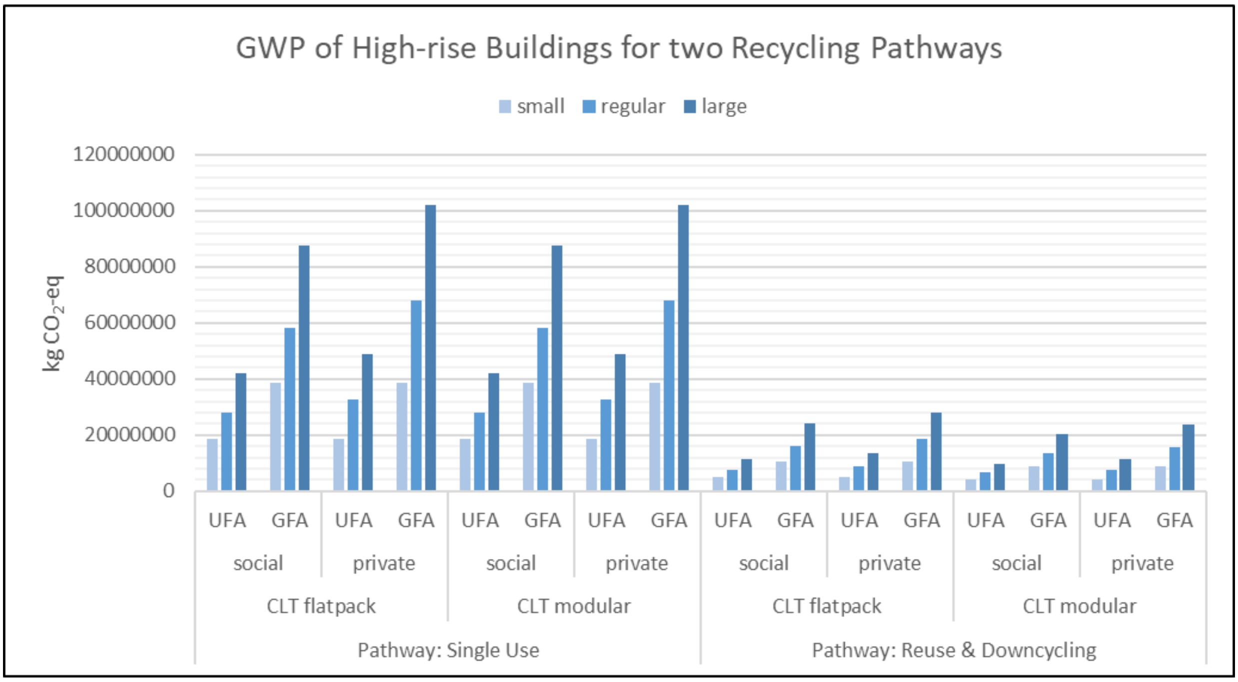

Figure 8: Comparison between two recycling pathways concerning GWP expressed in kg CO_2-equivalence of two WCS alternatives in high-rise buildings for three dwelling sizes (small; regular; large) (GWP = global warming potential (kg CO_2-eq); UFA = usable floor area (m^2); GFA = gross floor area (m^2)).

As was the case for sub-question 1 in chapter 4.1, both WCS alternatives score virtually the same in the 'single use' scenario whereas in the 'reuse & downcycling' scenario, the CLT modular WCS alternative generated a lower GWP score. Hence, the results show no abnormalities.

Figure 8 underlines the significant environmental impact reduction that can be achieved by keeping wood material in use for a longer time period, thereby prolonging the carbon retention time in the built environment. The impact reduction through the 'reuse & downcycling' recycling pathway here is the same as in chapter 4.1: 73% for the CLT flatpack alternative and 77% for the CLT modular alternative.

4.5 Total Wood Material Requirement for Mid- and High-rise Residential Dwellings

The final sub-question concerns the hypothetical total wood material requirement for the realization of 17,000 dwellings in the city of Leiden between 2020-2030. As described in 3.1.2, 12,750 of these dwellings will be in high-rise buildings and 4,250 in mid-rise buildings. Half of these dwellings are social housing and the other half private rent. In this sub-chapter, the parameters 'dwelling size' and 'material intensity' were quantified. All calculations were carried out using only GFA values since the focus lies on the total material demand.

The wood material demand for all mid- and high-rise buildings consisting of regular-sized dwellings built with the CLT flatpack and the CLT modular WCSs is shown in Figure 9A and B, respectively. The wood material demand for all buildings consisting of smaller or larger dwellings is shown in Figure 10.

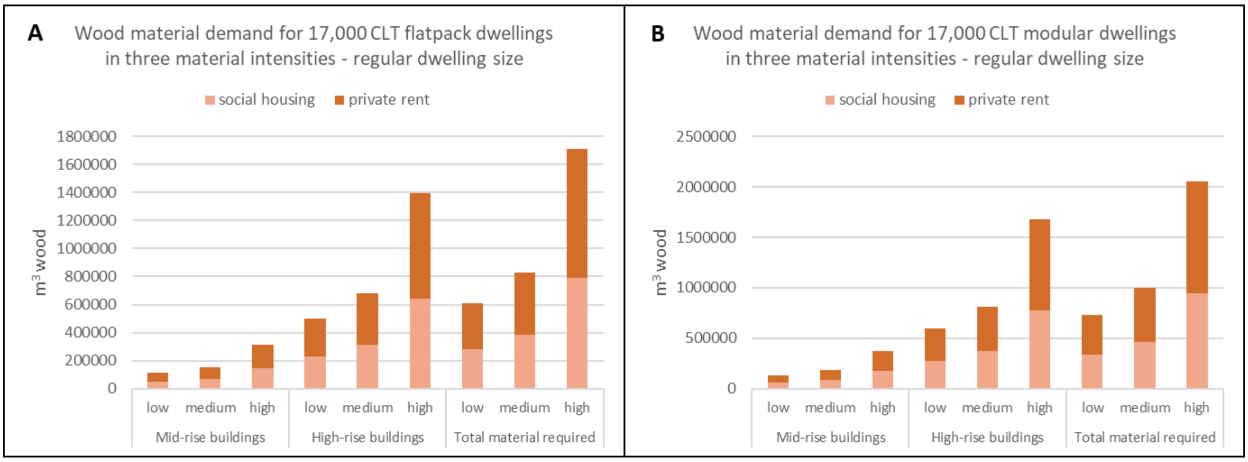

Figure 9: Wood material demand in m^3 wood for regular-sized dwellings (social housing & private rent) on three material intensity levels (low, medium, high). Material demand is shown for both building types (mid- and high-rise) as well as for the buildings combined (total material required). ***A****: CLT flatpack WCS.* ***B****: CLT modular WCS.*

High-rise buildings show a higher material demand than mid-rise buildings for both WCS alternatives. On all three material intensity levels, the material demand of high-rise buildings is about 4.4 times that of the mid-rise buildings. This can be explained on the one hand by the larger share of dwellings being high-rise dwellings (75% of total dwellings) and on the other hand by the larger GFA per dwelling in high-rise buildings.

As mentioned above, the number of private rent and social housing dwellings is distributed equally. However, private rent dwellings have a larger GFA than social housing dwellings (except in the smaller dwellings scenario). This means that private rent dwellings have a higher wood material demand than social housing dwellings as can be seen in Figure 9 and Figure 10C-D. In both mid- and high-rise buildings on all material intensity levels, 54% of the total wood material demand is attributed to private rent dwellings and 46% to social housing dwellings. This distribution is in line with the pre-determined GFA dwelling dimensions (see Table 1): the GFA of a regular-sized private rent dwelling (106 m^2 in mid-rise; 146 m^2 in high-rise) is 54% of the GFA of the regular-sized private rent dwelling and social housing dwelling combined (197 m^2 in mid-rise; 271 m^2 in high-rise).

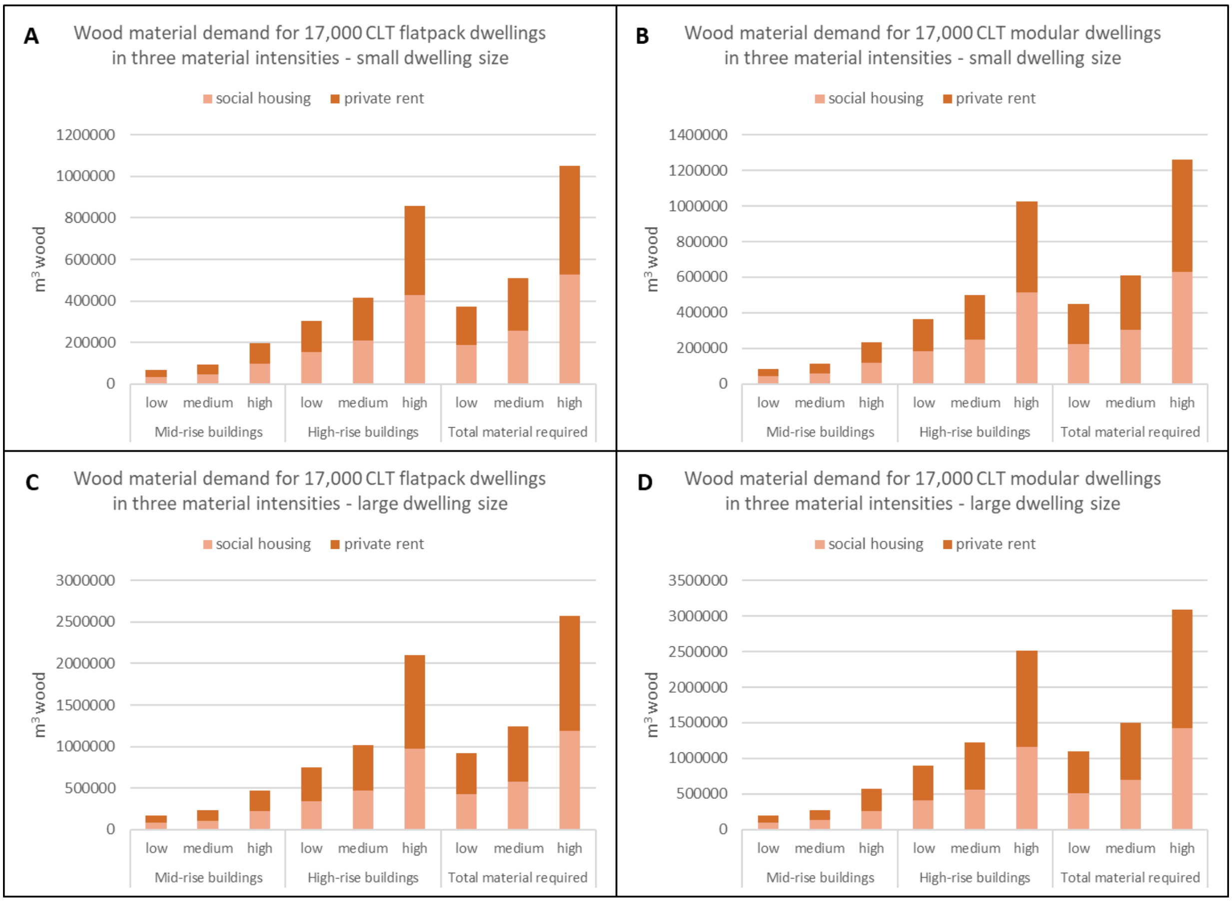

*Figure 10: Wood material demand in m^3 wood for smaller dwellings (**A-B**) and larger dwellings (**C-D**) (social housing & private rent) on three material intensity levels (low, medium, high). Material demand is shown for both building types (mid- and high-rise) as well as for the buildings combined (total material required). **A&C**: CLT flatpack WCS. **B&D**: CLT modular.*

In the smaller dwelling size scenario shown in Figure 10A-B, the material demand for social housing dwellings is equal to that of private rent dwellings in both mid- and high-rise buildings. This is because the GFA is equal for both dwelling types. This scenario shows a significant reduction in wood material demand compared to the regular-sized dwelling scenario. In the scenario with the lowest material requirement, wherein solely smaller dwellings are built with a low material intensity, the total demand for the CLT flatpack WCS would be 373,641 m^3 of wood and for the CLT modular WCS 448,369 m^3.

The larger dwelling scenario shows a higher wood material demand for all dwelling- and building types than in the regular-sized dwelling scenario and the smaller dwelling scenario. The most material-intensive scenario would consist of building solely larger dwellings with a high material intensity. This would result in a total demand of 2,570,344 m^3 of wood when utilizing the CLT flatpack WCS and 3,084,413 m^3 of wood when utilizing the CLT modular WCS.

Between the scenarios with the lowest material requirement and the highest, the difference in material demand is 2,196,703 m^3 for the CLT flatpack WCS and 2,636,044 m^3 for the CLT modular WCS. This translates to a hypothetical maximum material demand reduction of 85% for each WCS alternative. The largest hypothetical material demand reduction possible is between small, low material intensity dwellings built with CLT flatpack and large, high material intensity dwellings built with CLT modular: a difference of 88%.

The total material requirement for the 17,000 dwellings depends on the dwelling size and the material intensity per m^2, as well as on the choice of WCS alternative. In all cases, the CLT modular WCS had a material demand 1.2 times higher than the CLT flatpack WCS. This is the same factor value as the assumed wood material demand of the CLT modular WCS as described in chapter 3.1.2.1.

4.6 Maximum Hypothetical Environmental Impact Reduction

At this point, it should be noted that the results of this study require some nuance. The author is aware that the scenarios used in this study – and therewith the scenarios quantified in this sub-chapter – do not align with current trends. These trends include the incapacity of the construction sector to shift rapidly towards more sustainable construction systems due to the sectors' conservative nature, price competitiveness, and the increasing number of larger dwellings inhabited by smaller households (less people per m^2 housing): in the real-world context, the probability that the scenarios depicted here will be followed through is highly unlikely. Be that as it may, these results serve as indicators of what would theoretically be possible concerning WCS environmental impact reduction.

With each of the five sub-questions covered, a combination of their outcomes could now be modelled in order to find out what the hypothetical maximum environmental impact reduction per WCS alternative could be. To this end, one scenario with the least-favourable sustainability choices (the so-called 'worst-case scenario') and one scenario with sustainability choices that showed effective in environmental impact reduction (the so-called 'best-case scenario') were quantified and compared for both WCS alternatives. The parameter settings of the two scenarios are shown in Table 11.

Table 11: Parameter settings for the worst- and best-case scenarios.

Parameter	Worst-case scenario	Best-case scenario
recycling pathway	single use	reuse & downcycling
dwelling size	large	small
building service life (years)	50	100
material intensity	medium	medium
wood resource country	The Netherlands	The Netherlands

One parameter that is the same in both the worst- and best-case scenario is the material intensity. Although material reduction is considered an additional sustainability measure, it is uncertain what the possible minimum (or maximum) material intensity could be in the real-life situation, especially in high-rise buildings. Therefore, the choice was made to carry out the comparison with the medium material intensity level in both scenarios.

The results are shown in Figure 11. Because there is no difference in GWP per m^2 GFA for mid- and high-rise buildings, the results in Figure 11A apply for both mid- and high-rise building types.

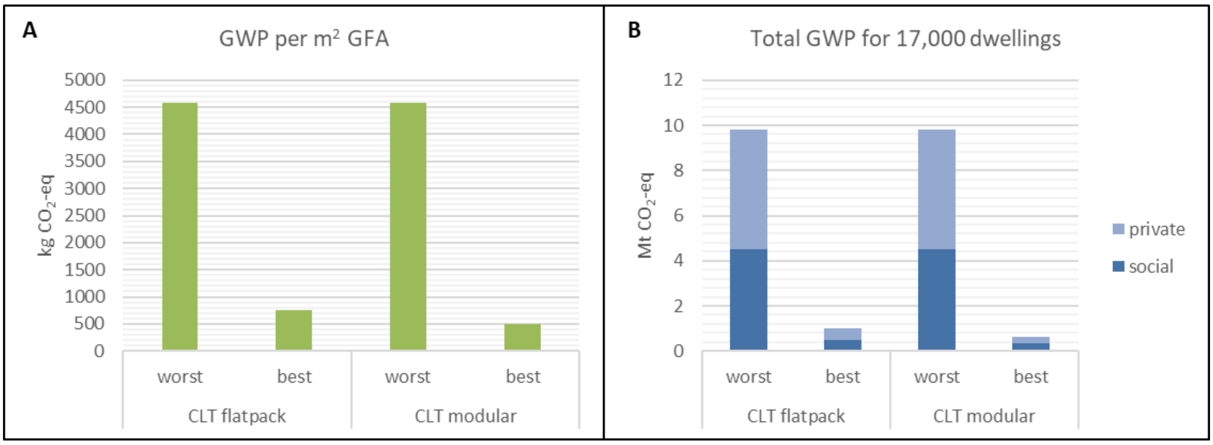

Figure 11: Worst- and best-case scenario outcomes for the CLT flatpack and CLT modular WCS alternatives. ***A****: GWP per m^2 GFA expressed in kg CO_2-eq.* ***B****: Total GWP of 17,000 dwellings distributed over private and social dwellings, expressed in megaton (Mt) CO_2-eq. Of the 17,000 dwellings, 4,250 are mid-rise and 12,750 are high-rise. The number of private and social dwelling types are distributed equally in both mid- and high-rise buildings (GWP = global warming potential (kg CO_2-eq); GFA = gross floor area (m^2)).*

The graphs in Figure 11 show the combined effect of several additional sustainability choices on lowering the GWP of WCSs. In both Figure 11A and B, the CLT modular WCS alternative shows a lower GWP score than the CLT flatpack WCS in the best-case scenario. In the worst-case scenario, both alternatives score virtually the same. In the best-case scenario, when considering the included parameters and the level of detail of the LCA model, the CLT modular WCS is the alternative with the lowest environmental impact. Note however that this only applies if the WCS is subjected to the additional sustainability choices as described in Table 11.

For the total building stock of 17,000 dwellings (Figure 11B), the maximum hypothetical impact reduction is from 9.81 Mt to 0.98 Mt CO_2-eq (91.0%) for the CLT flatpack WCS and from 9.81 Mt to 0.65 Mt CO_2-eq (92.3%) for the CLT modular WCS. In the best-case scenario, the CLT modular WCS alternative therefore has a lower environmental impact than the CLT flatpack alternative. However, the difference between the two alternatives is only marginal.
The maximum impact reduction per m^2 GFA for CLT flatpack and CLT modular is 83.7% and 89.2%, respectively.

As can be seen in Figure 11B, the private dwellings are responsible for the larger share of the total GWP in the worst-case scenario even though the number of private and social dwellings is distributed equally. Furthermore, in the best-case scenario, both dwelling types show an equal share of the total GWP. This is because in the worst-case scenario, the dwelling dimensions of private dwellings are larger than those of social dwellings (see Table 1). In the best-case scenario, wherein the dwelling sizes are small, the dwelling dimensions are the same for private and social dwellings.

5 Discussion

Goal of the study
The goal of this study was to determine what effect certain parameters and sustainability choices have on the life cycle environmental impact of two WCS alternatives utilized in mid- and high-rise residential buildings. These choices include cascading of WCSs and downcycling into particleboards, as well as optimization of dwelling use by means of extending the BSL and decreasing dwelling sizes. The effect that the choice in wood resource country has on the environmental impact of WCSs was tested for four countries that deliver wood material to the Netherlands. In addition, the Netherlands as a hypothetical future wood resource country was included as well. Furthermore, the total environmental impact of the 17,000 mid- and high-rise apartment building dwellings to be built in the city of Leiden, as well as their hypothetical wood material requirements, were quantified per alternative.

This explorative study showcased hotspots for further research concerning lowering the environmental impact of WCSs. The method for doing so was a scenario-based life cycle assessment (LCA). Based on the outcome of the LCA, the effect of sustainability choices on the environmental impact of two WCS alternatives could be formulated. Although current real-world trends mitigate against the likelihood of a successful execution of the environmental impact reduction scenarios examined in this study, the results showcase and indicate what would theoretically be possible to achieve concerning WCS environmental impact reduction.

This study connected theory and practice by combining data and information from publications and previous studies, Dutch wood construction practitioners, and from the municipality of Leiden. The analysis was conducted in cooperation with the municipality of Leiden. In this context, the starting point of this study was in part the urbanisation and sustainability goals of the municipality of Leiden. The results and recommendations of this study may be useful to municipalities in the Netherlands as well as other countries.

Key results and insights
The four recycling pathways as well as the additional sustainability choices tested in this LCA all had a positive effect on lowering the environmental impact of both WCS alternatives. For the total building stock of 17,000 dwellings, the maximum hypothetical impact reduction is 91% for CLT flatpack and 92.3% for CLT modular WCSs.

Cascading in the form of material reuse and downcycling had a substantial effect on the environmental impact of both WCSs (sub-question 1). The most effective scenario is when both reuse and downcycling are implemented: compared to the single use scenario, the GWP is reduced by 73% for the CLT flatpack alternative and 77% for the CLT modular alternative. This shows the significant effect that prolonged carbon retention times have on the environmental impact.

The difference in GWP between the two WCS alternatives becomes apparent in the 'reuse' and reuse & downcycling' recycling pathways. The lower GWP reduction rate of the CLT flatpack alternative is due to the lower wood material intensity per m^2, resulting in a lower beneficial effect from biogenic carbon storage.

The GWP per m^2 becomes lower as the building service life (BSL), therewith the carbon retention time, increases (sub-question 2). Furthermore, the GWP per dwelling and building decreases when the choice is made for smaller dwellings (sub-question 3).

Of the five wood sourcing countries included in this study, Sweden shows the lowest GWP per m^3 wood imported (sub-question 4). The main GWP contributor is electricity generation required for the CLT production process. Sweden has the most renewable-based electricity mix, whereas the Czech Republic has the most fossil-based electricity mix.

The hypothetical maximum wood material requirement reduction is 88% (sub-question 5). This reduction rate is achieved in the scenarios with low wood material intensities per m^2 and smaller dwellings.

Because the scenarios with CLT and TFC hybrid WCS alternatives could not be quantified, these WCSs could not be included in the analysis. Scoring TFC WCSs in this study could have generated interesting comparisons with CLT WCSs, especially for the mid-rise buildings.

Sensitivity analysis

As part of the life cycle analysis, a sensitivity analysis is usually carried out. The goal of a sensitivity analysis is to assess the robustness of the LCA model with respect to variations and uncertainties in the methods and data used. This is done by adjusting some of the parameter values by + or – 10% followed by observing a (dis)proportionate change in the model output. However, since these types of adjustments were already implemented for answering some of the sub-questions (i.e. variations the in BSL time period; dwelling size; material intensity), carrying out an additional sensitivty analysis was deemed unnecessary.

Limitations of the study

The set of scenarios formulated for this study is limited and, as in any study, prone to biases. Scenario formulation is on a case-specific basis to answer a certain research question and often has little common ground with scenarios formulated in other studies. The usefulness of scenario-based LCAs is thereby limited as comparability between results from existing and follow-up studies is hindered (Fishman et al., 2021). However, for explorative studies, scenario-based LCA is considered an adequate tool in pointing out areas of interest for future studies.

The included WCS components in the product scope was limited to the wood material in the floors, walls and ceilings, although WCSs typically contain other components and materials as well. Complete buildings would also include building components for insulation, windows and doors, electronic appliances, piping, and foundations. Some of these building components could be bio-based as well, which could lower the environmental impact of the building. Furthermore, wooden buildings would likely require less material for the building foundation due to the building weight reduction compared to conventional buildings (Friederichs, 2021; Lootens, 2021; van Lith, 2021). Given that building foundations in the Netherlands typically consist of carbon-intensive concrete, this could significantly reduce the overall environmental impact of wooden buildings as opposed to conventional buildings. Inclusion of some of these elements in the product scope would have allowed for a more complete assessment. However, since the study focused on the wooden floors, walls and ceilings of the buildings, the exclusion of other building components could be justified.

Although there are more WCS alternatives in existence or being developed, only two WCS alternatives (CLT flatpack and CLT modular) were analysed in this study. WCS alternatives that potentially have a lower environmental impact may have been left out of the assessment. Furthermore, not all distinguishing features of the WCS alternatives were included and could therefore not be assessed. These include features such as modularity, design for circularity or recyclability, and utilization of secondary wood material from an anthropocenal source. These features were not included due to a lack of data availability and because there is no available method to incorporate and score them in an LCA.

The exclusion of TFC WCSs in this study is unfortunate. Although TFC may provide less wood mass for carbon storage, it would also require much less wood material per dwelling. This way, more dwellings could be constructed with the same amount of wood material demand projected for the number of dwellings in this study. TFC WCSs are especially well-suited for low- and mid-rise buildings, and could be utilized in hybrid WCS for high-rise structures.

The two TFC WCS alternatives were ultimately excluded from this study due to a technical issue with the LCA software used. The issue is that when using a parameter in the formula of a reference flow, the results are altered in such a way that they are rendered useless for the assessment. Issues of this kind have been reported by other LCA practitioners in the past. It appears that this issue with the Activity Browser is not limited to biogenic carbon LCAs.

The reuse scenarios are built on assumptions of what will be done in the future, as there is no data yet on reuse of the WCSs included in this study. It should be noted that reuse of WCSs in the future bears a high level of uncertainty: it is unknown what the decisions on what to do with the WCSs in the future are.

Not all life cycle stages were included in the scope of this study. Including all life cycle stages would have led to a higher level of completeness and hence credibility of the results. If for example the maintenance, repair and replacement stages could have been assessed, one alternative may have proven less material- and labour-intensive than the other. As for the operational energy requirement in the use-phase of the building, differences in levels of energy efficiency may put one WCS alternative in a more favourable light than the other. Although rapid construction time is characteristic for WCSs, savings made in time, energy and labour at the construction site could not be scored. However, since the focus of this study was only on the wood material in floors, walls and ceilings and not on building components that influence the energy efficiency level of dwellings further such as insulation, window dimensions or shading mechanisms, the operational energy use was not included.

Downcycling of wood elements into particleboards is not a high-value recycling option, especially concerning WCSs. Particleboard production is considered one of the last recycling options for end-of-life wood products. Discarded WCS wood with little or no damage however can potentially be reused or repurposed for other functions before being downcycled into particleboards. For example, elements can be utilized for other building components or purposes in the future that we do not know of. These other uses could increase the biogenic carbon storage time considerably whilst replacing virgin wood demand for the other products. Although including these other uses in the scope would allow for more real-world scenarios, the choice was made to not include them. Nevertheless, the effect of prolonged carbon storage could still be scored with the scenario of WCS downcycling into particleboards.

Only one impact category, the global warming potential (GWP), was assessed. Including additional impact categories in the LCA could have generated other insights and would have allowed the results to be interpretated from a different angle. As biogenic material typically requires land where it can grow, the impact category for land-use and land-use change (LULUC) should be included in studies involving large quantities of biogenic material such as this study. However, further investigation is needed on how carbon storage credits should affect the LULUC impact category (Hoxha et al., 2020).

The national energy mixes used in the LCA do not include electricity imports from neighbouring countries. These imports could significantly alter the composition of a national energy mix, thereby making the mix contain more or less renewable energy than without electricity imports. This should be noted and taken into account when choosing a country for WCS production.

Recommendations for future studies

This study explored how the environmental impact of WCSs could be reduced through certain sustainability choices. However, the scope and data used were limited. It is therefore recommended to broaden the scope and combine the outcome of this study with other study topics concerning sustainability of the built environment. This could generate results that have a higher level of completeness and are closer to the real-world situation. Below are some recommendations for future studies.

Including more life cycle stages in the LCA would allow for a more complete assessment and for a higher distinction between WCS alternatives. For example, one WCS may prove more maintenance-intensive than the other or require less energy during construction or dismantling practices. Also, comparing these factors with conventional construction systems may generate additional valuable insights.

Including the scoring of the substitution effect would add an extra dimension to the LCA and could improve the environmental impact of the WCS alternatives dramatically. This effect is twofold: First, demand for carbon-intensive construction materials such as concrete and steel used in conventional construction systems would be reduced. Second, the reuse of the WCSs in a secondary building would prevent the demand for wood material otherwise required for the construction of said building. The same can be said for wood demand for particleboard production.

The potential of recycling of conventional building materials should not be neglected. Combining studies on resource extraction of conventional building materials from urban mines with studies on bio-based construction materials would generate results that are more reflective of the situation in the near and more distant future, and could therefore provide policy makers with more useful information.

Broadening the product scope by including more building components is recommended. By including any or all building components such as insulation systems, heating systems, building foundations and building facades, future assessments would obtain a higher level of completeness. Furthermore, some of these building components can potentially consist of bio-based materials.

Addition of WCS characteristics such as design for flexibility, disassembly, circularity or modularity could enhance the contrast between WCS alternatives. At the time of writing, such characteristics are hardly quantifiable in LCAs. The scoring of these principles would add another dimension to the profile of WCS alternatives. Development of an LCA method by the LCA community that allows for scoring these principles is highly desirable.

An important design factor that could enhance the sustainability of buildings is design for flexibility. This means that one building could change its purpose of use, for example from office space to residential space. There are plenty examples of repurposing decommissioned office buildings for housing. Design for flexibility can optimise the process of repurposing building space from one type of use to another. This way, chances are that a building would be renovated rather than demolished, which would prolong the building service life significantly. Letting a building stand as long as possible is in itself a sustainability measure. Scoring these factors in a future study would be desirable.

Technological changes should be taken into account when studying long-term climate impacts (Peñaloza, 2017). This can be achieved by using dynamic models in LCAs that account for processes that may take place in the future, and by employing multiple scenarios with several methodological settings.

Lastly, the complexity of forest systems for different countries should not be underestimated. In LCAs, the dynamic interactions between species in forest systems, as well as the influence of forestry on these, is often overlooked or subject to generalizations. In addition, the effects of short- and long-term climatic changes on forest systems, which are becoming increasingly unrelenting, should be properly addressed. Certain WCSs require certain wood types and tree species: it should be taken into consideration that countries or areas in Europe that provide the proper forest systems for WCSs today may not be able to do so in the future.

6 Conclusion

The aim of this study was to explore how certain sustainability choices can reduce the life cycle environmental impact of cross-laminated timber (CLT) flatpack and CLT modular wood construction system (WCS) alternatives. This study underlines the significant effect that prolonged biogenic carbon storage in WCSs through high-end reuse followed by downcycling into particleboards has on lowering the environmental impact of WCSs. In addition, the total wood material requirement for the realization of 17,000 mid- and high-rise residential dwellings was calculated for different scenarios.

The scenarios formulated and the level of detail of the LCA model do not align with the current real-world situation, nor with current trends in the construction- and housing sector. Therefore, the figures presented should be seen in the bigger context and their actual realization should not be perceived as highly feasible. However, the results can be useful to policy makers as indicators of what would theoretically be possible concerning environmental impact reduction of WCSs, and may be helpful to local governments in selecting sustainability choices and sustainable alternatives to conventional construction methods.

When considering the included parameters and the level of detail of the LCA model, the maximum hypothetical environmental impact reduction for the total of 17,000 dwellings is 91% for CLT flatpack and 92.3% for CLT modular WCSs. The maximum impact reduction per m^2 GFA for CLT flatpack and CLT modular was 83.7% and 89.2%, respectively. The CLT modular WCS alternative had a marginally lower environmental impact than the CLT flatpack alternative.

When choosing a wood resource country for CLT WCS production, decision makers should pay attention to the countries' national electricity mix as well as the road transportation distance from the wood resource country to the building construction site. In this study, wood from the Netherlands showed the lowest environmental impact due to the least amount of transportation emissions. However, since the Dutch forest resource is at the time of writing limited and its electricity mix considerably fossil-based, Sweden would be the more realistic wood resource candidate: of the five countries, its electricity mix has the largest share of renewable energy sources and lowest amount of carbon emissions.

The maximum hypothetical reduction in wood material demand was 88%. This reduction was achieved when the choice was made for constructing small-sized dwellings with a low wood material intensity per m^2 using the CLT flatpack WCS, as opposed to large-sized dwelling with a high wood material intensity per m^2 using the CLT modular WCS.

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