Master's thesis

Maximization of carbon storage in timber in residential dwellings in the Netherlands until 2050 and 2100

Image source: Dovetail Partners (2010)

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Abstract

It is expected that there will be an increased need for 1-2 million new residential dwellings in the Netherlands in the coming decades. As the Dutch government has set targets to decrease CO_2-eq emissions in their climate agreement, increasing the amount of timber used in residential buildings could greatly reduce associated CO_2-eq emissions and increase associated carbon storage. However, the Netherlands also faces issues of low wood availability. The aim of this research is to identify strategies that enable high-quality reuse of timber from residential dwellings in the Netherlands by providing an overview of the potential for carbon storage in structural timber until 2050 and 2100, taking into account strategies to maximize the length of use of timber elements. High-quality reuse is defined as reuse in in a same or similar function as the first use.

To determine the potential for carbon storage, the use of reused timber, and the avoided CO_2 emissions, this research uses literature review, expert interviews, data analysis, scenario analysis, and a Material Flow Analysis. By creating scenarios on the number of residential dwellings constructed, the use of timber in dwellings, and the rates of reuse based on identified maximization strategies, ranges are provided for the virgin and reused timber use, associated carbon storage and thus delayed emissions, and the avoided CO_2 emissions from incineration. The most important maximization strategies to increase the length of use of timber structural elements until 2050 and 2100 are developing new disassembly techniques for existing dwellings, developing quality standards for (reused) timber elements, improving the infrastructure for reuse of elements and materials, and creating a marketplace with an overview of supply and demand of secondary materials. To increase the length of use of structural timber elements on the longer term, it is also important to take into account design strategies that allow for easy dis- and reassembly.

This research provides several recommendations for policymakers that could facilitate increased use of timber in residential dwellings, which increases carbon storage within the built environment, and increased cascading and therefore higher-value reuse of structural timber elements, which lowers the demand for virgin timber and the quantities of high-quality timber incinerated with energy recovery.

Keywords: timber construction, carbon storage, cascading, scenario analysis, Material Flow Analysis

Contents

List of abbreviations

Abbreviation	**Description (*Dutch name*)**
BENG	Nearly Zero Energy Buildings (*Bijna Energieneutrale Gebouwen*)
BIM	Building Information Model
BRP	Biomass resource pool
CBS	Central Bureau for Statistics
CCS	Carbon capture and storage
CLT	Cross-laminated timber
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
EIB	Economic Institute for Construction (*Economisch Instituut voor de Bouw*)
EPBD	European Energy Performance of Buildings Directive
EPD	Environmental product declaration
FSC	Forest Stewardship Council
GFA	Gross floor area
GHG	Greenhouse gas
Glulam	Glue-laminated
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
JIT planning	Just-in-time planning
LCA	Life cycle assessment
LVL	Laminated veneer lumber
MDF	Medium-density fiberboard
MFA	Material Flow Analysis
MMC	Modern methods of construction
MPG	Environmental Performance of Buildings (*MilieuPrestatie Gebouwen*)
NO_x	Nitrogen oxides
ODD	Overview, design concepts, details
OSB	Oriented strand board
PBL	Dutch Environmental Planning Bureau (*Planbureau voor de Leefomgeving*)
PCD	Principle of circular design
PEF	Product Environmental Footprint
PEFC	Programme for Endorsement of Forest Certification
Prefab	Prefabricated
rwe	Roundwood equivalent
SDE	Stimulation Regulation Sustainable Energy Production *(Stimuleringsregeling Duurzame Energieproductie)*
TFC	Timber frame construction
TR	Transformation rate
WLO	Future exploration of Prosperity and Living Environment (*Toekomstverkenning Welvaart en Leefomgeving*)
X-lam	Cross-laminated timber

1. Introduction

1.1 Societal background

As buildings have long lifetimes, the buildings constructed in the coming 100 years are of crucial importance (Rozinga, 2019). In the Netherlands, residential buildings accounted for the largest market share of new construction in 2016 (39%); other shares include utility buildings (31%) and civil engineering projects (30%) (EIB, 2018). In 2018, global carbon dioxide (CO_2) emissions of the construction sector amounted to 36% of total global final energy use and 39% of energy- and process-related emissions. Of these emissions, 11% originated from the manufacturing of building materials and products such as steel, cement and glass (Global Alliance for Buildings and Construction et al., 2019).

In the Netherlands, the Dutch government has set a target in their Climate Agreement (*Klimaatakkoord*) of a 49% reduction in greenhouse gas (GHG) emissions in 2030 compared to 1990, which translates to a reduction of 3.4 megatons (Mt) CO_2-equivalent (CO_2-eq) compared to 1990 for the built environment (Rijksoverheid, 2019). In their research on climate benefits of the construction of timber residential buildings in the Netherlands, W/E Adviseurs (2016) found a potential CO_2-eq reduction of 6-42%, considering the entire life cycle. Research on CO_2 emissions reduction of new buildings, comparing biobased materials (including timber) with conventional building materials, showed a CO_2 reduction potential of 30-35% (W/E Adviseurs, 2018). Currently, only 2% of the total weight of materials used in the residential and utility construction sector in the Netherlands consists of timber (NIBE Research, 2019). There is thus a large potential to reduce CO_2 emissions associated with the construction of residential and utility buildings by increasing the share of biobased materials and timber.

The Dutch population is projected to grow in the coming decades. The CBS projects a possible increase of over 2 million households by 2050 (NIDI & CBS, 2020). Consequently, a need of 1.1 million additional dwellings before 2035 is projected, with a potential addition of another 1 million dwellings before 2050 (Studio Marco Vermeulen, 2020). Such a large new dwelling demand in the Netherlands could result in large amounts of associated CO_2-eq emissions, but by increasing the amount of timber used in residential buildings, the associated CO_2-eq emissions could be reduced by up to 40% (NIBE Research, 2019). In order to limit global warming to 1.5°C above pre-industrial levels, CO_2 removal from the atmosphere is likely required in the coming decades in order to achieve the net negative emissions required to lower global temperatures (IPCC, 2018). One of the methods to achieve negative emissions is building with timber, thereby storing carbon for extended periods of time (Heräjärvi, 2019). Although it is not explicitly stated as a method to achieve negative emissions by the IPCC, the potential for carbon storage through building with timber is prevalent in literature. This can have significant effects on atmospheric and terrestrial carbon levels (Figure 1): Churkina et al. (2020) estimate the potential for global carbon storage within new timber dwellings to be between 0.01 and 0.68 Gt per year until 2050. Figure 1 illustrates that, before the industrial revolution, carbon was extracted from the atmosphere by vegetation during millions of years, which enabled a slow accumulation of terrestrial carbon. Since the industrial revolution, the rapid combustion of fossil fuels has increased the atmospheric carbon content, while terrestrial carbon sources have been diminished. To limit global warming in the future, fossil carbon emissions should be reduced drastically, while enabling reforestation and afforestation. Additionally, increasing the biogenic carbon content within the built environment could allow additional storage of carbon for long periods of time (Churkina et al., 2020).

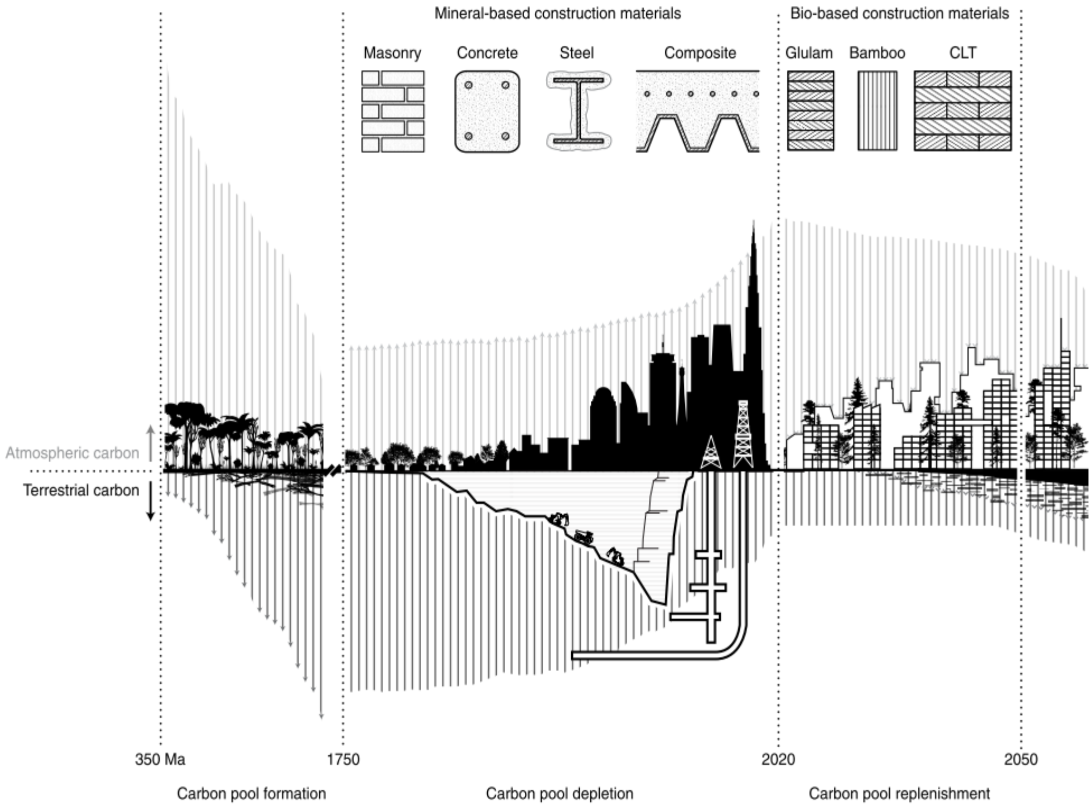
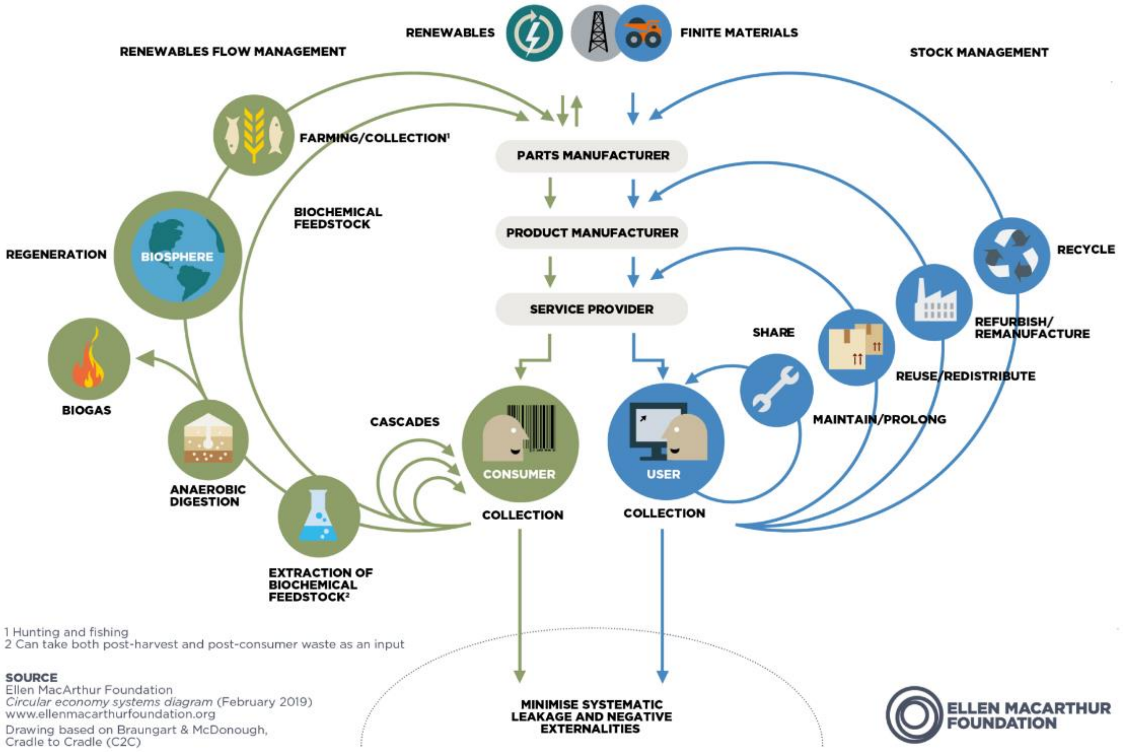


Figure 1. Formation, depletion and potential replenishment of terrestrial carbon concentrations and atmospheric carbon concentrations over time (Churkina et al., 2020).

Within the construction sector, there are discussions about the environmental benefits of storing carbon in timber buildings, as it is often assumed that at the end-of-life phase, the wood is incinerated (Bijlo, 2021). The concrete industry uses this narrative to justify the continued use of cement in residential buildings (Jansen, 2020; Vermeulen, 2020). The largest share of recycling in the Netherlands currently consists of the production of pallet blocks and stackable pallets and the utilized recycling capacity in 2015 was estimated at approximately 260 kilotons (kt). However, the largest share of wood is incinerated with energy recovery at the end-of-life (Van Bruggen & Van der Zwaag, 2017). Currently, this replaces fossil fuels in the energy mix of the Netherlands. Fossil electricity shares were 90% in 2010 and 70% in 2020 (CBS, 2021a). Replacing this fossil share by electricity from biomass can thus be considered favorable. However, as the Dutch government aims to increase the share of renewable electricity to 70% in 2030 (Rijksoverheid, n.d.) and to have a 'CO_2-free electricity system' in 2050 (Rijksoverheid, 2019), the use of biomass for electricity loses its importance and it becomes more favorable to use biomass in material end uses, where carbon can be stored in materials for various lengths of time. These discussions illustrate that there is a need to investigate how the length of carbon storage within timber elements can be increased, to avoid incineration at the end-of-life. Another end-of-life option that would avoid direct CO_2 emissions is landfilling, although from a circularity perspective this is not a high-value end use, and CO_2 will still be gradually emitted as it decomposes (Geng et al., 2017).

In the Netherlands, nearly half (48%) of the nationally used timber and wood-based products is used in the building industry (Oldenburger et al., 2016). In 2019, 1,100 kt of timber were used in the Dutch residential and utility construction sector (NIBE Research, 2019). NIBE Research (2019) states that to allow this entire sector to build using timber frame construction (TFC), an additional 1,900 kt would be necessary. The largest share of wood in the Netherlands is imported, from Europe (about 88%) and outside Europe (NIBE Research, 2019). For the wood sourced from the Netherlands, which was 2.25 million m^3 in 2016 (of which 1.3 million m^3 is directly used for compost and small space heaters), the wood and timber sector has set up an action plan that strives for a doubling of current production (Algemene Vereniging Inlands Hout et al., 2016). Even when this action plan succeeds and European wood production is able to grow by 50% by 2030 (NIBE Research, 2019), it will most likely not meet wood demand, as that may double or even triple by 2030 (Algemene Vereniging Inlands Hout et al., 2016). If the focus is set to decreasing the amount of wood incinerated at the end-of-life and increasing cascading, the need for primary feedstock would be lower than if new buildings would use virgin wood, thus allowing more room for a growing implementation of timber in buildings (NIBE Research, 2019). The reduction of primary feedstock is also one of the goals of the Circular Economy (Figure 2). Primary wood is a part of the biosphere and is thus a part of the biological material flows (left). Once wood is used to manufacture building elements, it enters the cycle of technical material flows (right). Within the technical material flows of the butterfly diagram (Figure 2), reuse is preferred over remanufacturing, which is preferred over recycling, which is preferred over incineration. These different concepts are important to consider in this research and are further elaborated on in section 2.2, in which the theory of cascading is discussed.



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

SOURCE
Ellen MacArthur Foundation
Circular economy systems diagram (February 2019)
www.ellenmacarthurfoundation.org
Drawing based on Braungart & McDonough,
Cradle to Cradle (C2C)

Figure 2. Butterfly diagram visualizing the continuous flows of biological (left) and technical (right) materials (Ellen MacArthur Foundation, 2019).

1.2 Scientific background

To estimate carbon storage in the built environment, several different types of studies have been conducted. Hafner and Rüter (2018) selected 48 case buildings, estimating the carbon storage of Germany. Amiri et al. (2020) estimated the carbon storage potential of new European buildings until 2040 by reviewing 50 case buildings. They stressed that carbon storage capacity is primarily influenced by the quantities of timber elements used in the structural components of buildings (Amiri et al., 2020). Research by Heräjärvi (2019) estimated the volume of carbon stored in new timber buildings annually and discussed their role as a compensator of annual CO_2 emissions for Finland and globally. Churkina et al. (2020) conducted research on global demand for and construction of new buildings, the net storage potential of carbon, and the associated carbon emissions by analyzing four different scenarios (Churkina et al., 2020). Research conducted by Kalt (2018) quantified potential long-term climate benefits resulting from increased use of timber in construction in the Austrian residential building sector, considering savings from material substitution and carbon stock changes.

This research focuses on the Netherlands, as the potential to reduce CO_2 emissions by increasing timber in the built environment is large due to the projected high dwelling demand in the coming decades and the current low share of timber in new residential dwellings. Considering these studies, some issues for the case of carbon storage in the Netherlands arise. Basing an analysis on a single building type brings a risk of considerable underestimation or overestimation of carbon storage (Amiri et al., 2020; Hafner & Rüter, 2018), and basing calculations of timber usage on a single figure for few building types may only provide a rough estimate of total carbon storage (Amiri et al., 2020; Heräjärvi, 2019). Additionally, research conducted on a non-Dutch national, European, or global level will not create a representative picture of carbon storage for the Netherlands.

NIBE Research (2019) conducted research on the technical potential of biobased materials in residential and utility buildings in the Netherlands based on four case studies and included scenarios for 2030 and 2050. They stressed that in the life cycle assessment (LCA) system, carbon storage is not accounted for in timber structures, nor are CO_2 emissions associated with incineration, neglecting the effect of temporarily storing carbon on the Global Warming Potential (GWP) (NIBE Research, 2019). Keijzer et al. (2021) researched the potential of carbon storage in timber buildings in the Netherlands, using a model that does take into account temporary biogenic carbon storage in the LCA methodology for sustainability performance. The environmental product declaration (EPD), based on the European standard EN 15804, and the Product Environmental Footprint (PEF), prescribe that credits associated with temporary carbon storage or delayed emissions should not be considered (Durão et al., 2020). In the newest version of the EN 15804 (A2, 2019), 'climate change – biogenic' has become a separate impact category per January 1st, 2021, which enables the differentiation between mitigation of CO_2 emissions by storing carbon in biobased products such as wood (Keijzer et al., 2021). In the current LCA method, this temporarily stored carbon is not yet counted towards the GWP (Keijzer et al., 2021). Not taking into account the temporary carbon storage negates the effects that this can have on reducing or delaying atmospheric CO_2 emissions (Breton et al., 2018; Head et al., 2021; Keijzer et al., 2021; NIBE Research, 2019). Negative emissions technologies are required to limit global warming to 1.5°C (IPCC, 2018), it is thus important to consider the effect of temporary carbon storage, which is why this is taken into account in this research.

1.3 Knowledge gap

According to Leguijt et al. (2020), there are no scenarios available on the development of the demand for timber in the built environment and associated storage of biogenic carbon in the Netherlands until 2050 or 2100. In several research papers, scenarios were created on biogenic carbon storage within timber in the built environment until 2050 with different spatial scopes, namely Japan (Kayo et al., 2015, 2019), Austria (Kalt, 2018), and with a global scope (Churkina et al., 2020). Other research papers aimed to extrapolate their models further until 2100 with different spatial scopes as well, namely Ontario, Canada (Chen et al., 2008) and Austria (Kalt, 2018). However, these spatial scopes are not representative for biogenic carbon storage in residential buildings in the Netherlands. As especially structural elements can have lifetimes of many decades, this long timeframe until 2100 is very relevant to describe in addition to the shorter timeframe until 2050.

As discussed in section 1.1, there is a need to investigate building strategies that can enhance the length of carbon storage within timber elements. These strategies may be applied in the construction phase, such as design that allows for easy deconstruction, and the demolition phase, such as implementing the cascading principle (Risse, 2019). Research on carbon storage potential at the national, European and global level do not take cascading into account (Amiri et al., 2020; Breton et al., 2018; Geng et al., 2017), although some of these studies do point to its potential benefits (Churkina et al., 2020; Head et al., 2021; Heräjärvi, 2019; Kalt, 2018; Keijzer et al., 2021; NIBE Research, 2019). Studies on effects of cascading on the efficiency of timber utilization do not quantify potential carbon storage (Höglmeier et al., 2017; Odegard et al., 2012; Oldenburger, Reichgelt, et al., 2020; Risse, 2019; Sakaguchi et al., 2017; W/E Adviseurs, 2018), or do not consider carbon storage as a separate indicator (Jarre et al., 2020).

Standardization and prefabrication of building elements drive down costs and allow for efficient construction (Bronsvoort et al., 2020), but it has not been published to what extent standardized and prefabricated elements can in practice be reused. It is speculated that this could be limited, for instance due to the use of glue (Sakaguchi et al., 2017). Thus, the extent to which cascading and possible other methods enhance the length of carbon storage requires further research.

1.4 Research questions

Based on the background information and knowledge gap, the following research question is posed:

"What are technically viable strategies to maximize carbon storage in timber in residential dwellings in the Netherlands until 2050 and 2100?"

To answer this research question, the answers to several sub-questions are required:

1. How many and what types of new dwellings are expected to be built until 2050 and 2100?
2. How much timber could become available from dwellings being demolished until 2050 and 2100?
3. What are current driving forces and limitations behind the strategies of building with timber?
4. What is the technical potential for building with timber?
5. What are ways to change the current strategies of building with timber to maximize the length of use of timber elements?
6. What quantities of virgin and reused wood could be used in new dwellings and how much carbon storage is associated with this?

This research focuses on residential dwellings; other building and construction types, such as utility buildings, civil constructions, and biobased elements such as guard rails and lamp posts are not considered. Additionally, the focus of this research is on structural elements; specific small components such as doors, furniture, fastening bolts, and interior and exterior finishing are not considered.

The types of timber construction systems considered in this research are timber frame construction (TFC) and cross-laminated timber (CLT). TFC is currently the dominant timber construction system in the Netherlands (Strengers et al., 2018; Studio Marco Vermeulen, 2020), and CLT is regarded as a promising construction system (Hildebrandt et al., 2017), with a high rate of growth in the market (Jauk, 2020; Van der Lugt & Harsta, 2020).

Regarding the production of wood for residential dwellings, this research assumes that the wood is sourced from sustainably managed forests. The sourcing of wood in practice is therefore left out of the system boundaries.

Two timeframes are considered: 2020-2050 and 2020-2100. The first timeframe allows for a more accurate representation of what the carbon storage in residential dwellings could be, since population dynamics and technological advancements can be projected more accurately. Structural elements of buildings often remain in buildings for over 50 years (Global Alliance for Buildings and Construction et al., 2019; Head et al., 2021; Höglmeier et al., 2017; Kalt, 2018), so an outlook for the carbon storage potential until 2100 is also required. For this long-term view, assumptions need to be made.

To enable cascading of wood, the demolition process may need to be more precise and rather be a deconstruction process, which may also require more time, different equipment, and more financial resources (Risse et al., 2019). Though these aspects are important to consider when assessing feasibility of increased cascading, for this assessment they are not considered in this research.

Constructing buildings from timber does not automatically result in lower use-phase emissions. These emissions are important to consider in a life cycle approach, but they are not considered within the scope of this research, which limits the focus to the carbon storage potential of timber dwellings.

Based on the research questions and scope, the research framework was set up (Figure 3).

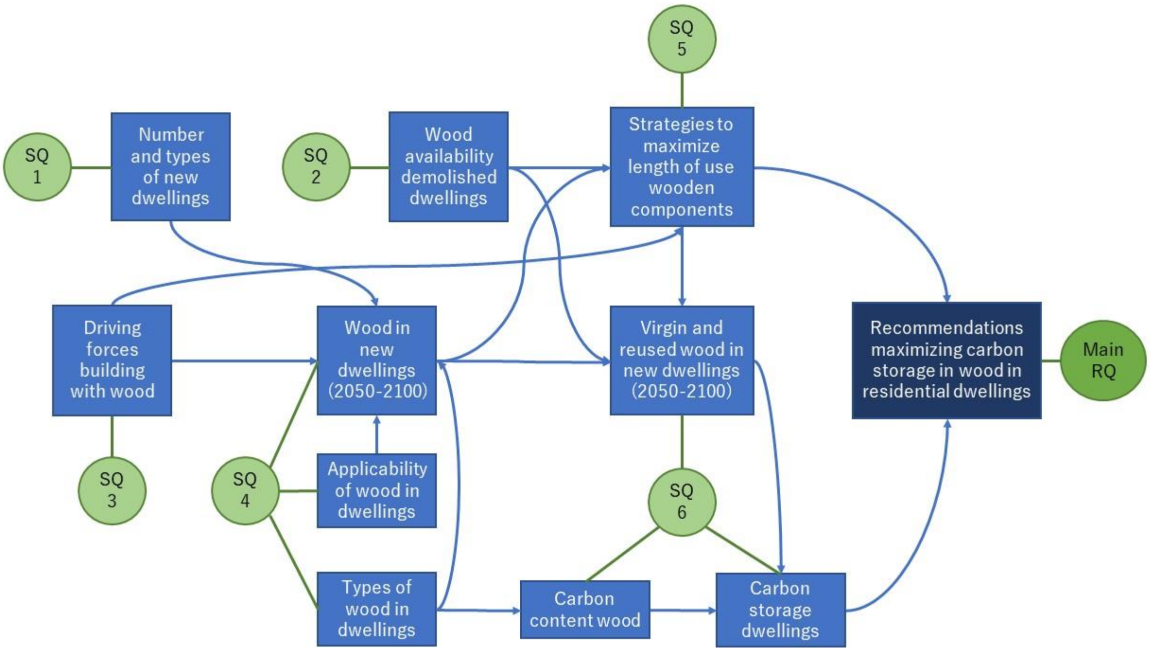


Figure 3. Research framework indicating the contents of the research, connected to the associated sub-questions (SQs) and main research question (RQ).

1.5 Scientific and societal relevance

This research aims to identify ways to enable high-quality reuse of timber from residential dwellings, thereby preventing incineration. It is expected that possible ways to do this are cascading, prefabrication, and standardization (Konijnenberg, 2014). An overview of the potential for carbon storage in structural timber elements in residential buildings in the Netherlands until 2050 and 2100 is provided, taking into account strategies to maximize the length of use of timber components. This is done by combining existing data on residential buildings with scenarios on new dwellings, demolished dwellings, and carbon storage length maximization practices, and a Material Flow Analysis (MFA) of wood and carbon flows, including cascading potential. This enables a comparison of how much virgin wood could be avoided when measures to maximize carbon storage length are implemented.

Increasing the length of carbon storage provides two advantages: incineration will be prevented, thereby contributing to lowered atmospheric CO_2 levels, and by enabling cascaded use of timber the primary feedstock demand is lowered. Increasing the share of timber within residential dwellings will enable the reduction of GHG emissions, contributing to the government's GHG emission reduction targets and ultimately to the mitigation of global warming. By finding the most efficient ways to handle timber, this will enable the provision of housing for the projected increased population while avoiding the issues of low wood availability.

2. Theory

2.1 Biogenic carbon storage in wood

Biogenic carbon originates from biological processes and, unlike fossil carbon, belongs to the fast domain of the global carbon cycle, with faster reservoir turnover rates (IPCC, 2013). For biogenic carbon, the turnover rates are 1 to 100 years for vegetation carbon and 10 to 500 years for soil carbon, whereas for non-biogenic carbon from fossil fuels, turnover rates exceed 10,000 years (IPCC, 2013), effectively resulting in net emissions of non-biogenic carbon to the atmosphere on a human lifetime scale.

Guest et al. (2013) defined four ways of storing biogenic carbon from biomass, which are also visualized in Figure 4: (1) in alive and dead biomass components as a part of the biomass resource pool (BRP) within the biosphere; (2) in products or as landfill waste in the anthroposphere; (3) in biochar added to soils in the biosphere; (4) via carbon capture and storage (CCS) in the geosphere. This research focuses on the second way of storing biogenic carbon from biomass. Biogenic carbon is captured in trees during their growth period where it is locked into the biomass of the trees, after which timber products are made from these trees, allowing for the carbon to remain stored as a product in the anthroposphere (Van der Lugt & Harsta, 2020).

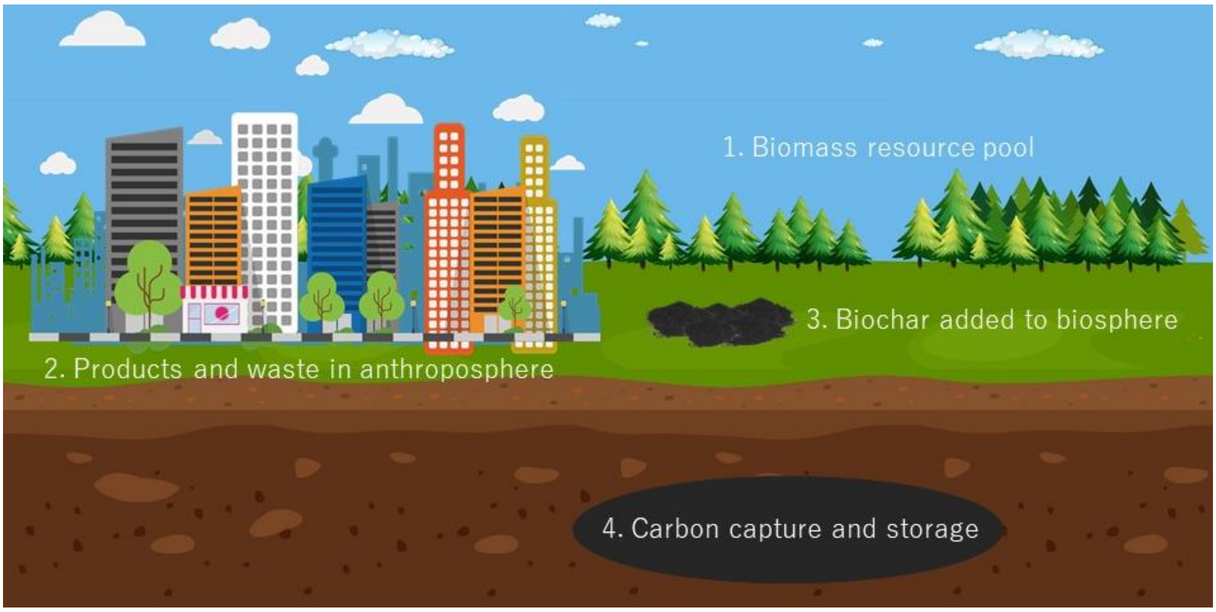


Figure 4. The four ways of storing biogenic carbon from biomass, as defined by Guest et al. (2013).

Storing biogenic carbon in buildings could generate necessary mitigation efforts and GHG removals (Breton et al., 2018). The concept of biogenic carbon storage in wood underlies this research: the atmospheric CO_2 content can be reduced by using the carbon stored biogenically by trees for a prolonged time in (building) materials. Biogenic carbon storage, coupled with sustainable regrowth of biomass resources, can reduce atmospheric CO_2 concentrations and thereby lead to an increase in upwelling terrestrial long-wave radiation leaving the earth system, effectively decreasing the rate of global warming (Guest et al., 2013).

Within the scientific community, there are discussions on whether it would be preferable from an environmental perspective to use timber in buildings, functioning as a biogenic carbon sink, or to leave forests to grow, sequestering more carbon during their growing period (Coomes et al., 2014; Lippke et al., 2011; Lundmark et al., 2014; Stockmans, 2020). However, due to the narrow scope of this thesis, this topic is further elaborated on in section 5.2.3 of the discussion of this research.

2.2 Cascading use of wood

In bioeconomy strategies, the cascading use of biobased products is encouraged as an answer to potential future biomass limitations (Meyer, 2017). According to Jarre et al. (2020), there is no common definition of the cascading concept, although it is recognized that the aim is to increase efficiency of biomass use by increasing reuse, recycling, and lastly incineration with energy recovery. Cascading is a method that enhances the efficiency of resource use by reuse of a unit of a resource for high-value applications, and finally for energy generation (Höglmeier et al., 2017). Cascading thereby saves raw materials and can increase positive effects from the substitution of finite materials by renewable resources (Gustavsson & Sathre, 2011).

As an example, in the case of timber used in buildings, high quality recovered timber in large dimensions and without contamination, such as structural beams, should first be used to produce timber of smaller dimensions. At the end-of-life, these can be chipped and used in a further cascade step as particleboards, and finally be incinerated with energy recovery, rather than being immediately used for energy production after the first product life as a structural beam (Figure 5).

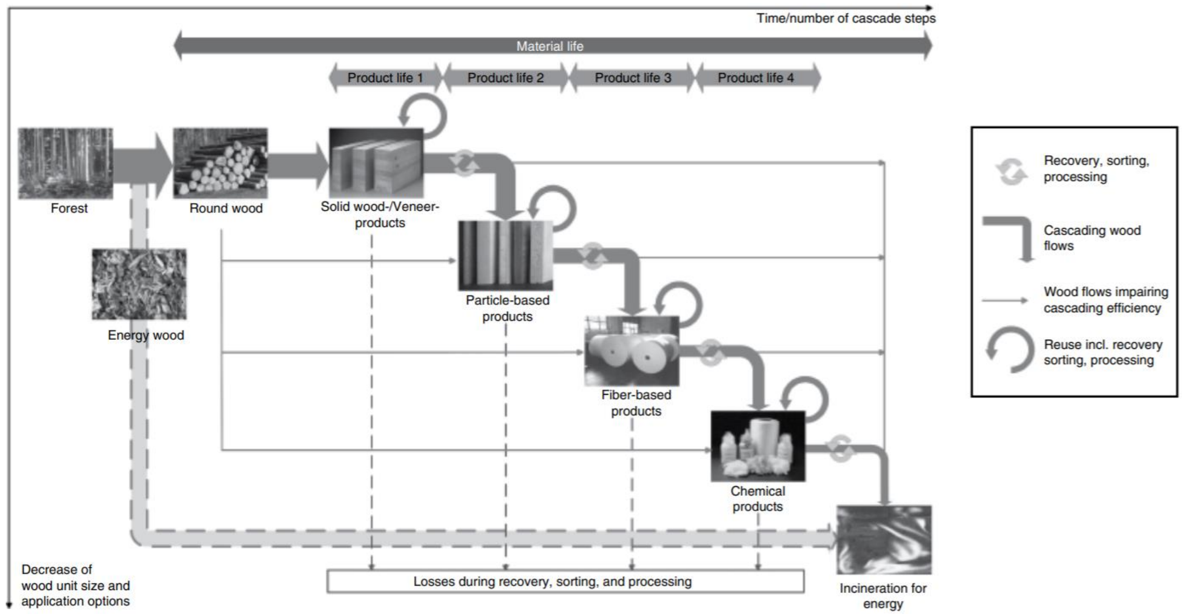


Figure 5. The concept of cascading of wood (Höglmeier et al., 2015).

Cascading often closely follows the 10 R principles: timber elements should be used for high-quality purposes, such as reuse, remanufacturing, or recycling of elements to be used in new buildings, rather than low-quality purposes, such as incineration with energy recovery (Risse, 2019). This is visualized in Table 1 below. When the strategies related to product function (principles 1-3) are not applicable, as is the case in this research, strategies related to product use (principles 4-8) and useful application of materials (principles 9 and 10) come in place (Van der Lugt & Harsta, 2020). Therefore, for this research, R principles 4-10 are relevant and 1-3 are outside the scope.

Table 1. 10 R principles, with principle 1 being the most favorable and principle 10 being the least favorable (Bag et al., 2021).

1	Refuse	Making a product redundant by discarding its function or by offering the same function with a completely dissimilar product.
2	Rethink	Making product use more intensive.
3	Reduce	Use of lesser natural resources in manufacturing.
4	Reuse	Use of discarded product by another user which is still in working condition and the original functionalities are present.
5	Repair	Repairing and maintenance of defective product so that it can be used with original function.
6	Refurbish	Restoring an old product to bring it up to date.
7	Remanufacture	Use parts of discarded product in a new product with the same function.
8	Repurpose	Use discarded product or its parts in a new product with a different function.
9	Recycle	Apply recycling for processing materials to obtain the same or lower quality of product.
10	Recover	Use incineration of material for energy recovery.

The concept of cascading is often compared to the value pyramid, which was originally based on economic value of biomass end uses (Verburg, 2007). This pyramid is adapted to the scope of this thesis (Figure 6) where large building elements have the highest value and length of carbon storage, thus cascading would retain these aspects.

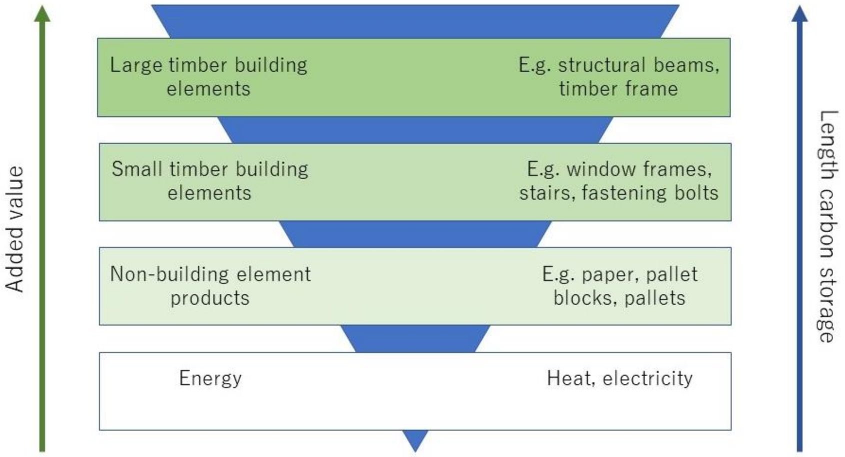


Figure 6: Value pyramid for timber presenting product categories on the left side and product examples on the right side. The highest valued end use is large building elements, which also have the highest carbon storage length, thus resulting in an upside-down pyramid. Adapted from (Verburg, 2007).

The concept of cascading underlies this research: as it is expected that there will be a higher demand for timber for building elements than can be provided (Algemene Vereniging Inlands Hout et al., 2016), it will be necessary to implement cascading as a means to both increase their lifetime and length of carbon storage and reduce the need for virgin feedstock.

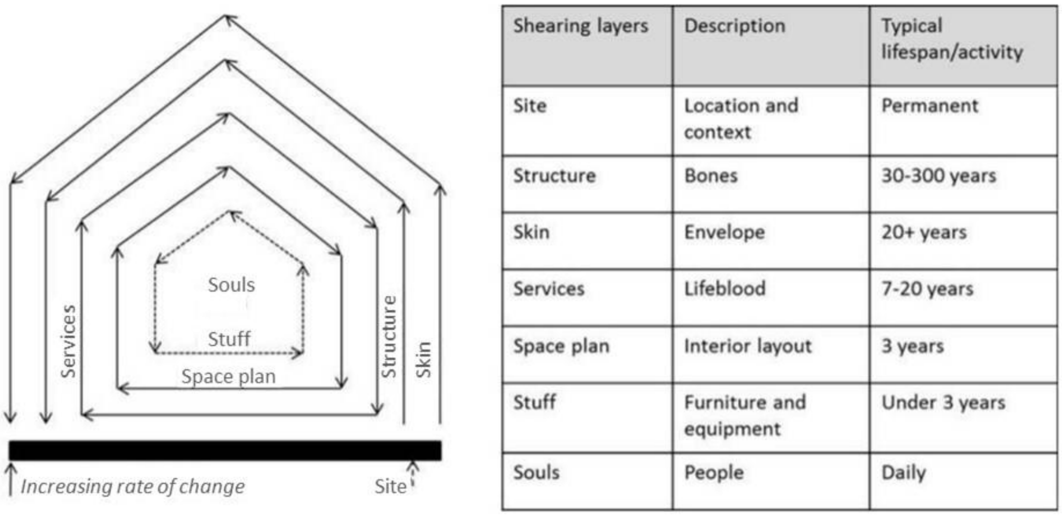
2.3 Principles of circular design

Strongly linked to the R principles discussed in section 2.2, several principles of circular design (PCD) have been defined (Ellen MacArthur Foundation, n.d.; Schut et al., 2015b):

1. **Low-material design**: the use of less materials leads to the use of less raw materials and also causes less waste and environmental impacts. This is most effectively done by limiting on-site waste by implementing more industrial construction. Additionally, the waste flows created on-site or at a

sorting facility should be accurately sorted, allowing high-quality reuse of materials (Schut et al., 2015b).

2. **Modular design**: different parts of a structure likely have different technological or economic lifetimes. This is most comprehensively depicted in the Shearing layers concept developed by Brand (1994) (Figure 7). In modular design, the different parts of a building should all have an optimum lifetime, investigating possibilities to efficiently replace the different parts as modules.



Shearing layers	Description	Typical lifespan/activity
Site	Location and context	Permanent
Structure	Bones	30-300 years
Skin	Envelope	20+ years
Services	Lifeblood	7-20 years
Space plan	Interior layout	3 years
Stuff	Furniture and equipment	Under 3 years
Souls	People	Daily

Figure 7. Shearing layers of change (Brand, 1994).

3. **Adaptive design**: this concept assumes that the foundation and structure of buildings could fulfil different function during their lifetimes. Adaptive design of buildings allows for adaptation to the requirements and needs of the time (Schut et al., 2015b).
4. **Design for deconstruction**: when different building elements are connected, currently the possibility of deconstructing these elements for reuse is hardly ever taken into account, which often makes it impossible to detach building elements and leave them undamaged and suitable for reuse (Schut et al., 2015b).
5. **Design for recycling**: design takes accountability for the recyclability of materials. This concept is often a part of the so-called Ecodesign and Cradle-to-Cradle concepts, which underline the importance of not only the recyclability of materials, but also the ability to separate different materials from each other at the end-of-life phase (McDonough & Braungart, 2002; Schut et al., 2015b).
6. **Recycle for design**: a new concept which aims for demolition and recycling companies to align their processes more to the demand of producers, so circular design can be increasingly implemented, which requires technological improvements to enable the required quality of materials (Schut et al., 2015b).
7. **Materials passport**: the availability of information about the composition of elements, products, or materials is crucial for the ability to reuse these elements, products, or materials after the end-of-life of the design they were a part of. Current recycling technology is based on investigative and detective methods, but for products that are designed at present, materials passports are being developed (Madaster, n.d.; Schut et al., 2015b). This is still in its infancy, but materials passports on the basis of digital tools such as the Building Information Model (BIM) 3D design tool show promising results (Emanuel & Van den Bosch, 2020). Consequently, the information documented in this materials passport should be stored and remain accessible until the end-of-life of the product it belongs to (Schut et al., 2015b).

2.4 Scenario analysis

Scenario analysis is often used to address challenges that are characterized by uncertainty and complexity, as scenarios can help explore different future pathways and can therefore be a useful tool in supporting policies and guiding action towards a more sustainable future (Fauré et al., 2017). Scenarios are often used in research where there may be considerable uncertainties regarding many different factors involved, with the objective to explore possible uncertainty ranges and provide insight into the implications that different long-term developments may have (Kalt, 2018). Scenarios can be described as coherent and plausible stories about the possible future pathways of combined human and environmental systems (Swart et al., 2004). They generally include a definition of system boundaries, the characterization of current conditions and processes that drive change, an identification of uncertainties and assumptions on how these are resolved, and images of the future (Swart et al., 2004).

Börjeson et al. (2006) distinguish three main categories of scenarios: predictive, explorative, and normative scenarios, which can be further divided into sub-categories. These sub-categories and the question they aim to answer are presented below in Table 2.

Table 2. Main categories of scenarios, sub-categories, and the questions they aim to answer (Börjeson et al., 2006).

Main category	Question to be answered	Sub-category	Question to be answered
Predictive	What will happen?	Forecasts	What will happen, on the condition that the likely development unfolds?
		What-if	What will happen, on the condition of some specified events?
Explorative	What can happen?	External	What can happen to the development of external factors?
		Strategic	What can happen if we act in a certain way?
Normative	How can a target be reached?	Preserving	How can the target be reached, by adjustments to the current situation?
		Transforming	How can the target be reached, when the prevailing structure blocks necessary changes?

It is possible to choose only one of the scenario types to explore within a study, but it is also common for research to implement a combination of different scenario types (Börjeson et al., 2006; Höjer et al., 2008). Oftentimes when studies perform scenario analysis, there is a form of reference or business-as-usual scenario in order to compare the impact of altering the quantitative parameters and qualitative factors influencing the system with the system as it will most likely develop with its current values for these parameters and factors (Börjeson et al., 2006; Höjer et al., 2008; Reilly & Willenbockel, 2010; Singh & Strømman, 2013).

Scenario analysis can be performed based on quantitative data, qualitative data, or a combination of both. Quantitative tools based on databases are often suitable for assessing scenarios within a shorter time span, whereas qualitative assessment methods might be more suitable for long-term transformative scenarios (Fauré et al., 2017). As quantitative analysis often relies on models using mathematical algorithms and relationships to represent human and environmental systems, this is often used for predictive analysis, which is appropriate for simulating well-understood systems over sufficiently short times (Swart et al., 2004). However, as complexity and/or the studied time span increases, the accuracy of prediction decreases. This limitation means that quantitative analysis of complex systems or long time spans could benefit from being complemented by qualitative scenario exploration. This can better capture other factors influencing the future, such as systemic shifts and unpredictable unknows or non-quantifiable issues such as (societal) values, cultural shifts, and institutional features (Fauré et al., 2017; Swart et al., 2004).

2.5 Material Flow Analysis

Material Flow Analysis (MFA) refers to the accounting in physical units of different life cycle stages of materials, for instance extraction or harvest, production processes, (chemical) transformation, manufacturing, consumption, recycling, and disposal (Bringezu & Moriguchi, 2002). The main advantage of an MFA is that it obeys the law of conservation of matter and thus forms a natural science basis, which can be checked for consistency and probability (Baccini & Brunner, 2012). The most important engineering metals (iron, steel, copper, lead, zinc, aluminum, silver, and chromium) have been studied through MFA most often, so these material cycles are the most well-understood (E. Müller et al., 2014).

MFA systems can be described in different basic elements, namely processes, stocks, flows, and the system boundaries (Baccini & Brunner, 2012; E. Müller et al., 2014). A process is defined as the transformation, transport, or stock change of the studied material, and fulfills the mass balance principle described in Equation 1 (Baccini & Brunner, 2012):

$$S_t = \sum_{t_0}^{t} (input_t - output_t) + S_{t_0}$$

Equation 1

where: S_t = stock after time step t; t_0 = time initial time step; t = current time step; S_{t0} = existing stock at initial time step (Baccini & Brunner, 2012). Thus within a process, a stock of materials can exist. In most models only the use phase process contains a stock and the other processes transform materials without accumulating a stock (E. Müller et al., 2014). In Equation 1, the input and output are the material flows into and out of the process. A material flow is defined as the amount of material mass that enters or exits a process for a given unit of time (Baccini & Brunner, 2012). The system boundaries of the studied system determine the spatial and temporal extent of the studied system (Baccini & Brunner, 2012; E. Müller et al., 2014). This determines which of the physical processes are included in the studied system and which of the remaining processes for the technosphere and ecosphere are excluded (Risse, 2019). The different elements of MFA systems are visualized below in Figure 8.

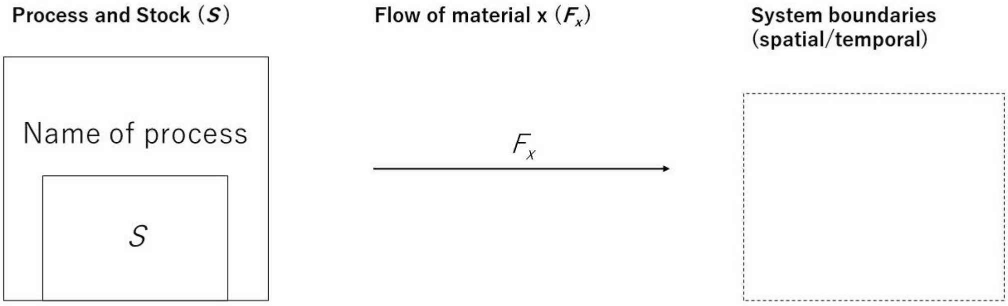


Figure 8. System elements of an MFA: process, stock, flow, and system boundaries. Adapted from (Baccini & Brunner, 2012).

At the foundation of an MFA, there are three basic principles: an MFA can be static or dynamic; top-down or bottom-up; prospective or retrospective (E. Müller et al., 2014). When an MFA is static, it describes a 'snapshot' in time of the studied system, and when an MFA is dynamic, it describes the behavior of the studied system over a period of time (W. Q. Chen & Graedel, 2012). Two methods can be used to measure the material stock of a process: a top-down approach and a bottom-up approach. In the top-down approach, the stock is derived from the net flow, which is the difference between inflows and outflows. In the bottom-up approach, the stock is directly estimated by summing the material present within the system boundaries at a certain time (Gerst & Graedel, 2008). An MFA can be either prospective, in which it looks into the future using data extrapolation, or retrospective, in which it analyzes past stocks and flows based on historical data, or a combination of both (E. Müller et al., 2014).

Müller et al. (2014) simplified the standardized ‘overview, design concepts, details’ (ODD) protocol, originally developed for individual-based and agent-based models, to be applicable to the less complex MFA. The elements of this protocol provide guidelines for which information should be provided in order for an MFA to be executed transparently, and are presented below in Table 3.

Table 3. Elements of the ODD protocol for MFA (Müller et al., 2014).

Overview	Purpose	What is the purpose and general framework of the model?
	Materials (goods, substances)	What materials (goods/substances) are included? Are materials further divided into material categories (and subcategories)?
	Processes	What processes are included? Do they transform, transport, or store materials? Are processes further divided into process categories (and subcategories)?
	Spatial and temporal scale and extent	What is the spatial and temporal scale and extent of the study?
	System overview	What is the structure of the system regarding processes, stocks, and flows?
Design concepts	Basic principles	Static or dynamic, top–down or bottom–up, retrospective or prospective?
	Static or dynamic modeling approaches	How are stocks and flows modeled? What are the extrapolation methods for exogenous variables?
	Dissipation	How does the model account for dissipation?
	Spatial dimension	How does the model account for the spatial distribution of stocks and flows?
	Uncertainty	How does the model account for data and model uncertainty?
Details	Initial condition	How is the initial state (e.g., the initial stocks and flows) of the model set?
	Model input data	What data is used as input to the model?
	Model output data	What data is generated as model output?
	Evaluation	What methods (e.g., for data aggregation and visualization) are used to evaluate the results?
	Detailed model description	What, in detail, is the formal description (e.g., equations) of the system and what are the algorithms (e.g., solution procedures) used for the calculations?
		What are exogenous and endogenous model variables? What are the model parameters, their dimensions, and reference values?

2.6 Case study description

This section gives a case study description of the topic of this research, namely building with timber in the Netherlands taking into account the cascading potential. The different paragraphs discuss relevant literature on the different concepts that are important for providing background knowledge on the case study.

2.6.1 Standardization of building elements

In response to the increased need for efficiency in the timber industry in the 20th century, several industrial wood-based panels were developed in standard sizes, typically 1220 by 2440 mm (Van der Lugt & Harsta, 2020). Using a standardized approach for the construction of building elements has several benefits. Through standardization, the construction process can be better controlled, which ensures a calculated concept resulting in a reduction in failure costs, smaller units can be built without affecting the cost price, and construction time can be reduced (P. Klok, 2013). These benefits have resulted in a large uptake of different timber panel sizes in the furniture and construction industries (Van der Lugt & Harsta, 2020).

There are many different standard sizes for timber used in construction which can also be divided into different strength classes, depending on the required structural properties of the design of the building that the timber is used for. Some common standard head sizes of timber used in timber frame construction (TFC) (Friesland Prefab, n.d.) and cross-laminated timber (CLT) (De Groot Vroomshoop Gelijmde Houtconstructies B.V., 2017), are presented below (Table 4).

Table 4. Common standard head sizes for timber elements for timber frame construction (Friesland Prefab, n.d.) and cross-laminated timber (De Groot Vroomshoop Gelijmde Houtconstructies B.V., 2017) in the Netherlands.

Common head sizes timber frame construction, Thickness (mm) x width (mm)			**Common head sizes cross-laminated timber, Number of layers: thickness (mm) x width (cm)**			
38 x 89	36 x 270	59 x 156	3	60 x 245; 275; 295	5*	160 x 245; 275; 295
38 x 120	38 x 285	59 x 171	3	80 x 245; 275; 295	7	180 x 245; 275; 295
38 x 140	40 x 146	57 x 194	3	90 x 245; 275; 295	7	200 x 245; 275; 295
38 x 170	40 x 171	69 x 194	3	100 x 245; 275; 295	7	240 x 245; 275; 295
38 x 184	46 x 146	69 x 219	3	120 x 245; 275; 295	7*	220 x 245; 275; 295
36 x 196	46 x 171	69 x 244	5	100 x 245; 275; 295	7*	240 x 245; 275; 295
36 x 220	44 x 194	69 x 269	5	120 x 245; 275; 295	7*	260 x 245; 275; 295
38 x 235	44 x 219	71 x 146	5	140 x 245; 275; 295	7*	280 x 245; 275; 295
36 x 245	59 x 146	71 x 171	5	160 x 245; 275; 295	8**	300 x 245; 275; 295
			5	180 x 245; 275; 295	8**	320 x 245; 275; 295
			5	200 x 245; 275; 295		

* Cover layers consist of 2 length-wise layers

** Cover layers and inner layer consist of 2 length-wise layers

When constructing a building using TFC or CLT, the building elements most likely have standardized sizes (Centrum Hout, 2005; De Groot Vroomshoop Gelijmde Houtconstructies B.V., 2017; Friesland Prefab, n.d.), as this decreases prices (Bronsvoort et al., 2020). When building elements become available from the deconstruction of buildings, they may need to be downsized due to damage to the outer layer or on the sides. Therefore, the concept of standardized elements needs to be taken into account in this research, as elements may need to be remanufactured to the next smaller standard-sized element.

2.6.2 Prefabrication of building elements

Almost all contemporary buildings integrate prefabricated components to a certain degree, from for instance a single prefabricated window system to more intricate prefabricated building modules (Boafo et al., 2016). Several different terms are used in literature for prefabrication of building elements, namely industrialized building systems, off-site construction, off-site fabrication, prebuilt construction, and modern methods of construction (MMC) (Boafo et al., 2016; Švajlenka et al., 2017). The term modular construction is also often used interchangeably with prefab construction (Bertram et al., 2019), though modular construction in this research has a different definition: the construction of a building system that is designed for easy disassembly. MMC can be divided into on-site MMC, which consist of traditional materials combined with innovative manufacturing processes and are realized and assembled directly on site, and off-site MMC, which consist of prefab panels or prefab modules that are produced in a factory, after which the finished elements are transported to the building site and assembled there (Švajlenka et al., 2017). The latter category of MMC is relevant to this section, as the definition for prefabricated building elements in this research is: building elements that are manufactured in a specialized (off-site) facility, in which various materials or building systems are joined to form an element of a larger final assembly, which are transported to the building site, where they are assembled (on-site). The terminology followed in this research is prefabricated (prefab) building elements.

Prefab construction methods cover a range of different approaches and systems (Bertram et al., 2019; Boafo et al., 2016). The degree of complexity of the elements being brought together varies for these different approaches (Figure 9). The simplest methods are single elements clipped together using standard connections.

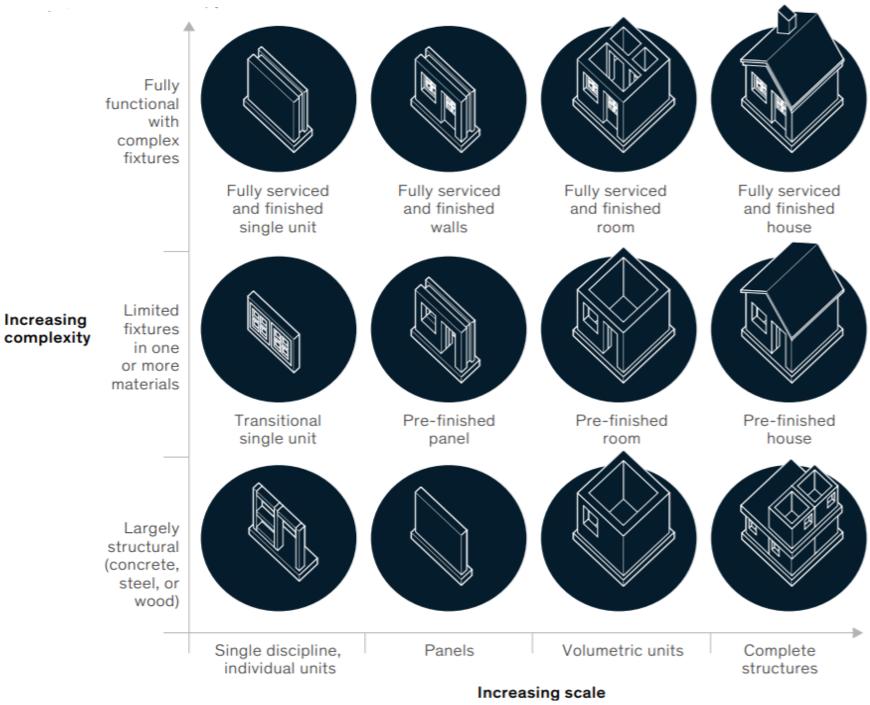


Figure 9. Complexity and scale of prefab construction approaches and systems (Bertram et al., 2019).

Prefabrication of timber building elements has the benefit of improved quality control, enabling a shorter building time, minimal nuisance in the form of dust and noise from the building site, reduced construction waste, reduced on-site labor, and low overall construction costs. Therefore, these industrially produced elements have become the standard building system when using timber in construction (Bronsvoort et al., 2020; Jaillon & Poon, 2009). By using prefab building elements, construction quality and safety can be increased, while construction times, overall costs, material waste, and the impact on the environment can be reduced (Boafo et al., 2016).

Prefab building elements can be designed in a modular way (Bronsvoort et al., 2020; Hough, 2019), which may facilitate deconstruction and reuse at the end-of-life. This concept is important as it is important to know to what extent residential buildings are built using prefab elements and to what extent reuse of prefab elements is possible. Building technologies have improved over time as the concepts of modularization, prefabrication, and recyclability were implemented, but the focus was still mainly on the assembly process of construction: structures were assembled and then covered and glued by other materials, making reuse challenging and making them unsuitable for disassembly at the end-of-life (Ferreira Silva et al., 2020). Nevertheless, a case study of prefab modular buildings using conventional building materials, including steel, concrete, and timber elements in China (Boafo et al., 2016) revealed that practically all building materials were reused, except for a share of gypsum and copper wire.

2.6.3 Timber frame construction

A high-quality construction method for buildings up to four floors is timber frame construction (TFC) (Strengers et al., 2018). This traditional light-weight system featuring timber joists and studs is the most widely used timber construction system worldwide (Van der Lugt & Harsta, 2020). In the Netherlands, TFC is a proven construction method, with an existing and well-functioning infrastructure with available knowledge and a methodology that complies with the Building Decree (*Bouwbesluit*) (Studio Marco Vermeulen, 2020). TFC is one of the most important construction methods for the structural elements of residential buildings in the Netherlands: between 1950 and 2020, hundreds of thousands of buildings were constructed using TFC (Studio Marco Vermeulen, 2020). In the Netherlands, the main wood type used for TFC is coniferous wood (Oldenburger, Reichgelt, et al., 2020).

In TFC, the frame of a building is made of timber, construction boards such as oriented strand board (OSB), medium-density fiberboard (MDF), or plywood, are attached to the skeleton and insulation material is placed in between (Lidelöw, 2016). There are generally two types of TFC systems: balloon framing and platform framing. In balloon framing, studs run across the entire height from bottom to top plate, forming a complex and stable system, and in platform framing, studs run from floor to floor which facilitates quicker construction but is somewhat less stable (Van der Lugt & Harsta, 2020). An example of the possible components of a single-floor TFC building is presented below (Figure 10).

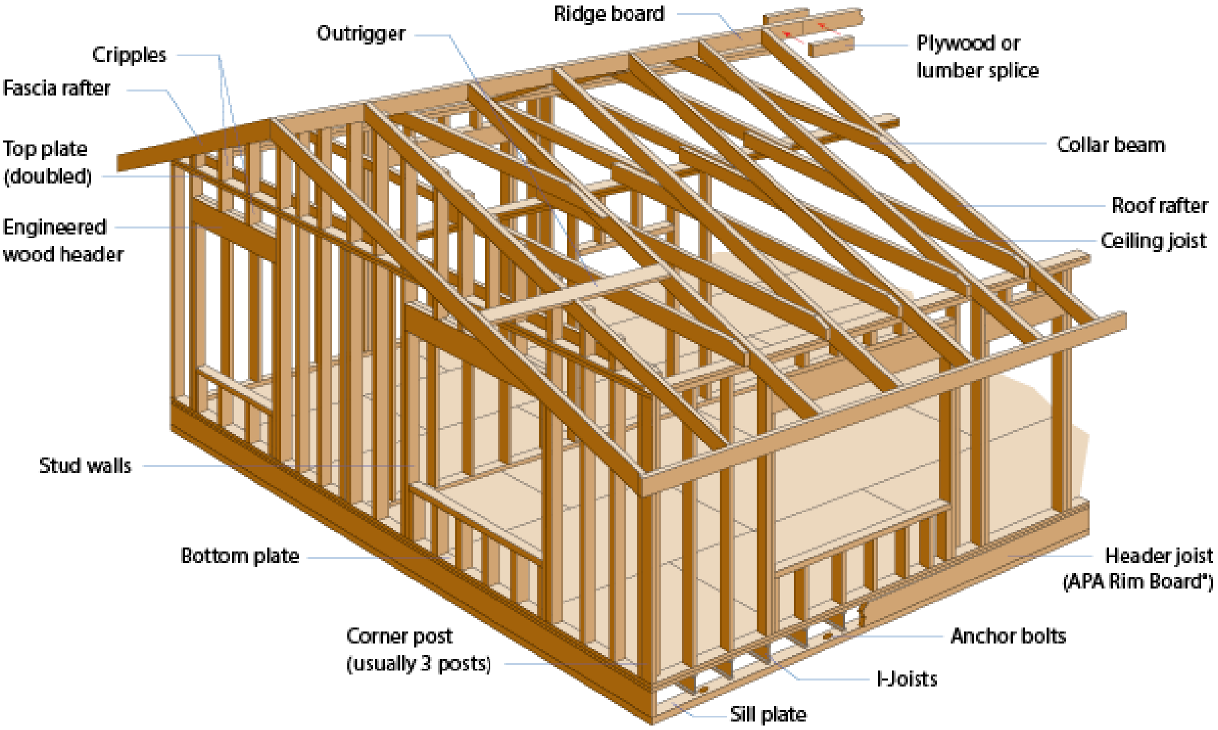


Figure 10. Example of the possible components of the frame of a building using timber frame construction (The Engineered Wood Association, n.d.).

TFC lends itself well to prefabrication, which, combined with the light weight and possibilities of integrating services within the panels (Van der Lugt & Harsta, 2020), also makes it very suitable for modular design, which benefits disassembly and reuse (Bronsvoort et al., 2020). Prefabricated TFC closed panel systems are particularly effective in passive house designs, i.e. houses that have low use-phase energy consumption as the required airtightness and low U-values (which determine the extent to which heat is lost) are easier to achieve by building off-site with timber (Hough, 2019). However, because of the light weight, the acoustic and structural performances and fire safety can be challenging, especially for houses with multiple floors and for apartment buildings (Van der Lugt & Harsta, 2020).

When constructing above four stories, TFC loses its advantages over mass building systems (Strengers et al., 2018). In building with higher heights, the TFC system should be replaced or complemented with mass timber panels, to ensure strength and stiffness: combining cross-laminated timber (CLT) and TFC works well, with timber framing being particularly suitable for facades due to the insulation possibilities and material efficiency (Van der Lugt & Harsta, 2020).

2.6.4 Mass timber construction

Mass timber refers to large structural components comprising of laminated smaller boards or lamella, such as cross-laminated timber (CLT, also referred to as X-lam) panels or glue-laminated (glulam) beams (Churkina et al., 2020). The performance of mass timber buildings is generally more consistent in terms of, among others, structure, fire safety, and acoustics than buildings using traditional TFC, with the potential to substitute steel and concrete for structural applications (Van der Lugt & Harsta, 2020).

Glulam was the first engineered wood product, with glulam beams consisting of at least two dried, often finger-jointed softwood boards glued together longitudinally (Johansson, 2016). Glulam beams commonly use the tree species spruce, pine, fir, and larch, and are strength-graded according to the EN 14080 standard, making it more consistent in strength than solid timber (Van der Lugt & Harsta, 2020). CLT has gained a significant market share since the introduction in the 1990s (Van der Lugt & Harsta, 2020). Therefore, this research focuses on the use of CLT in buildings using mass timber. The European production of CLT was estimated at just over 1 million m^3 in 2020, with Austria, Germany, and Switzerland as the largest producers (Jauk, 2020). Due to the growing popularity, the combined production of these countries and the newcomers the Czech Republic and Italy increased by 15% in 2020 compared to 2019. It is expected that there could be a possible annual production in Europe of around 2 million m^3 in 2022, which is twice the volume recorded in 2020 (Jauk, 2020).

CLT is a relatively new construction material, with the development in the 1990s motivated by the need for the sawmill industry to create a higher value use for side boards (Brandner et al., 2016). CLT panels consist of solid timber panels made up of three or more layers of cross-glued timber boards, which may also consist of combined finger-jointed boards (Waugh Thistleton Architects, 2018) (Figure 11), and gives the material great strength, stability, and uniform performance and makes it suitable for medium- and high-rise buildings (Bronsvoort et al., 2020; Hough, 2019). The size of CLT panels depends on the manufacturer, but generally they are between 60 and 500 mm thick, 3000 mm wide and with a length of up to 24 m (Johansson, 2016). CLT has similar structural properties to reinforced concrete, but is five times lighter and is used for the structural elements of buildings (Studio Marco Vermeulen, 2020). CLT panels are very suitable for prefabrication, as holes for doors and windows and grooves for electrical fittings are easy to prepare beforehand (Johansson, 2016). There are also CLT boards manufactured using nails, screws, or dowels instead of adhesives, but the properties of these types of panels vary more compared to glued panels (Johansson, 2016).

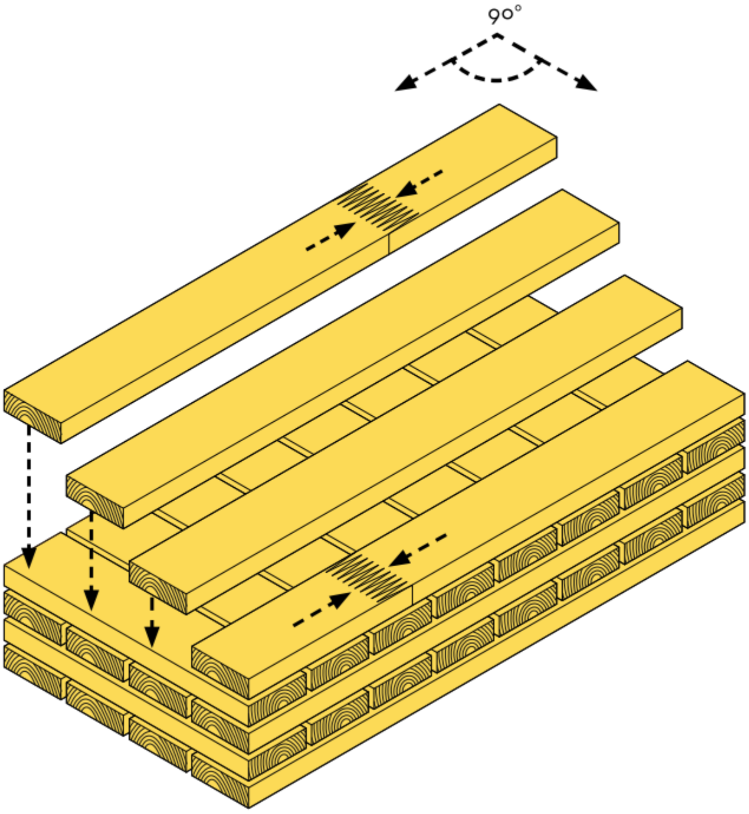


Figure 11. Cross-laminated timber (CLT) element, displaying solid and finger-jointed wood boards and the cross-glued direction of the boards (Waugh Thistleton Architects, 2018).

2.6.5 Overview of the system

Taking into account the previous paragraphs of section 2.6, a simplified overview of the system relevant to this research is presented below (Figure 12). Figure 12 shows the different sections that will be taken into account within the system boundaries. The different levels of cascading are present in the form of timber reprocessing for reuse, timber reprocessing for lower-value use, such as for particleboard, and incineration with energy recovery. Figure 12 also visualizes that there is currently no clear distinction for the quality of wood that is either reprocessed for lower-value use or incinerated with energy recovery.

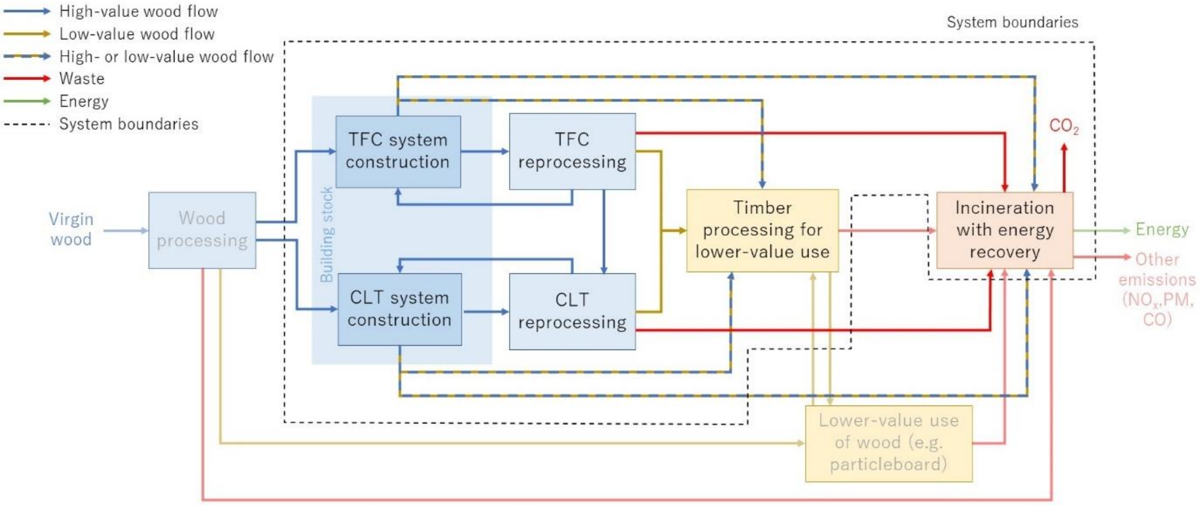


Figure 12. Overview of the simplified system of building with wood in the Netherlands, taking into account the different pathways of cascading.

3. Methods

3.1 Analytical framework

The analytical framework (Figure 13) presents an overview of the methods for each sub-question, and what the obtained data for each sub-question is. Several sub-questions require data or information that have resulted from a previous sub-question, which is indicated with the blue arrows flowing between sub-questions.

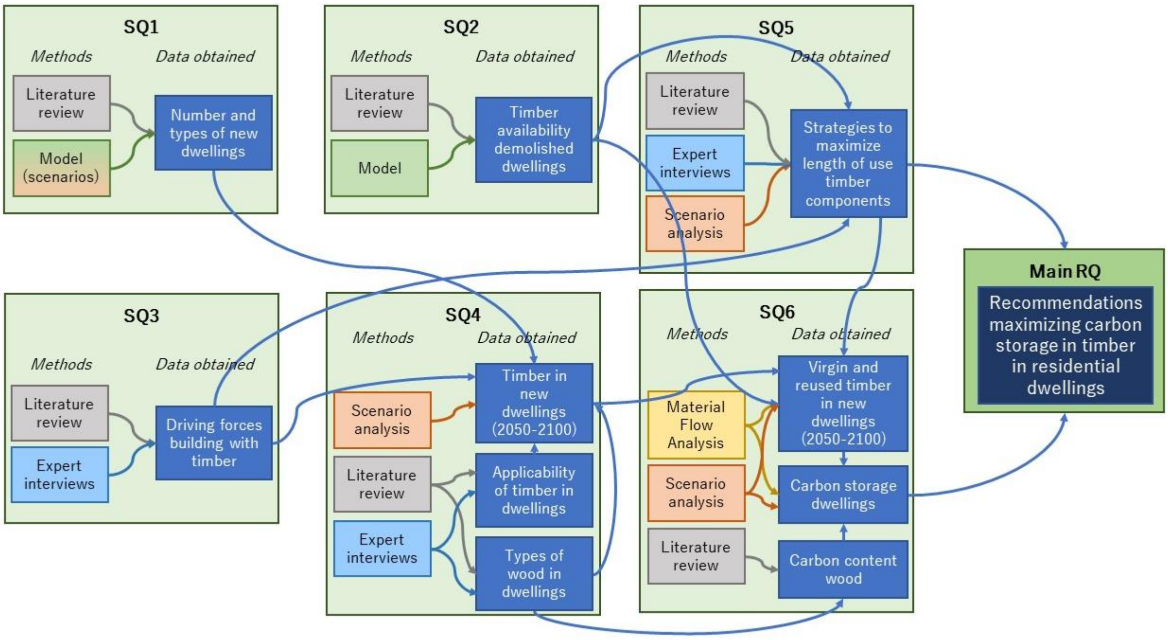


Figure 13. Analytical framework, indicating the methods and obtained data for each sub-question (SQ) and the flows of information using arrows.

3.2 Sub-question 1: Number and types of new dwellings

The goal of sub-question 1 was to determine the number and types of new dwellings that are projected to be constructed until 2050 and 2100. These data were necessary in order to determine the applicability of timber in new dwellings, as the number of dwellings influences the total number of dwellings that could be constructed using timber and the types of dwellings determine the quantities of timber that could be used in each dwelling type. A combination of literature review, data collection, scenario analysis, and definition of assumptions were used to answer this sub-question. The data were collected through literature review and from the Vesta MAIS 5.0 model.

3.2.1 2020-2050: Literature review and data from Vesta MAIS 5.0 model

For retrieving scientific articles and reports, the search engines Google Scholar, SCOPUS and WorldCat were used. Additionally, gray literature, such as government reports or data published by governmental organizations like the Dutch Environmental Planning Bureau (*Planbureau voor de Leefomgeving*, PBL), was consulted. To retrieve this literature, the search engine Google was used.

To determine the demand for new dwellings until 2050 and 2100 and what types of dwellings these would consist of, an existing model is used: the open source Vesta MAIS 5.0 model, developed by the PBL (Van den Wijngaart, 2020), from now on referred to as the Vesta model. The Vesta model is a spatial energy model of the built environment (including residential buildings, office buildings, stores, and hospitals) and greenhouses. The goal of the Vesta model is exploring possibilities to reduce the energy use and CO_2 emissions of the built environment until 2050 and it has been in continous development since 2010 (Schepers et al., 2019).

The Vesta model itself contains data from the Ruimtescanner model (PBL, n.d.) on projected new buildings until 2050, divided into two Future Exploration of Prosperity and Living Environment (*Toekomstverkenning Welvaart en Leefomgeving, WLO*) scenarios: the WLO High (*WLO_hoog_concentratie*) and Low (*WLO_laag_spreiding*) scenarios. These two scenarios are based on assumptions, which are described below (Table 5).

Table 5. Assumptions regarding High and Low WLO scenarios (Van Gemeren et al., 2016).

Topic	**Scenario High**	**Scenario Low**
National inhabitants	2030: 18.0 million 2050: 19.2 million	2030: 17.1 million 2050: 16.4 million
National jobs of at least 12 hours per week	2030: 8.2 million 2050: 8.6 million	2030: 7.6 million 2050: 7.3 million
National sectoral structure	Strong growth of business services in addition to quaternary services (healthcare). Only industry and agriculture are shrinking.	Strong growth in quaternary services (care). Shrinkage in all other sectors.
Births and deaths	Increase in fertility in urban regions and the Randstad compared to elsewhere. Regional differences in life expectancy in line with previous years.	Regional differences in life expectancy in line with previous years.
Foreign migration	Regional differences in line with previous years.	Increase in (return) migration from urban regions and the Randstad compared to elsewhere.
Domestic migration	Migration patterns of recent years persist.	Migration to urban regions and the Randstad is slowing down.
Housing plans and possibilities	Large part of the housing plans up to 2025 have been realized. After 2025, housing construction where there is demand within the housing possibilities. In addition, spatial planning restrictions are slightly less restrictive than in the other scenarios. Building in undeveloped areas with slightly higher housing densities than now.	Smaller part of housing plans realized until 2025. Little new construction after 2025, thus the existing stock becomes more decisive. Current spatial planning restrictions are tightly enforced. Building in current densities.
Within existing built environment	Transformation relatively high.	Low transformation.

These WLO Low and High scenarios were used to determine the possible development of the number of new dwellings in the future, and these were used as a basis for scenarios Low pop. (population) and High pop. in this research. Additionally, scenario Middle pop. was identified. To identify scenario Middle pop., the average between the number of new dwellings for each dwelling type in scenarios Low pop. and High pop. was assumed. These scenarios are considered predictive what-if scenarios: neither of these scenarios is necessarily considered the more likely scenario, hence they reflect what will happen provided that the assumptions or developments listed in Table 5 occur (Börjeson et al., 2006).

Using ArcMap (version 10.8.1), the data provided by the Vesta model were converted to a Microsoft Excel file containing all the data on new dwellings for the two WLO scenarios for the periods 2020-2030, 2030-2040, and 2040-2050 for the different dwelling types, following the steps in Figure 14.

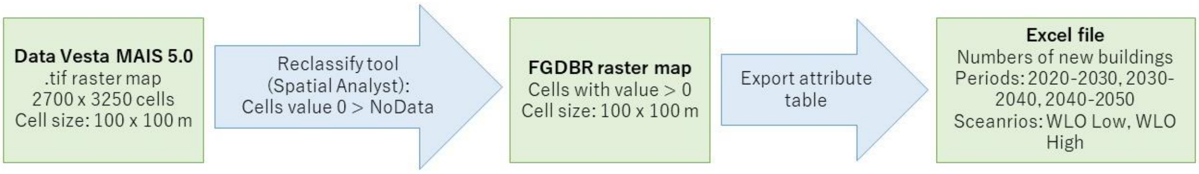


Figure 14. Methods to extract data from Vesta MAIS 5.0 model and convert it to a Microsoft Excel file.

The data contain 15 dwelling types. The WLO scenarios project that there will be no new dwellings for the dwelling types houseboat and caravan until 2050, so these two dwelling types are excluded in this research. The other 13 dwelling types can be classified into narrower categories (Folkert & Van den Wijngaart, 2012), which is especially useful for the two dwelling types ‘unknown’ and ‘various’, that are ambiguous. These narrower categories are presented in Table 6.

Table 6. Classification dwelling types (Folkert & Van den Wijngaart, 2012).

Type of dwelling Vesta MAIS 5.0	**Dwelling type reclassification**
Farms and horticulture	Detached
Detached bungalows	
Terraced houses single-family	Terraced house
Unknown	
Various	
Semidetached	Semi-detached
Canal house mansion	
Multi-floor maisonettes	Apartment/flat
Multi-floor canal house	
Student residence flat	
Flats up to 5 floors	
Flats 5 floors or more	
Retirement homes	

3.2.2 2020-2100: Literature review and assumptions

Trends population and households

To determine the number and types of new dwellings until 2100, assumptions need to be made on population and household growth. Assumptions on net growth of the housing stock cannot be related one-on-one with annual household growth, as the construction of residential dwellings is also influenced by factors such as migration, economic factors and policies (De Jong et al., 2019), though economic factors and policies were not factored into this research. This research used a population prognosis as published by the CBS (2019), which provides a prognosis until 2060, as well as a low and high 95% confidence interval. These intervals were used as the assumptions for the scenarios Low pop. and High pop., with the prognosis providing data for scenario Middle pop. The trends of the population prognosis until 2060 were extrapolated until 2100 to provide an estimate of the population of the Netherlands until 2100.

The number of houses cannot directly be related to the population size, but rather to the number of households. In 2020, the number of households in the Netherlands was 7,997,800 (CBS, 2020b). Basing their research on the population prognosis of the CBS (2019), Van Duin et al. (2018) project that the number of households in the Netherlands will increase to 8.8 million in 2060. Taking into account the prognosis of the CBS (2019), this increase in households corresponds to an average ratio of persons per household of 2.177 in 2020, and 2.222 in 2060 (Table 7).

Table 7. Data defining persons per household in 2020 and 2060.

Year	2020	Source	2060	Source
Population	17,415,000	CBS (2019)	19,552,000	CBS (2019)
Number of households	7,997,800	CBS (2020b)	8,800,000	van Duin et al. (2018)
Persons per household	2.177	-	2.222	-

Calculation number of new dwellings

To determine the number of dwellings that will be constructed beyond 2050, Equation 2 was used. It is important to note that restrictions on the construction of new buildings such as regulations and permits are not taken into account, and the resulting number of new dwellings is thus a simplified representation.

$$New\ dwellings = Households - Dwelling\ stock - Transformation + Demolition$$

Equation 2

Transformation and demolition

It is important to take into account that a share of the new required dwellings will not be realized by building new houses, but by transforming other existing buildings like office buildings, stores, or social real estate. This has already been taken into account in the data provided by the Vesta model, but needed to be taken into account for the period 2050-2100. The assumed annual transformation rates for scenarios Low pop., Middle pop., and High pop. are presented in Table 8.

Table 8. Annual transformation rates 2050-2100. Values based on (CBS, 2020a).

Scenario	Transformation rate (TR) (buildings/year)	Assumptions
Low pop.	7,792	25% lower than average transformation rate 2012-2019
Middle pop.	10,389	Average transformation rate 2012-2019
High pop.	12,986	25% higher than average transformation rate 2012-2019

The average demolition rate of from 2012 to 2020 was 11,296 (CBS, 2021c). The Economic Institute for Construction (*Economisch Instituut voor de Bouw*, EIB) developed prognoses for the demolition of buildings until the year 2030-2050 (Van Leeuwen et al., 2020). Van Leeuwen et al. (2020) assume that after this period, the number of dwellings being demolished will flatten out as the number of buildings constructed in the period 1945-1970 will decrease significantly, because these types of buildings age quickly and are of relatively poor quality. This research assumes the demolition rate will remain at the highest rate described by the EIB until 2070, when likely all dwellings from 1945-1970 have been demolished. After this period, it is assumed that the demolition rate will decrease, as buildings will have been constructed with higher quality (Hubbs, 2019; Libero Aankoop, n.d.), following the reversed trend with which the demolition rate has increased according to the EIB, dropping to the average demolition rate of the period 2012-2020.

3.3 Sub-question 2: Timber available from demolished dwellings

The goal of sub-question 2 was to determine the quantities of timber that will become available from demolished dwellings over the period 2020-2100. These data were necessary in order to determine the quantities of timber that could be reused in new dwellings. A combination of literature review, data collection, and definition of assumptions were used to answer this sub-question. The data were collected through literature review.

3.3.1 Material use dwellings 1945-2020

To determine the quantity of timber that becomes available from demolished dwellings, it was necessary to make assumptions about the materials used in these dwellings. There is no concrete dataset available in which it is stated which materials are used and to what extent these are used within dwellings built in the past. Research by Arnoldussen et al. (2020) has quantified material flows for the residential and utility sector for the year 2014 and aims to provide a perspective for the year 2030. In their research, they identify the numbers of different types of buildings that were demolished in the year 2014 (Table 9). In this research, it was assumed that the buildings being demolished until 2100 are demolished following the same percentages as those identified in Table 9.

Table 9. Number of demolished dwellings in 2014 (Arnoldussen et al., 2020).

Type of dwelling	Detached	Semi-detached	Terraced house	Apartment/flat	Total
Demolished dwellings	650	660	3,760	5,920	10,990
Demolished dwellings (%)	5.9%	6.0%	34.2%	53.9%	100%

There were no data available on the amount of materials used in the different types of dwellings built in the different construction periods since 1945. Therefore, it was assumed that the amount of materials used in these dwellings remains constant over time. Arnoldussen et al. (2020) have defined the average amount of materials necessary per m^2 to construct a dwelling for the four discussed types, as well as their average gross floor areas (GFA). An overview of this is presented further in the results (section 4.2.1).

3.3.2 Available timber dwellings 1945-2020

In 2014, about 3% of the materials used for the construction of dwellings consisted of timber (Arnoldussen et al., 2020), whereas in 2019 this was only 2% (Cobouw, 2019; NIBE Research, 2019). Apart from these years, there are no datasets available in which it is stated to what extent timber is used for the construction of dwellings. Therefore, data on the use of timber in construction in general were used as a proxy to estimate the percentages of timber used in the construction of dwellings from 1945 until 2020. The year 1945 is used, as it was assumed that the largest share of dwellings demolished in a given year will have a lifetime of 75 years (D. B. Müller, 2006). Additionally, the year 1945 was chosen because the largest share of existing dwellings was constructed from 1945 until the present (Figure 15).

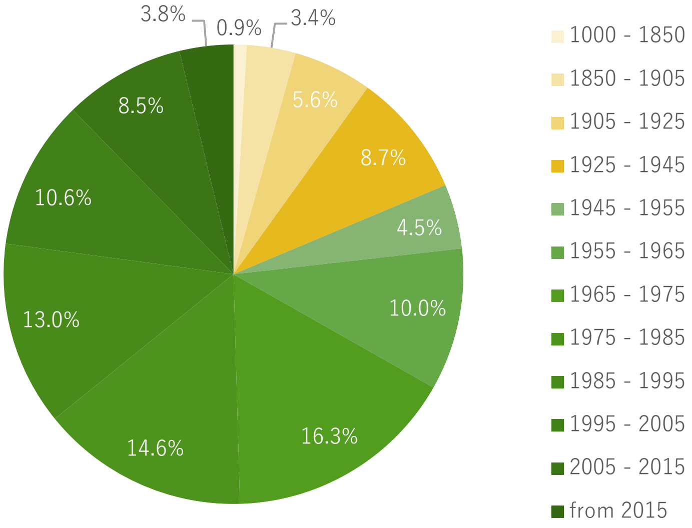


Figure 15. Share of dwellings by year of construction. Figure constructed from data from CBS (2021c).

Table 10 presents which data on the use of timber in construction were used as a proxy to estimate the percentages of timber used in the construction of dwellings from 1945 until 2020.

Table 10. Data used as a proxy to determine the timber used in residential dwellings for the period 1945-2019.

Period	Type of data	Sources
1945-1968	Extrapolation trend 1969-2019	(Cobouw, 2019; Fraanje, 1999; NIBE Research, 2019; Oldenburger, 2016; Rijksoverheid, 2018)
1969-1982	Timber use in residential dwellings in the Netherlands	(Fraanje, 1999)
1983-1995	Linear interpolation data	(Fraanje, 1999)
1996	Timber use in residential dwellings in the Netherlands	(Fraanje, 1999)
1995-2000	Timber use in construction in the Netherlands	(Oldenburger, 2016)
2000-2016	Timber use in construction in the Netherlands	(Rijksoverheid, 2018)
2017-2018	Linear interpolation data	(Cobouw, 2019; NIBE Research, 2019; Rijksoverheid, 2018)
2019	Timber use construction of residential dwellings in the Netherlands	(Cobouw, 2019; NIBE Research, 2019)

As CLT is a relatively new construction system, it was assumed that the 450 currently existing CLT dwellings (Vermeend & Hauer, 2020) will be demolished in the period 2090-2100, and the rest of the dwellings constructed in 1945-2020 were TFC systems. The data from Table 10 are all presented in tons. In order to make the available timber comparable to the timber used in dwellings, this was converted into m^3, based on the specific weight of the wood types used for TFC and CLT dwellings.

The available timber from demolished buildings can then be estimated using Equation 3:

$$Available\ timber = demolished\ dwellings * \frac{total\ materials\ per\ dwelling * \%\ timber\ used}{average\ specific\ weight\ wood\ types}$$

Equation 3

3.4 Sub-question 3: Future driving forces and limitations

The goal of sub-question 3 was to determine the driving forces that increase the timber used in residential dwellings and limitations for timber use in residential dwellings. Creating an overview of these driving forces allowed for identification of which benefits and disadvantages exist in timber construction, which formed the basis to investigate how the use of timber in dwellings can be increased. Additionally, these driving forces formed the basis for the scenarios on wood use in residential dwellings developed in sub-question 4. A combination of literature review and expert interviews was used to answer this sub-question, as combining literature with insights from experts creates an extensive overview of the most important driving forces. For this research, interviews were conducted with seven interviews experts in the field of design, construction and demolition. The experts interviewed in this research are presented below (Table 11).

Table 11. Name, company, and fields of expertise of experts interviewed for this research.

Name	Company	Fields of expertise
Mark Timmer	Vadeko BV	Production of prefab TFC elements
Boris Zeisser	Natrufied Architecture	Design of nature-inclusive building designs, CLT
Alex Verkuijlen	New Horizon	Urban mining
Victor de Beus	Tala	Design of modular CLT dwellings
Rudy van Gurp	TBI, HOUTbaar	Design of modular LVL and CLT dwellings
Olav Wiggers	Wonen in Hout	Suppliers TFC and CLT dwellings
Dennis Grootenboer	RAU Architects	Design of timber buildings, design for reassembly

These interviews were semi-structured: a guide of questions was used and, depending on which questions demand more attention for each interviewee, allowed for a varying order of questions and depth. This results in a conversation-type interview, which aims to understand the answers thoroughly (Harrell & Bradley, 2009). The interviews were held by organizing video calls via Microsoft Teams.

As the focus of these interviews was gathering specific information on applicability of timber and wood types used in construction of residential buildings, the interviews were analyzed by marking down the most important information to be used to answer the sub-question. Summaries of the interviews are available upon request. For each interview, the interviewee was asked to fill in an Informed Consent Form, to ensure that no misunderstandings on the handling of the data obtained in the interviews would arise. These forms are available upon request.

3.5 Sub-question 4: Potential for building with timber

The goal of sub-question 4 was to determine the quantities of timber used in new dwellings that are projected to be constructed until 2050 and 2100. These data were necessary in order to determine the extent of timber use in residential dwellings, as the quantities of timber define the potential for carbon storage in timber, as well as the potential demand for using secondary timber. A combination of literature review, data collection, scenario analysis, and definition of assumptions was used to answer this sub-question. The data were collected through literature review and expert interviews.

3.5.1 Expert interviews

To obtain information on the applicability of timber in residential dwellings, the experts mentioned in section 3.4 were consulted. Combining literature with information obtained from these experts creates the most accurate representation of the applicability of timber.

3.5.2 Scenario analysis

As it is not certain to what extent timber can be used in buildings in the future, three different scenarios were set up which aim to describe the developments of building with timber in residential dwellings until 2100. CLT is a promising technology, but it is not certain what the capacity of CLT may be in the future (Hildebrandt et al., 2017). Dutch residential dwellings mostly consist of low- to mid-rise buildings (TU Delft, n.d.), where the application of CLT might not be necessary and instead the more simple TFC could suffice.

The three scenarios, Conventional Focus, Moderate Timber, and Wood Revolution, cover ranges describing the extent to which timber will be used in residential dwellings until 2100, and the development of the extent to which CLT will be used until 2100 in residential dwellings besides TFC, which is currently the dominant form of building with timber (Oldenburger, Van Den Briel, et al., 2020). The three scenarios are visualized in Figure 16. It is important to note that in these scenarios, the feasibility of the supply of wood was not considered, it was thus assumed that there are no limiting factors related to the availability and price of the different types of timber elements considered. The scenarios range in the extent to which they focus on the use of wood in new dwellings (x-axis) and the extent to which they focus on increasing the application of CLT (y-axis). The assumptions and storylines behind these scenarios can be found in section 4.4.1.

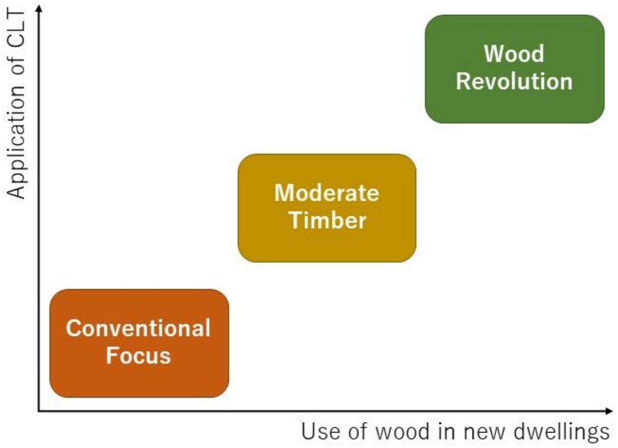


Figure 16. Scenarios describing the use of timber and CLT in new residential dwellings.

Of these three scenarios, scenario Conventional Focus is considered a predictive what-if scenario as it is a reference scenario that describes what will happen in the case historical developments carry on. Scenarios Moderate Timber and Wood Revolution are considered explorative strategic scenarios: they describe how the consequences can vary depending on which future development unfolds, where the goals are not necessarily absolute, but target variables are defined (Börjeson et al., 2006). The quantifications of these scenarios are discussed in results section 4.4.1.

3.5.3 Calculating number of TFC and CLT residential dwellings

The first step to determining the number of dwellings from TFC and CLT was to determine the number of timber residential dwellings per dwelling type. It was assumed that the ratio of dwelling types made from timber mimics the ratio of new dwelling types defined in sub-question 1 (see results section 4.1.5). To calculate the number of dwellings from timber for each decade, the average percentage of dwellings from timber over the decade was used in the calculation. Therefore, for each dwelling type in each decade the number of dwellings from timber was calculated using Equation 4:

$$Dwellings\ from\ timber = Total\ new\ dwellings * \%\ dwellings\ from\ timber$$

Equation 4

The next step was to define the number of dwellings from CLT and TFC for each dwelling type. For the dwelling type apartment/flat, it was assumed all dwellings are made using CLT, thus Equation 5 was used:

$$Dwellings\ CLT\ apartment/flat\ (10\ yrs) = Dwellings\ from\ timber * 100\%$$

Equation 5

Since the percentages of dwellings constructed using TFC and CLT vary for the dwelling types detached, semi-detached, and terraced house, Equation 6 and Equation 7 were used:

$$Dwellings\ TFC\ (10\ yrs) = Dwellings\ from\ timber * average\ \%\ TFC\ (10\ yrs)$$

Equation 6

$$Dwellings\ CLT\ (10\ yrs) = Dwellings\ from\ timber * average\ \%\ CLT\ (10\ yrs)$$

Equation 7

3.5.4 Quantities of timber in dwellings

To define the quantities of timber in the different dwelling types, quantities found in literature and obtained through expert interviews were used. These quantities were then combined into an average number of timber used in each dwelling type, for the construction methods TFC and CLT.

Using these quantities of timber and the numbers of dwellings from TFC and CLT for each dwelling type, the total quantities of timber required for residential dwellings from timber was calculated using Equation 8:

$$Total\ timber\ use = \sum dwellings\ TFC * timber\ use\ TFC + \sum dwellings\ CLT * timber\ use\ CLT$$

Equation 8

3.6 Sub-question 5: Maximization strategies length of use building with timber

The goal of sub-question 5 was to determine which strategies to increase cascading of structural timber elements exist, and with that enhance the length of carbon stored in timber. Creating an overview of maximizations strategies allowed for identification of which strategies are the most relevant and applicable. Additionally, these strategies formed the basis for the scenarios on reuse of structural timber elements developed in this sub-question. A combination of literature review, data collection, scenario analysis, and definition of assumptions was used to answer this sub-question.

3.6.1 Expert interviews

To obtain information on reusability and design options that increase this, the experts mentioned in section 3.4 were also consulted for this sub-question. Combining literature with information obtained from these semi-structured expert interviews creates the most accurate representation of the reusability of timber.

3.6.2 Scenario analysis

As it is not certain to what extent different timber components can be reused, remanufactured, and recycled, several scenarios were set up to describe the different pathways of cascading. Based on the literature review and expert interviews, three scenarios were set up: scenario Primary, scenario Reuse, and scenario Mix. These scenarios provide a range for the potential for cascading timber building elements that describes the possible percentages that could be achieved until 2050 and 2100.

Scenarios Primary, Mix, and Reuse, cover ranges describing the development of the extent to which timber from residential buildings is used on high-value or lower-value levels of cascading until 2100 and are visualized in Figure 17. The scenarios range in the extent to which they focus on decreasing primary demand by increasing strategies to maximize the length of the use of timber products (x-axis) and the extent to which they focus on decreasing emissions from incineration with energy recovery (y-axis). The assumptions and storylines behind these scenarios can be found in section 4.5.5.

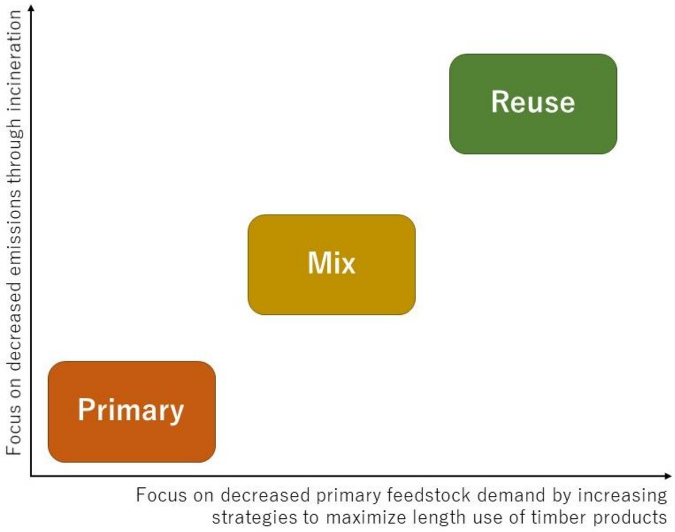


Figure 17. Scenarios on the development of cascading of timber from residential dwellings.

Of these three scenarios, scenario Primary is considered a predictive what-if scenario as it is a reference scenario that describes what will happen in the case historical developments continue (Börjeson et al., 2006). Scenario Reuse is a normative transforming scenario, with a high-level and highly prioritized target in 2050, namely the goal of the Dutch government to be entirely circular in 2050 (Rijksoverheid, 2016), which cannot be reached if the ongoing developments continue: this scenario is therefore a backcasting scenario, as it aims to describe what would be necessary to reach the set goal (Börjeson et al., 2006). Scenario Mix is also a backcasting scenario, though in this scenario the goal of the Dutch government is set in 2100, resulting in an increased possibility of reaching this goal. The quantifications of these scenarios are discussed in results section 4.5.5.

3.7 Sub-question 6: Quantities virgin and reused timber and associated carbon storage

The goal of sub-question 6 was to estimate the carbon storage within timber in residential dwellings, as well as the quantities of virgin and reused timber used for each scenario. Based on different combinations between the developed scenarios, the potential for reuse of timber in residential dwellings was quantified, along with the extent to which the length of carbon storage can be enhanced by reusing the timber elements. A combination of literature review, data collection, scenario analysis, definition of assumptions, and Material Flow Analysis (MFA) was used to answer this sub-question.

3.7.1 MFA

The MFA in this research used the ODD protocol discussed in section 2.5, following the elements from Table 3.

Overview

By applying an MFA, carbon flows from the sourcing of wood to the building elements wood is used in, to the share of elements that is reused, remanufactured, and recycled, and the share that is incinerated can be traced. This allows for a clear overview of the wood and carbon flows, resulting in a representation of the cumulative carbon storage in Dutch buildings over the periods 2020-2050 and 2020-2100. By quantifying the strategies of maximizing carbon storage, a comparison of the effects of these strategies can be made. An overview of the system is presented below (Figure 18), adjusted slightly from the system overview presented in section 2.6.5.

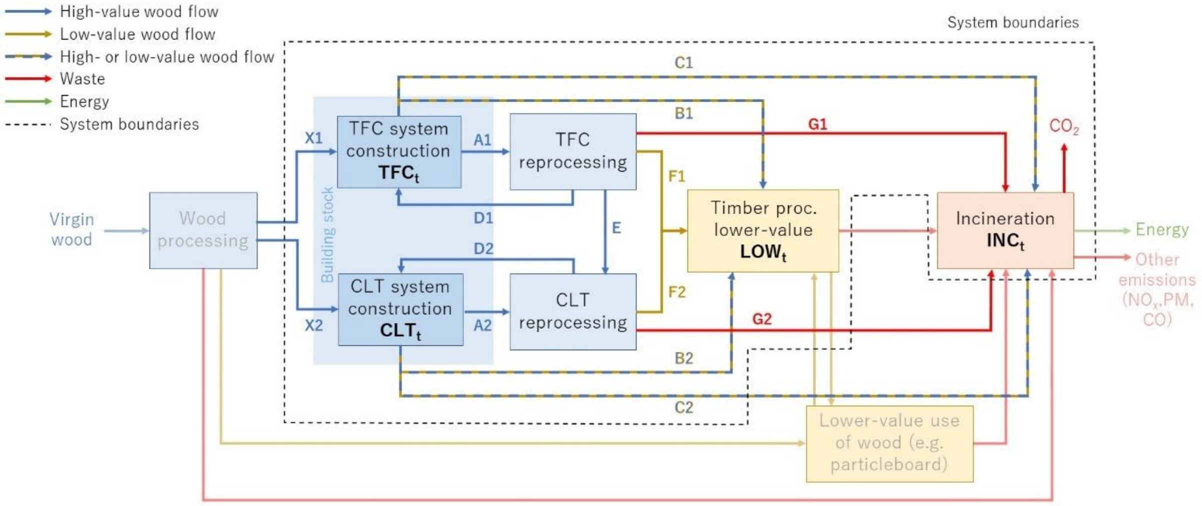


Figure 18. Overview of the system of the construction and cascading routes of timber residential buildings in the Netherlands, including processes, stocks, and flows. The elements left out of the system boundaries have been faded. The arrows within the system boundary are the ones that are labelled with a code, and the CO_2 outflow from incineration.

Figure 18 shows the processes (with stocks) as boxes and the flows with arrows and an accompanying code. For simplicity reasons, since lower-value end use products are outside of the system boundaries of this research, the timber components that become available in the demolishing process that are used for other lower-value end uses, such as for particleboard, were grouped into one category.

Design concepts

Oftentimes, MFA is used to determine previous or current stocks and flows within a sector or of a material (Hekkert et al., 2000; Jasinevičius et al., 2018; Kayo et al., 2019), although some research does aim to make predictions with MFA (Mantau, 2015). In this research, the MFA takes into account the current stocks and flows, and using the data obtained in the previous research questions, an MFA for the periods 2020-2050 and 2020-2100 was set up based on the different scenarios constructed throughout this research. Therefore, the design was a dynamic MFA, which aims to describe the behavior of the system over time (W. Q. Chen & Graedel, 2012). This MFA estimates the in-use stocks from the cumulative difference between inflows and outflows: a top-down approach (Gerst & Graedel, 2008; E. Müller et al., 2014). A combination of retrospective and prospective analyses was used. Retrospective analysis was used through the past stocks and flows based on historical data that have been defined in sub-question 2 and form the basis for the timber available from the building stock. Historical data have also been used in sub-questions 1 and 3 to determine the future developments of timber construction. These data, combined with assumptions and future scenarios, were extrapolated to create a future prospective analysis.

The exogenous variables considered in this system were socioeconomic data on population size determined in the scenarios Low pop., Middle pop., and High pop. which in part determined the flows X1 and X2, and the average of lifetime of timber products of 75 years, defined in section 3.3.2, which was incorporated into the available timber flows A1 and A2.

The forms of dissipation from the system considered in this research were the lower-value use of wood, modelled as stock LOW_t, and dissipation in the form of incineration with energy recovery, modelled as stock INC_t. In reality, these forms of dissipation are not stocks. For the lower-value use of wood, the wood either flows continuously in a cycle of use and reuse for lower-value end uses or is incinerated when the material is no longer reused. For incineration with energy recovery the wood is incinerated, thereby yielding energy and emitting CO_2, nitrogen oxides (NO_x), particulate matter (PM), and carbon monoxide (CO) (RVO, 2020a).

Spatial distribution entails the location of resources and in-use stocks (E. Müller et al., 2014). Although the spatial extent of the research has been defined, namely the Netherlands, the spatial distribution of the stocks and flows within the Netherlands was not taken into account. The location of resources is determined by the sourcing of wood, which is left out of the system boundaries (see section 1.4), and the spatial distribution of in-use stocks is determined by the entire residential dwelling sector in the Netherlands and was thus considered too complex to include in this research.

The data included in this MFA were acquired from many different sources with varying reliability. Because it is difficult to quantify the uncertainty of the input data and the different parameters of the model, this MFA used scenario analysis as a form of sensitivity analysis of the rates for different levels of cascading and populations size, and application of timber in residential dwellings. Sensitivity analysis is often done for MFAs in research (Cheah et al., 2009; Daigo et al., 2009; Davis et al., 2007; E. Müller et al., 2014; Pauliuk et al., 2013), although this is often done in the form of single adjusted variables, not in the form of scenario analysis.

Details

The stocks in the MFA model are indicated in boxes in Figure 18. The formulas, initial states at $t = 0$ (2020) and the data used for these input states are presented below in Table 12.

Table 12. Stocks of MFA model: name, formula, initial state value, data source(s).

Stock	Formula	Value at t = 0 (m^3)	Source
TFC_t	$TFC_t = TFC_0 + X1 - A1 - B1 - C1$	113,379,199	Timber availability defined in SQ2 (methods: section 3.3.2; results: section 4.2.2)
CLT_t	$CLT_t = CLT_0 + X2 - A2 - B2 - C2$	24,750	
LOW_t	$LOW_t = LOW_0 + B1 + B2 + F1 + F2$	0	-
INC_t	$INC_t = INC_0 + C1 + C2 + G1 + G2$	0	-

In this MFA, the scenarios defined in sub-question 5 (see results section 4.5.5) are used as a basis for the calculations of the flows, except for the flows X1 and X2. Nevertheless, flows X1 and X2 depend on the demand for primary wood use and are thus indirectly influenced by the values of all other flows in the system. The formulas and values for x within these formulas are presented below in Table 13. It is important to note that the values for x presented in Table 13 are the values in the indicated year. The development of the values within these scenarios was assumed to be linear.

Table 13. Flows in the MFA model: name, formula, values for x in formula based on cascading scenarios.

Flow	Formula for Δt	Value for x (2020)	Value for x (2050)			Value for x (2100)		
			Primary	Mix	Reuse	Primary	Mix	Reuse
A1	$A1 = TFC_{available} * x$	0%	0%	37.5%	100%	0%	100%	100%
A2	$A2 = CLT_{available} * x$	0%	0%	37.5%	100%	0%	100%	100%
B1	$B1 = TFC_{available} * x$	46%	46%	28.8%	0%	46%	0%	0%
B2	$B2 = CLT_{available} * x$	46%	46%	28.8%	0%	46%	0%	0%
C1	$C1 = TFC_{available} * x$	54%	54%	33.8%	0%	54%	0%	0%
C2	$C2 = CLT_{available} * x$	54%	54%	33.8%	0%	54%	0%	0%
D1	*If* $D1 > TFC_{in}$, *then:* $D1 = TFC_{in}$ *Else:* $D1 = A1 * x$	-	-	32.2%	85.9%	-	85.9%	85.9%
D2	$D2 = A2 * x + E$	-	-	34.2%	91.2%	-	91.2%	91.2%
E	*If* $D1 > TFC_{in}$, *then:* $E = A1 * x + (D1-TFC_{in})$ *Else:* $E = A1 * x$	0%	0%	5.3%	14.1%	0%	14.1%	14.1%
F1	*If* $D1>X1$, *then:* *For scenario Primary:* $F1 = A1 * x$ *For scenario Mix:* $F1 = A1 * x + 0.5(D1-X1)$ *For scenario Reuse:* $F1 = A1 * x + (D1-X1)$ *Else:* $F1 = A1 * x$	-	-	28.8%	0%	-	0%	0%
F2	*If* $(D2 + E) > CLT_{in}$, *then:* *For scenario Primary:* $F2 = A2 * x$ *For scenario Mix:* $F2 = A2 * x + 0.5(CLT_{in}-(D2+E)$ *For scenario Reuse:*	-	-	32.1%	9%	-	8.8%	8.8%

	F2 = A2 * x + (CLT_{in} - (D2+E) *Else:* F2 = A2 * x							
G1	*If* D1>X1, *then:* *For scenario Primary:* G1 = A1 * x + (D1-X1) *For scenario Mix:* G1 = A1 * x + 0.5(D1-X1) *For scenario Reuse:* G1 = A1 * x *Else:* G1 = A1 * x	-	-	33.8%	0%	-	0%	0%
G2	*If* (D2 + E) > CLT_{in}, *then:* *For scenario Primary:* G2 = A2 * x + (X2-(D2+E)) *For scenario Mix:* G2 = A2 * x + 0.5(X2-(D2+E) *For scenario Reuse:* F2 = A2 * x *Else:* G2 = A2 * x	-	-	33.8%	0%	-	0%	0%
X1	X1 = TFC_{in} - D1	-	-	-	-	-	-	-
X2	X2 = CLT_{in} - D2	-	-	-	-	-	-	-

For the flows A1-C2, X1, and X2, parameters were used in the formulas which require an input value. The input values for $TFC_{available}$ and $CLT_{available}$ were based on the timber availability defined in sub-question 2 (see results section 4.2.2). The input values for TFC_{in} and CLT_{in} were based on the timber demand, defined in sub-question 4 (see results section 4.4.3). These input values are very extensive, since they differ for each population and wood use scenario, and are thus presented in Table 22 in Appendix I. It is again important to note that the values for the parameters presented in Table 22 are the average values over the course of the relevant time period.

For data aggregation and to model the calculations, Microsoft Excel was used, which allows for a comprehensive link between the data and the model itself. Additionally, the software used to visualize the results, STAN (subSTance flow ANalysis) (version 2.6.801), uses Microsoft Excel as an interface for data import and export. STAN is a freeware for material flow analysis following the Austrian standard ÖNorm S 2096, which enables building graphical models by using predefined components (processes, stocks, flows, and system boundaries) and displays all flows in a Sankey diagram, where the width of a flow is proportional to its value (TU Wien, 2012).

3.7.2 Calculating carbon storage and CO_2

From the modelling of the MFA of wood and timber for the different scenarios, the associated carbon storage was calculated. By calculating the associated carbon storage, an overview is created of the carbon (C) storage within the different material stocks, as well as the carbon that was not stored in high-value timber elements, but rather stored in lower-value end use products or lost to incineration.

The carbon storage of timber can be calculated by using the carbon content of the different types of wood used for timber in residential dwellings, which was found in existing literature and is presented in Appendix II. Therefore, the carbon storage of timber was calculated using Equation 9:

$$C\ storage\ (t) = timber\ volume\ (m^3) * specific\ volume\ \left(\frac{t}{m^3}\right) * C\ content\ timber\ (\%)$$

Equation 9

The delayed CO_2 emissions associated with the resulting carbon stored in timber can be easily calculated following the EN 16449:2014 calculation (Van der Lugt & Harsta, 2020), which is based on the atomic weights of carbon (12) and carbon dioxide (44). Based on the product biogenic carbon content and the volume of wood, density and moisture content Equation 10 was used (European Committee for Standardization, 2014):

$$CO_2\ emissions = \frac{44}{12} * cf * \frac{\rho_\omega * V_\omega}{1 + \frac{\omega}{100}}$$

Equation 10

where

cf	is the carbon content of the timber (%);
ω	is the moisture content of the product. In the absence of specific product details, 12% may be used as default value;
ρ_ω	is the density of timber (kg/m^3);
V_ω	is the volume of timber (m^3).

For the carbon content of timber in Equation 9 and Equation 10, a carbon content weight-percentage of 50.4% was used, as this is a commonly used percentage to calculate the carbon within woody biomass (Centrum Hout, n.d.-b; Profft et al., 2009; Wirth et al., 2004). For this research product details on the moisture content of different timber products were not encountered, thus the default value of 12% was used.

3.7.3 Calculating average lifetime carbon in system

To determine the increased length of use of timber in the system, the average lifetime of carbon in the carbon stock of the system (see Figure 18) was calculated. The lifetime of carbon is defined as the time that carbon has resided (for reused elements) and will reside during the entire element use phase(s) within the timber elements entering the building stock within the specified period. In this research, it is assumed that timber elements are reused once within the period 2020-2100. The longer the carbon is circulated within the timber construction systems, the longer it attributes to delayed atmospheric CO_2 emissions. The average lifetime was calculated for the carbon in the building stock that was modelled until 2100, by using several equations. First, the amount of carbon with a lifetime of 75 years (the standard assumed lifetime of dwellings, see section 3.3.2) was calculated (Equation 11):

$$C\ 75\ years_t = (C\ associated\ with\ timber\ used\ in\ dwellings_t * \%\ virgin\ timber)$$

Equation 11

Second, the amount of carbon with a lifetime of 150 years (two dwelling lifetimes) was calculated (Equation 12):

$$C\ 150\ years_t = (C\ associated\ with\ timber\ used\ in\ dwellings_t * \%\ reused\ timber)$$

Equation 12

Finally, the average lifetime of carbon in the system was calculated (Equation 13):

$$Average\ lifetime\ C\ (2020 - 2100) = \sum \frac{C\ 75\ years_t * 75 + C\ 150\ years_t * 150}{C\ 75\ years_t + C\ 150\ years_t}$$

Equation 13

4. Results

4.1 Sub-question 1: Number and types of new dwellings

4.1.1 Trends population and number of households

Based on the data and assumptions mentioned in section 3.2.2, projections of the population of the Netherlands until 2100 were determined for population scenarios Low pop., Middle pop. and High pop. (see Figure 42 in Appendix III). The number of persons per household presented earlier in section 3.2.2 (Table 7) was assumed to increase linearly from 2020 until 2060 and this linear trend is extrapolated until 2100. Combining the persons per household with the population prognoses for each scenario resulted in prognoses for the number of households until 2100 (see Figure 43 in Appendix III).

4.1.2 Number of new residential dwellings

The number of residential dwellings in the building stock in the Netherlands in 2020 was 7,891,786 (CBS, 2021b). Taking into account the data from the Vesta model for the period 2020-2050, and the assumptions mentioned in section 3.2.2 for the period 2050-2100, the results for the development of the number of residential dwellings are presented below (Figure 19). From Figure 19, it can be seen that in scenarios Middle pop. and High pop. the number of households remains above the number of dwellings until around 2060. In practice, this would entail that multiple singles, couples or families would need to live in one dwelling or that people would need to live in buildings that are not intended for residency, such as commercial buildings (Van Bockxmeer, 2020). This is due to the fact that the Vesta model takes into account restrictions surrounding regulations and permits. After 2050, these factors are not taken into account, thus creating a more simplified view of the number of dwellings that would be required to house the number of households living in the Netherlands. For scenario Low pop., it is projected that there will be a surplus in dwellings around 2050 and after 2090, which means that around these periods it is not necessary to build new dwellings.

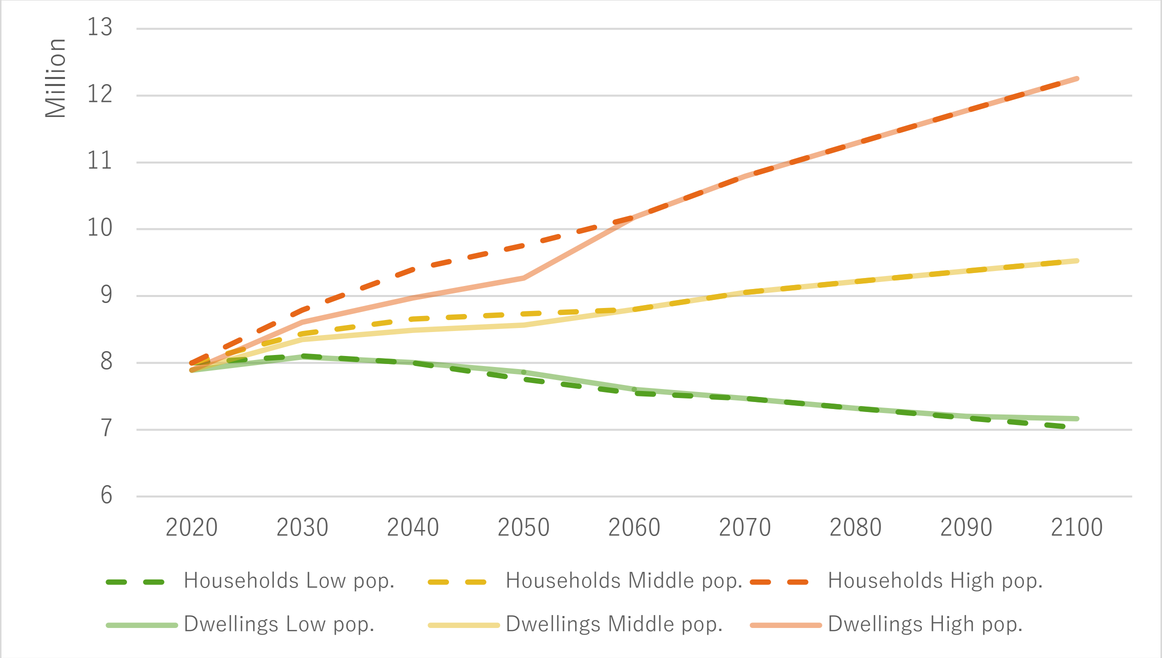


Figure 19. Number of households and number of dwellings in the Netherlands assumed in the three scenarios Low pop., Middle pop., and High pop. (2020-2100).

4.1.3 Defining number of new dwellings scenario Middle pop.

The data from WLO scenarios Low and High in the Vesta model were used as a basis for the scenarios Low pop. and High pop. in this research. To identify scenario Middle pop., the average between the number of new dwellings for each dwelling type is assumed. The results of the new dwellings for each scenario until 2050 are presented in Appendix IV (Figure 44).

4.1.4 Types of new dwellings

Using the reclassified dwelling types from Table 6 in section 3.2.1, the division of the different dwelling types for scenario Middle pop., based on the data provided for the period 2020-2050 by the Vesta model for scenarios Low pop. and High pop. and on the average between the number of new dwellings for each dwelling type, is presented below (Figure 20). The shares of different dwelling types is very similar for each decade for each of the three scenarios. Therefore, the types of new dwellings built in the period 2050-2100 were assumed to follow the average shares of the dwelling types identified over the period 2020-2050, with a distinction between scenarios Low pop., Middle pop., and High pop.

Figure 20. Average shares of dwelling types for population scenarios Low pop., Middle pop., and High pop. for the period 2020-2100.

4.1.5 Number and types of new dwellings until 2100

Taking into account the data provided by the Vesta model for the period 2020-2050, and the number of dwellings in the building stock combined with the assumptions on transformation and demolition, the results for the average annual number of new dwellings per decade are presented below (Figure 21). In Figure 21, it can be seen that the numbers of new dwellings built from 2050 onwards present different trends than those seen before 2050, especially for scenarios Low pop. and High pop. This is due to the fact that the numbers from 2050 onwards are solely based on the projected trends in population and households, not taking into account limitations for the construction of dwellings such as regulations or permits. As scenario High pop. takes into account a high population (and household) increase, Figure 21 shows that there will be a high demand for new dwellings. On the other hand, scenario Low pop. shows that there will be no need for new dwellings in the period 2050-2060, because the projected household trends would translate into a short dwelling surplus, which would also be the case from 2080 to 2100.

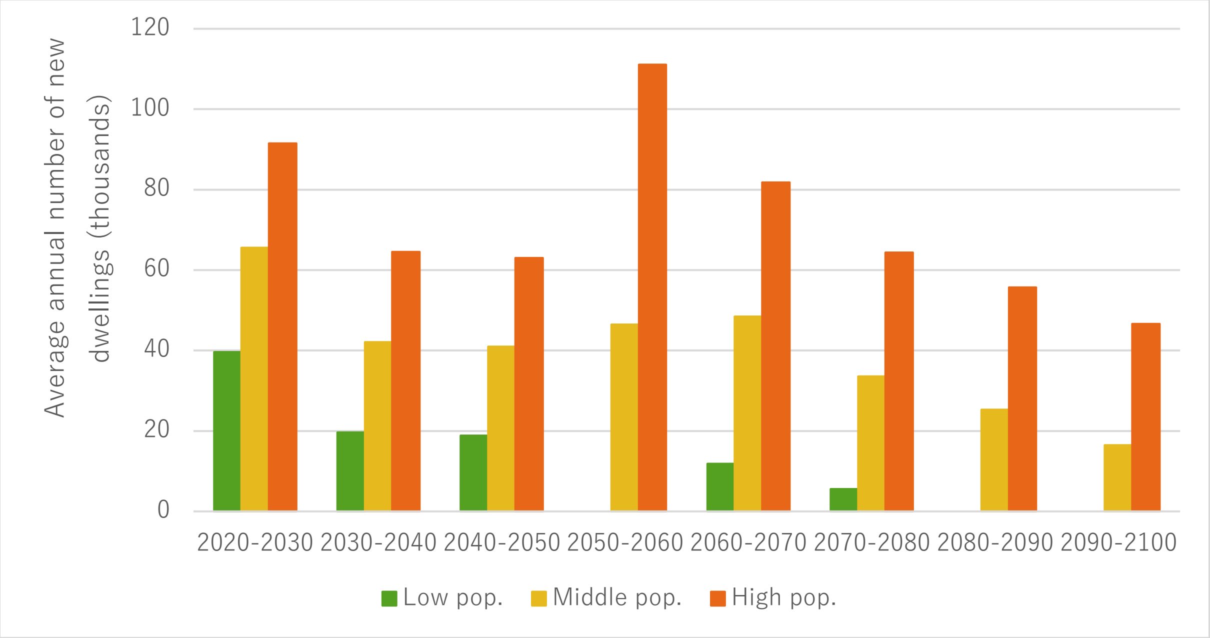


Figure 21. Average annual number of new dwellings built in the Netherlands for each decade.

4.2 Sub-question 2: Timber available from demolished dwellings

4.2.1 Timber quantities in existing residential dwellings

As discussed in section 3.3.1, Arnoldussen et al. (2020) have defined the average amount of materials necessary per m^2 to construct for each of the four types of dwellings, as well as their average gross floor areas (GFA). To determine the total amount of materials used in a dwelling type, the total materials used per m^2 and the average GFA of a dwelling were multiplied and converted into tons (Table 14).

Table 14. Average GFA and materials used for each dwelling type (Arnoldussen et al., 2020).

Type of dwelling	**Total materials used (kg/m²)**	**Average gross floor area (GFA) (m²)**	**Total materials used (tonnes)**
Detached	1,200	321	385.2
Semi-detached	1,430	178	254.5
Terraced House	1,120	182	203.8
Apartment/flat	1,630	86	140.2

Based on the combined data found in literature and the assumptions mentioned in section 3.3.2, the resulting trend for the percentage of timber used in residential dwellings from 1945-2020 in the Netherlands is presented below (Figure 22). In Figure 22 there is a gradual decrease in percentage of timber used in dwellings from 1945 until 1968, after which the percentage increases sharply. This is due to the fact that the percentages for 1945-1968 were derived from the overall trend seen from 1969-2020, and extrapolated to fit this trend. An explanation for the downwards trend of timber use in dwellings is the strong increase in concrete use for the construction of new dwellings seen in the second half of the 20th century after the second world war. The use of concrete for residential dwellings started in 1900 with about 0.2 t/m^2 GFA, which increased to about 0.5 t/m^2 in 1950, and then increased dramatically to 1.9 t/m^2 in 2000 (D. B. Müller, 2006). Constructing residential dwellings from concrete was a cheap option for the large dwelling demand, allowing the concrete industry to gain its current significant market share, which allowed it to become a widely used and cheap option for the construction of residential dwellings (P. Klok, 2013).

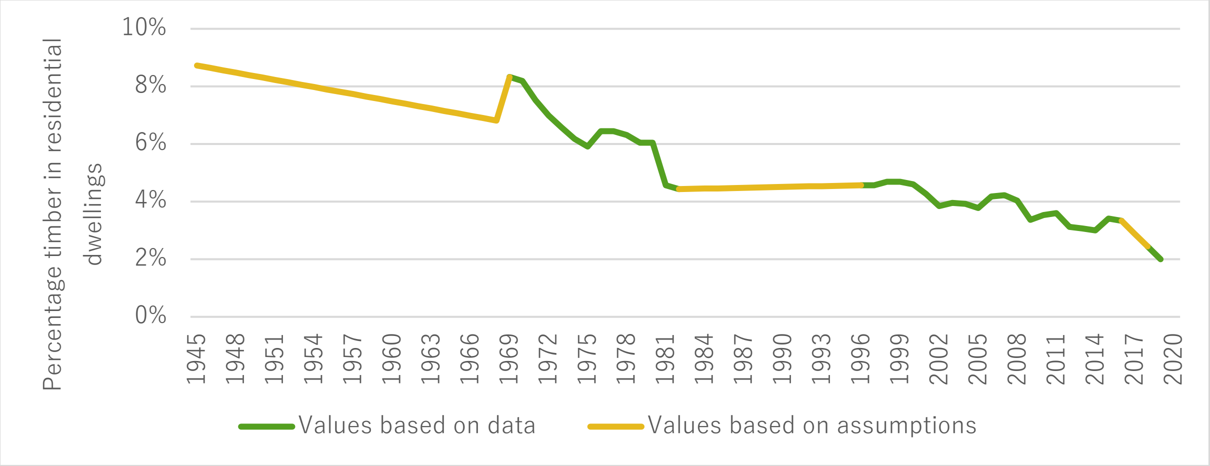


Figure 22. Mass-based percentage of annual timber used in residential dwellings in the Netherlands (1945-2019) based on (Arnoldussen et al., 2020; Cobouw, 2019; Fraanje, 1999; NIBE Research, 2019; Oldenburger, 2016; Rijksoverheid, 2018).

4.2.2 Timber quantities available from demolished dwellings (2020-2100)

It is assumed that the demolition of dwellings does not depend on the defined population scenarios. Taking into account the data provided by the EIB (Van Leeuwen et al., 2020) and the assumptions mentioned in section 3.2.2, the results of the average annual number of demolished dwellings for each decade are presented below (Figure 23). Taking into account the percentages of timber used in residential dwellings, the number of demolished dwellings, and total material use per dwelling, Equation 3 from section 3.3.2 was used to calculate the quantities of available timber from demolished buildings. The results are presented in Figure 23 as well.

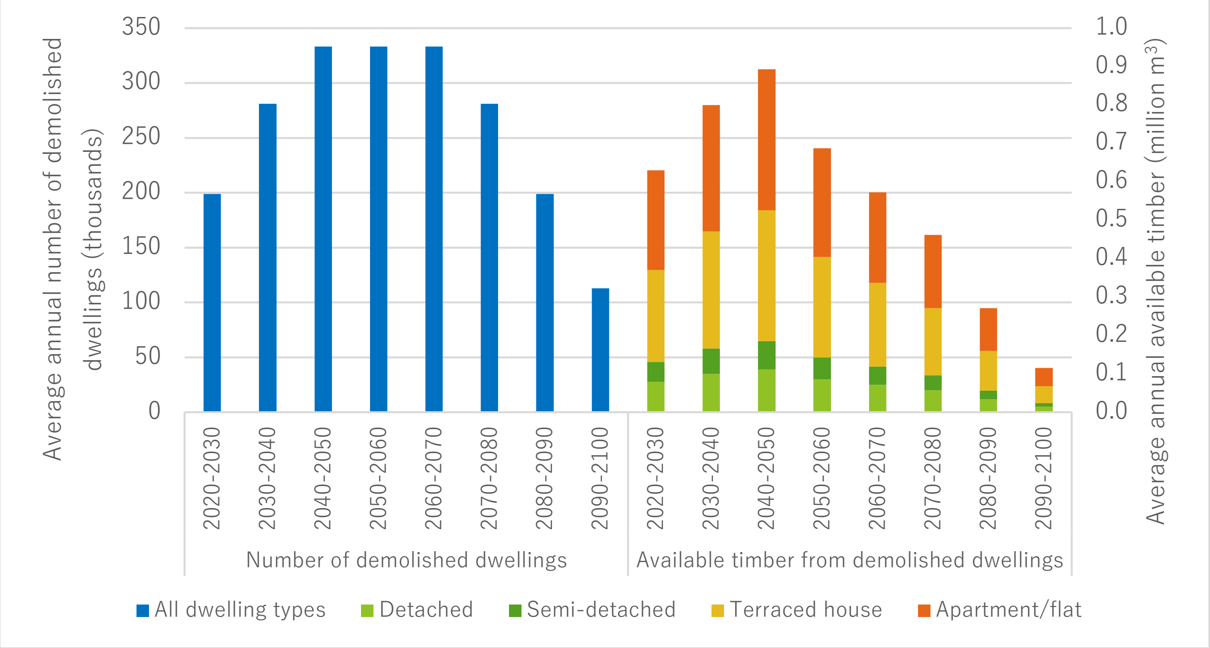


Figure 23. Prognosis of average annual number of demolished dwellings in the Netherlands (values for the periods 2020-2030, 2030-2040, and 2040-2050 from Van Leeuwen et al. (2020), values for remaining periods based on assumptions) and average annual available timber from demolished residential dwellings for each decade from 2020-2100 (in million m^3).

Figure 23 shows that until 2050, the average annual number of demolished dwellings increases, which is due to the fact that in these years increasingly more dwellings from 1945-1970 require demolition (Van Leeuwen et al., 2020). This is projected to remain the case until around 2060-2070, after which most of these dwellings will have been demolished. From 2070 onwards, the average annual number of demolished dwellings will decrease, as the quality of dwellings constructed at the end of the twentieth century and at the beginning of the twenty-first century are of better quality (Hubbs, 2019; Libero

Aankoop, n.d.). Figure 23 also shows that the largest quantities of timber will become available from apartments/flats and from terraced houses, followed by the dwellings types detached and semi-detached. This aligns with the fact that the most frequently built dwelling types in the future are projected to be apartments/flats and terraced houses (Figure 20). It can also be seen that the amount of available timber decreases more rapidly than the number of demolished dwellings, which is due to the fact that the timber content of existing dwellings has decreased over time (Figure 22).

4.3 Sub-question 3: Future driving forces and limitations

4.3.1 Driving forces for increased timber use in buildings

Environmental considerations

As mentioned in section 1.1, the Dutch government aims to decrease GHG emissions by 49% compared to 1990 levels by 2030 (Rijksoverheid, 2019), and using timber instead of conventional materials for the construction of residential buildings can realize CO_2-savings of 6-42% (W/E Adviseurs, 2016, 2018). Therefore, environmental considerations are one of the driving forces to build with timber, which is apparent from the conference by Van der Lugt et al. (2021), in which the many attending stakeholders from the construction sector agree that the societal costs for the material and energy use of the construction of residential buildings will be carried by society for centuries. Additionally, it is more and more common for consumers who want to design their own detached dwelling to choose for more sustainable and ecologically themed homes (O. Wiggers, personal communication, May 26, 2021). Although quantitative data on timber use in residential dwellings after 2019 is lacking, stakeholders see an increase in the demand for timber residential dwellings (V. de Beus, personal communication, May 21, 2021; R. van Gurp, personal communications, May 20, 2021; O. Wiggers, personal communication, May 26, 2021).

Material benefits

Timber for the construction of residential dwellings has some structural advantages over conventional materials. Compared to conventional construction materials, timber is of relatively low weight, which can increase the feasibility of projects on sites with ground and soil limitations (Van der Lugt & Harsta, 2020). This low weight also reduces the need for transport, as for instance a detached dwelling can be delivered within two to three truck loads (Paes et al., 2020), compared to seven truck loads for a conventional concrete-based detached dwelling (Sandanayake et al., 2018). Strength-wise, timber elements can absorb bending, pulling, and shear forces, whereas (lime)stone cannot (Paes et al., 2020). In high-rise buildings, where the structural integrity of buildings is important, CLT can achieve the same absolute strength as steel (Van der Lugt & Harsta, 2020). Timber can cause swelling and shrinkage problems, but in the case of CLT a lot of swelling and shrinkage problems are solved because of the structural integrity of cross lamination (Paes et al., 2020). Finally, timber requires less finishing (such as plastering or paint, as the timber can be left in sight) compared to conventional materials, which results in less material use and labor (Paes et al., 2020).

Time savings

One of the most direct benefits of using timber for the construction of residential dwellings is that, when based on prefab elements, there are large savings in the on-site construction time of dwellings. Compared to conventional reinforced concrete structures, prefab timber elements can be installed simply by using electric tools and even without secondary assembly, like windows or installations, when installed in off-site factories (Van der Lugt & Harsta, 2020). Waugh Thistleton Architects (2018) estimate possible time savings of 20-45% compared to similar reinforced concrete systems, which can save costs and increase the feasibility of time-critical projects. Van der Lugt et al. (2021) indicate that increased prefabrication of timber causes displacement of work to factories, which speeds up the building process. Serial TFC is a cheap and fast construction method, which can be a solution for the high need for residential dwellings (Paes et al., 2020), and although serial building is also possible with CLT, this requires good planning, but would have large benefits related to production speed when using prefabrication (Paes et al., 2020).

Reduced labor requirements

By realizing prefab mass timber systems, the number of on-site personnel can be reduced by 50-70% (Waugh Thistleton Architects, 2018), as it requires less labor at the construction site (Bovee et al., 2021; Van der Lugt et al., 2021). On-site construction activities associated with timber construction are less complicated than for traditional construction methods, enabling more people to perform the work required (R. van Gurp, personal communication, May 20, 2021; Waugh Thistleton Architects, 2018). As it is estimated that about 1 million new dwellings are required before 2035 (Studio Marco Vermeulen, 2020), this reduced labor requirement may prove important in order to meet this housing requirement (Bovee et al., 2021), as currently, labor availability in the Netherlands in the building sector is already in short supply.

Low disturbance construction site

Timber systems such as TFC and CLT are light and dry construction systems which lend themselves for quick installation (V. de Beus, personal communication, May 21, 2021; Van der Lugt & Harsta, 2020; B. Zeisser, personal communication, May 14, 2021). This results in reduced disturbance on the construction site, not only because of the fast construction time, but also because of the possibility to utilize less, smaller, and potentially electric equipment such as hand tools and smaller cranes (Bronsvoort et al., 2020; Studio Marco Vermeulen, 2020; Van der Lugt & Harsta, 2020). This will in turn reduce noise levels from the construction site, as well as polluting emissions such as CO_2, NO_x, and PM (Van der Lugt & Harsta, 2020).

Waste minimization

As the construction processes for building with timber are very different from those associated with conventional materials, wastes and failure costs associated with TFC or CLT elements are relatively low (Bovee et al., 2021). For instance, TFC elements are made in a factory with little waste and low failure costs of about 1%, whereas failure costs for traditional construction are about 11% (Paes et al., 2020).

4.3.2 Limitation for timber use in buildings

Costs

The most obvious limitation for constructing residential buildings from timber is the costs. Investment costs of biobased materials are currently about 10-20% higher than conventional materials (Van der Lugt et al., 2021). On the building level, building with structural CLT is about 10% more expensive than conventional construction using concrete (Schouten et al., 2020; B. Zeisser, personal communication, May 14, 2021). This is not the case for low-rise TFC, which is competitive with traditional building systems that use mineral raw materials (M. Timmer, personal communication, May 10, 2021) and can even be 30-40% cheaper (O. Wiggers, personal communication, May 26, 2021).

Traditionally, only the investment costs are taken into account in the overall costs, but certain benefits of timber buildings, such as construction time or health and environmental benefits, are now not valued in the overall building costs (Bovee et al., 2021). Another challenge is that the financial benefits of scaling up are larger for mineral materials than for timber, thus making large-scale projects more favorable when executed in mineral materials (O. Wiggers, personal communication, May 26, 2021). Additionally, there are currently few biobased materials available in the National Environmental Database (*Nationale Milieudatabase*, NMD): the costs to execute an LCA in order to be incorporated in the NMD can be a barrier for start-up companies (V. de Beus, personal communication, May 21, 2021; Schouten et al., 2020) and has not been a barrier for large established construction companies to introduce traditional construction materials. However, it is speculated that through market dynamics, the costs of building with timber will decrease on the long-term (Van der Lugt et al., 2021).

Public perceptions

There are certain misconceptions surrounding building with timber that are prevalent among the Dutch public, such as that the structural strength is lower than that of mineral materials, that fire safety is a large issue, that the acoustics are undesirable (E. Prins & Van Roeden, 2021), that timber construction is far more expensive than traditional construction (Ooijevaar, 2020), or that logging is mostly unsustainable (Studio Marco Vermeulen, 2020). Especially regarding sustainable forestry, the public can have strong negative emotions associated with discussions around cutting down trees (Studio Marco Vermeulen, 2020). Most people do not know that cutting down trees can cause improvements in existing forests and that in the Netherlands, *Staatsbosbeheer* (the state's forest management organization) has been cutting down trees at a lower rate than the rate at which trees grow for decades (C. Schouten, 2019). The largescale resistance against the cutting down of trees stems from worries surrounding the decrease in biodiversity (Bouma, 2019), the association of cutting down trees with deforestation of rainforests (Hough, 2019), and illegal logging, especially in Brazil (NOS, 2019). Nevertheless, the discussed misconceptions are becoming increasingly less common and more easy to explain to interested contractors and consumers (V. de Beus, personal communication, May 21, 2021; M. Timmer, personal communication, May 10, 2021).

Material downsides

Timber can cause some swelling and shrinkage problems, for which oftentimes moisture is the determining factor. However, when timber is kept dry or dried quickly many problems are eliminated: ventilation and dilatation are thus important (Paes et al., 2020). Important downsides to timber are the acoustics and specifically contact noise, although there are easy measures to mitigate this (V. de Beus, personal communication, May 21, 2021; Van der Lugt & Harsta, 2020). For CLT specifically, the walls are thicker than when using standard materials, which decreases dwelling surface area (Bovee et al., 2021). When building with timber, all elements need to be customized by the supplier before they arrive on site, so there is little room for alterations (Paes et al., 2020).

Change of building techniques

Because of the long development processes of residential dwelling construction, it will take time for timber to be implemented on a larger scale. When the projects that are currently in the development phase have been constructed, it is likely that the ambition level for constructing residential dwellings from timber can increase more rapidly (Van der Lugt et al., 2021). Contractors are used to working a certain way, which is currently with mineral materials, and as there are cost agreements in place between the parties involved in construction, shifting to building with timber means taking a risk (A. Verkuijlen, personal communication, May 19, 2021; O. Wiggers, personal communication, May 26, 2021). It is uncertain if councilors, construction companies, and investors are willing to take the risks of construction of timber buildings, especially for CLT (Bovee et al., 2021; V. de Beus, personal communication, May 21, 2021). By developing smaller projects of about 20-30 dwellings instead of large-scale projects, the risk for investors can be smaller (Van der Lugt et al., 2021). However, Paes et al. (2020) have experienced that although CLT is different than what contractors are used to doing, it seems they are more and more willing to look further than the current norm of mostly traditional building materials such as concrete and steel.

Oftentimes, it is called for that timber and biobased materials should be used where possible, but abiotic materials like steel and concrete should be used where necessary (Bovee et al., 2021; J. M. Schouten et al., 2020; Van der Lugt et al., 2021), which is in part motivated by the current scarcity of available timber products (M. Timmer, personal communication, May 10, 2021). This may render TFC dwellings more favorable for low-rise buildings than CLT, as low-rise buildings do not require the structural properties that TFC can provide, and TFC systems require less timber than CLT systems (M. Timmer, personal communication, May 10, 2021; O. Wiggers, personal communication, May 26, 2021). However, the feasibility of the sourcing of timber is excluded from the system boundaries of this research, thus this current scarcity of available timber products is not taken into account within the framework of this research.

Environmental and energy performance scores

The Environmental Performance of Buildings (*MilieuPrestatie Gebouwen,* MPG) is a mandatory part of every application for an environmental permit. The MPG indicates the environmental impact of the materials used in a building and is applicable to all newly built residential dwellings (RVO, 2021b). As of July 1, 2021, the maximum MPG for new construction was decreased from 1 to 0.8 to encourage sustainable construction, with the goal to reduce this maximum to 0.5 by 2030 (NOS, 2021). In the current MPG, using timber for buildings has a negative environmental impact (Bovee et al., 2021), as biogenic carbon storage in timber is not taken into account in the MPG calculations (Keijzer et al., 2021). Over two hundred parties involved in timber construction signed a manifesto in December 2020, with the aim to value the use of timber in the MPG differently (NOS, 2021). This illustrates the large ongoing discussion in which many parties argue that there should be a level playing field by calculating the actual environmental impacts in the MPG, including biogenic carbon storage (Bovee et al., 2021; V. de Beus, personal communication, May 21, 2021; B. Zeisser, personal communication, May 14, 2021)

Aside from the MPG, the Nearly Zero Energy Buildings (*Bijna Energieneutrale Gebouwen*, BENG) requirements are perceived as a barrier for a level playing field. Since January 1, 2021, all permit applications for new residential buildings need to comply with the BENG requirements, which stem from the Energy Agreement for sustainable growth and from the European Energy Performance of Buildings Directive (EPBD) (RVO, 2021a). In the case of high environmental temperatures, TFC and CLT systems warm up relatively fast when compared to mineral buildings, which is considered as negative in the BENG requirements, leading to higher insulation requirements for timber buildings (V. de Beus, personal communication, May 21, 2021; O. Wiggers, personal communication, May 26, 2021). An often-raised counterargument is that in the case of a heat wave, which may become more and more frequent in the future (E. J. Klok & Kluck, 2018; KNMI, 2015), timber buildings also cool down faster during the nighttime than mineral buildings (V. de Beus, personal communication, May 26, 2021; M. Timmer, personal communication, May 10, 2021).

4.4 Sub-question 4: Potential for building with timber

4.4.1 Scenarios building with timber

The key assumptions for wood use scenarios Conventional Focus, Moderate Timber, and Wood Revolution are described in Table 15, where it is important to note that the developments of shares for timber use and timber construction systems are assumed to increase and decrease linearly between the indicated years. Furthermore, the storylines behind the assumptions are described below in Box 1 to Box 3. It is important to note that none of these three scenarios are necessarily more likely than the others, they merely describe what could happen in the future (see section 3.5.2).

Table 15. Assumptions on quantities of wood use scenarios. Sources and assumptions described in notes.

Parameter in scenario		Time (period)	Wood use scenario					
			Conventional Focus		Moderate Timber		Wood Revolution	
Share residential dwellings from timber		2020	2.0%[1]		2.0%[1]		2.0%[1]	
		2050	4.8%[2]		42.2%		80.0%[3]	
		2100	25.0%		52.5%		80.0%	
Timber construction system			**TFC**	**CLT**	**TFC**	**CLT**	**TFC**	**CLT**
Shares TFC and CLT	Detached, terraced, semi-detached	2020	95.2%[4]	4.8%[4]	95.2%[4]	4.8%[4]	95.2%[4]	4.8%[4]
		2050	95.2%	4.8%	76.7%	23.3%	50.0%[5]	50.0%[5]
		2100	95.2%	4.8%	72.6%	27.4%	50.0%	50.0%
	Apartment/flat[6]	2020-2100	0%	100%	0%	100%	0%	100%

[1] Timber used in residential dwellings in the Netherlands (NIBE Research, 2019).

[2] Percentage timber new dwellings (Bronsvoort et al., 2020).

[3] Percentage timber new dwellings (Metropoolregio Amsterdam & Amsterdam Economic Board, 2020) and maximum percentage timber new dwellings (Bronsvoort et al., 2020).

[4] Shares of TFC and CLT for residential dwellings in 2020 (Oldenburger, Van Den Briel, et al., 2020).

[5] Potential for shares TFC and CLT (Bronsvoort et al., 2020).

[6] Assumption: apartments/flats are high-rise buildings and are constructed from CLT.

Conventional Focus

The storyline and assumptions behind wood use scenario Conventional Focus are presented in Box 1.

Box 1. Conventional Focus scenario, adapted from Bronsvoort et al. (2020).

Few investments are made in the industrialization of the timber industry in the Netherlands. Under the influence of the lobby of the CO_2-intensive industry CO_2 legislation has weakened, resulting in minimal price incentives to stimulate alternative materials. The application of biobased materials hardly increases from 2020 to 2100, due to the lack of willingness from the construction industry to switch from conventional materials to more sustainable alternatives. Only timber is used regularly, albeit for only a small part of the residential dwellings constructed: approximately 5% per year in 2030, increasing linearly to about 25% in 2100. A lack of investments has not enabled the construction of CLT dwellings to become attractive due to the high costs, resulting in the largest share (approximately 95%) of timber dwellings being constructed using TFC.

Wood Revolution

The total percentages of new dwellings constructed from timber in scenario Wood Revolution in this research are based on a combination of the 2030 Wood Evolution scenario as described by (Bronsvoort et al., 2020) and the goal set by the Metropole Region of Amsterdam (MRA), which is to build 20% of new dwellings using biobased materials in 2025 (Metropoolregio Amsterdam & Amsterdam Economic Board, 2020). This goal is selected as a reference in this scenario because it is currently the only quantified goal that has been set by a government body in the Netherlands, and it should be achievable (Bovee et al., 2021). The storyline and assumptions behind this scenario are presented in Box 2.

Box 2. Wood Revolution scenario, adapted from Bronsvoort et al. (2020) and Metropoolregio Amsterdam & Amsterdam Economic Board (2020).

The impact of legislation (such as an altered MPG, CO_2 tax, and subsidies for sustainable construction materials) on CO_2-intensive materials has turned out to be so effective that clients and contractors have accelerated the search for alternative materials, including biobased materials such as wood. Contractors and construction companies are more and more willing to look further than the current norm of mostly traditional building materials such as concrete and steel, and have therefore created an industry focused on meeting the timber demand. The available timber from forests within Europe has increased drastically from 2020 to 2100, along with sustainable forest management practices. As a result, the cost price of these materials has also fallen further. Of the new dwellings constructed annually, 20% is constructed from timber in 2025, increasing until 80% in 2042, after which the percentage plateaus: conventional materials such as steel and concrete are still used as they become increasingly available from the built environment, which is preferred over the discarding of materials. The reduced price of wood has stimulated the increased use of CLT in buildings beyond high-rise buildings, as CLT offers benefits over TFC (such as no swelling and shrinking, improved acoustics, and a better indoor climate), reaching a 50-50 divide for low-rise buildings in 2050. CLT has a higher potential to store carbon than TFC, but this also entails that CLT requires more resources than TFC systems: caution surrounding depletion of natural resources and ensuring sustainable forest management has led to the 50-50 divide to remain more or less stable until 2100.

Moderate Timber

The total percentages of new dwellings constructed from timber in scenario Moderate Timber are based on the averages found in the Conventional Focus and Wood Revolution scenarios. The storyline of this scenario is based on the Wood Evolution scenario as described by Bronsvoort et al. (2020) and is described in Box 3.

Box 3. Moderate Timber scenario, adapted from Bronsvoort et al. (2020).

Partly on the basis of announced laws and regulations that aim to give biobased materials such as wood an advantage, large-scale investments have been made since 2020 in the industrialization of building in wood and other biobased materials. As a result, the cost price of those materials has decreased significantly, the quality has improved and prefabrication has proven its advantage on construction sites. Although the impact of legislation and regulations has lagged behind, building with timber has become more commonplace in the Netherlands and the share has increased to 12% of the total market in 2025, and 45% in 2050. CLT is used increasingly more in construction of dwellings, reaching a share in the timber residential construction sector of approximately 25% in 2050. TFC systems are still used widely in the Netherlands and thus retain the largest share of dwellings from timber of over 70% from 2050 until 2100.

4.4.2 Technical potential number of dwellings from timber

The numbers of dwellings from TFC and CLT were calculated following the equations discussed in section 3.5.3. To show an indication of the average annual numbers of dwellings in TFC and CLT, the results for scenario Middle pop. are shown (Figure 24), for wood use scenarios Conventional Focus, Moderate Timber, and Wood Revolution. The results for scenarios Low pop. and High pop. are presented in Appendix V.

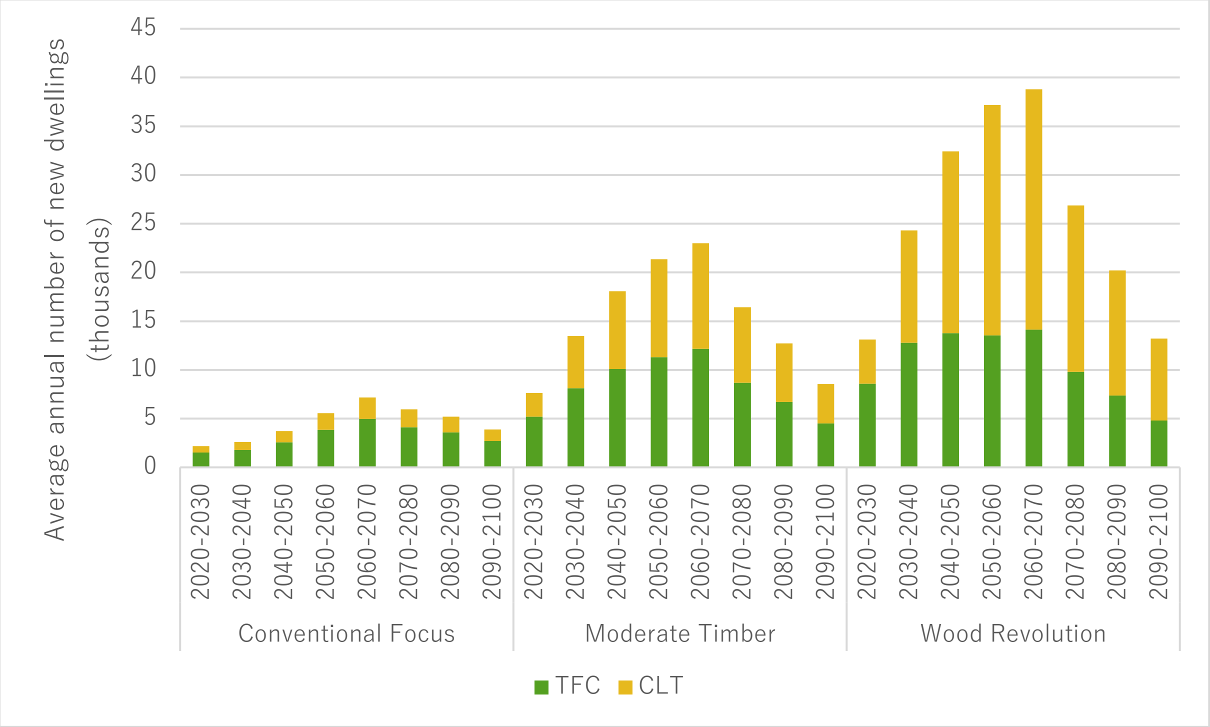


Figure 24. Average annual number of dwellings from TFC and CLT in the Netherlands from 2020-2100: scenario Middle pop.

Figure 24 shows that in scenario Conventional Focus, the numbers of dwellings from timber are low, with just over 2,000 new TFC and CLT dwellings annually (on average) in the period 2020-2030 and the highest contribution to timber dwellings in the period 2060-2070, with on average just over 7,000 new TFC and CLT dwellings annually. In each time period, the majority of dwellings is constructed using TFC systems. In scenario Moderate Timber, the numbers of dwellings from timber are higher than for scenario Conventional Focus, with just over 7,600 new TFC and CLT dwellings annually (on average) in the period 2020-2030 and the highest contribution to timber dwellings in the period 2060-2070, with on average just under 23,000 new TFC and CLT dwellings annually. Although in each time period the majority of dwellings is constructed using TFC systems, the ratio between TFC and CLT systems balances out towards 2100. In scenario Wood Revolution, the numbers of dwellings from timber are much higher than for scenarios Conventional Focus and Moderate Timber, with just over 13,000 new TFC and CLT dwellings annually (on average) in the period 2020-2030 and the highest contribution to timber dwellings in the period 2060-2070, with on average over 38,000 new TFC and CLT dwellings annually. From 2020 to 2040, the majority of dwellings is constructed using TFC systems and from 2050 to 2100, the majority of dwellings is constructed using CLT systems due to the benefits discussed in Box 2.

4.4.3 Timber quantities of residential dwellings

As there were no data available on the quantities of TFC or CLT used for the dwelling type semi-detached, it was assumed that the quantities of TFC and CLT are the average of the quantities for the dwelling types terraced house and detached. The quantities of timber used for the different dwelling and construction methods are presented below (Table 16).

Table 16. Average quantities of TFC and CLT for the dwelling types apartment/flat, terraced house, semi-detached, and detached. Sources are listed in the last column.

Dwelling type	Quantity TFC (m³)	Quantity CLT (m³)	Sources
Apartment/flat	-	33.1	(Van der Lugt & Harsta, 2020, p. 43) (Van der Lugt & Harsta, 2020, p. 154) (V. de Beus, personal communication, May 21, 2021)
Terraced house	20	42.5	(Oldenburger, Van Den Briel, et al., 2020) (V. de Beus, personal communication, May 21, 2021)
Semi-detached	23	48.8	Average of detached and terraced house[1]
Detached	25	55	(Oldenburger, Van Den Briel, et al., 2020) (Van der Lugt & Harsta, 2020, p. 41)

[1] Assumption, as terraced houses share two sides with one neighbor on each side, semi-detached dwellings share one side with a neighbor, and detached dwellings do not share a side with neighbors.

In order to calculate the quantities of timber demand in dwellings constructed from timber (TFC and CLT), wood use scenarios Conventional Focus, Moderate Timber, and Wood Revolution were combined with the numbers of new dwellings found in section 4.1 for scenarios Low pop., Middle pop., and High pop. The results for the average annual timber use for residential buildings are presented below (Figure 25).

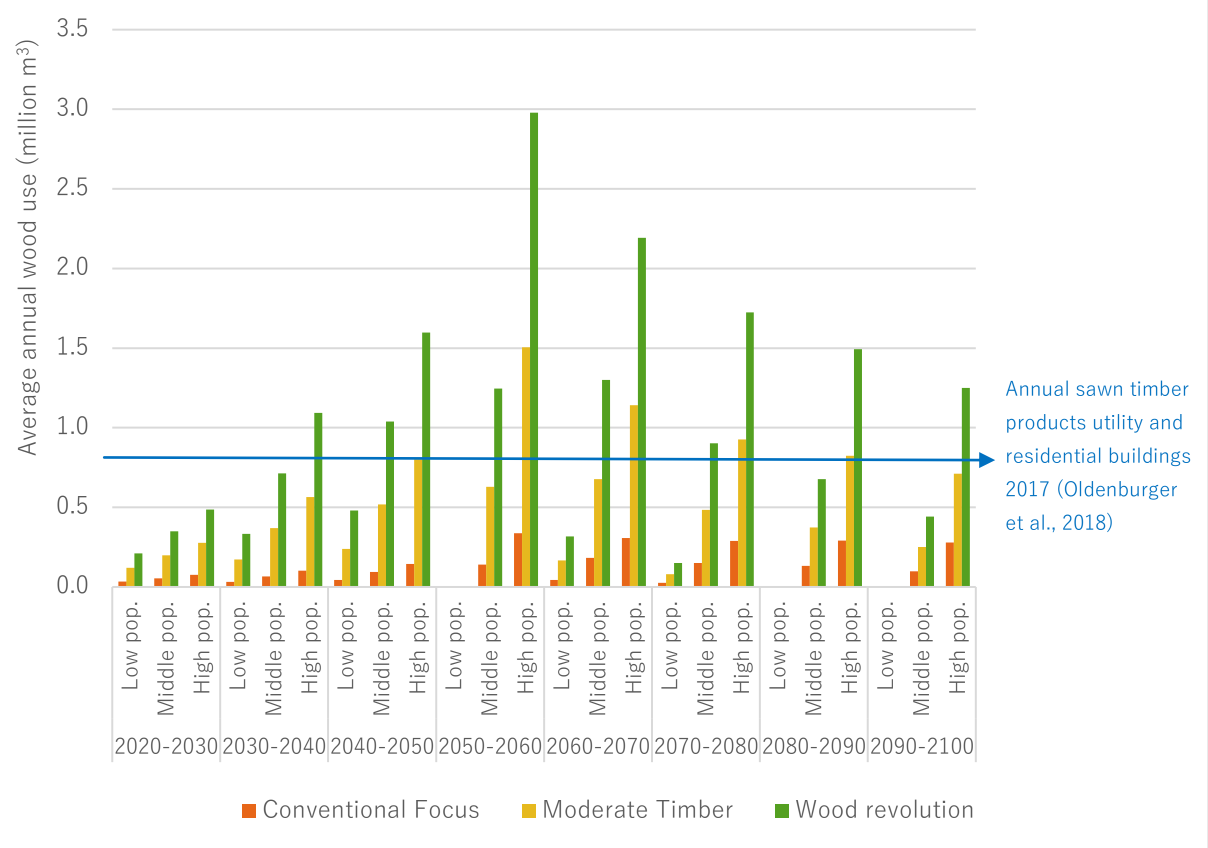


Figure 25. Average annual timber use in residential dwellings in the Netherlands until 2100 per decade under various population growth and wood use scenarios.

Figure 25 shows the average annual timber use in million m^3 for each combination of scenarios, leading to nine results for each decade. The differences in period 2020-2030 are minimal compared to the large differences seen between the different scenarios from 2030 onwards. To put these results in perspective: in 2017, the total annual volume of sawn timber used in residential and utility buildings was approximately 1.157 million m^3 roundwood equivalent (rwe), which amounts to about 857,000 m^3 sawn timber products[1] (Oldenburger et al., 2018). Although this research only takes into account residential dwellings, it can be seen that for scenario Low pop., all three wood use scenarios (Conventional Focus, Moderate Timber, and Wood Revolution) result in a significantly lower volume of annual timber use than today. The current annual consumption is exceeded in the period 2030-2100 in the High pop. and Wood Revolution scenario; in other scenarios for shorter periods.

4.5 Sub-question 5: Maximization strategies length of use building with timber

There are different types of strategies for the maximization of the length of use of timber elements in residential dwellings. First, the preconditions for reuse of timber are discussed. Second, use length maximization strategies are discussed: design strategies, strategies for disassembly, and strategies for the development of reuse logistics. Finally, the storylines and assumptions behind the scenarios for cascading potential of timber in residential dwellings, which are based on these maximization strategies, are presented. It is important to note that the design strategies are not taken into account in the scenarios for cascading potential. This research focuses on the periods 2020-2050 and 2020-2100, and assumes an average dwellings lifetime of 75 years. This means that the design strategies will only become relevant for the cascading potential 75 years after the first dwellings incorporating these strategies have been constructed. As residential dwelling construction has long development processes, the cascading potential of newly constructed dwellings becomes relevant after the temporal scope of this research.

4.5.1 Preconditions timber quality

There are certain preconditions for the quality of timber if it is to be reused or recycled for construction purposes: timber must be free of wood preservatives or other pollutants that have penetrated the wood, fungi and insects, and traces of metal that could damage reprocessing machinery, and it should also have sufficient strength and size qualities (Klinge et al., 2019). Generally speaking, timber from demolished dwellings that has been used as a structural element is of good quality and therefore lends itself well for reuse (Brol et al., 2015; Hafner, Ott, & Winter, 2014; Hafner, Ott, Bodemer, et al., 2014; A. Verkuijlen, personal communication, May 19, 2021). Additionally, the possibility of reusing smaller sections of timber (that would individually not suffice as a structural element) by combining them into a CLT element is being explored (A. Verkuijlen, personal communication, May 19, 2021).

4.5.2 Design

In this section, possible design strategies for the maximization of lifetimes of timber elements are identified and linked to the principles of circular design (PCD) discussed in section 2.3.

Materials

To optimize the use of timber, wood could in the first place be used to construct TFC elements as this uses less wood than CLT elements (Bovee et al., 2021; J. M. Schouten et al., 2020; Van der Lugt et al., 2021), enforcing PCD 1 (Low-material design). When buildings with TFC elements are demolished, these elements could be reused as TFC elements and the parts of timber that are not suitable for TFC elements anymore could be made into CLT elements (M. Timmer, personal communication, May 10, 2021), which connects well to PCD 5 (Design for recycling).

Contact between timber and other materials or substances like cement, insulation, or glues should be minimized where possible, and otherwise mitigated, as this decreases the possibilities for reuse of timber elements (A. Verkuijlen, personal communication, May 19, 2021). As such, PCD 4 (Design for deconstruction) should be upheld by creating building designs where timber is not irreversibly designed to be in contact with other materials or substances. Additionally, when reversible connections are implemented, it is important that plastering over connections is mitigated as much as possible, as this makes disassembly more difficult (M. Timmer, personal communication, May 10, 2021).

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[1] Conversion factor 1.35: 1.35 rwe is required for 1 m^3 sawn timber product (Oldenburger et al., 2018).

Connections

In timber construction, the connections are often the weakest part of the system, therefore determining the possibilities for the dimensions of timber elements (Van der Lugt & Harsta, 2020). It is thus important to find a suitable trade-off between the connection strength and the potential for reusability and disassembly that connections create. As timber construction systems are dry systems, the use of either wood or steel connections leads to the same suitability for disassembly, though Dutch contractors do prefer to use steel connections (B. Zeisser, personal communication, May 14, 2021). A new measuring method for the disassembly potential of construction elements quantifies the disassembly potential of connections on a scale of 1 (maximum disassembly potential) to 0 (no disassembly potential) (Van Vliet et al., 2021) (Table 17).

Table 17. Disassmebly potential of connections on a scale of 1 (maximum disassembly potential) to 0 (no disassembly potential) (Van Vliet et al., 2021).

Connection	**Disassembly potential**
Click system	1.0
Nuts and bolts	0.8
Screws	0.8
Nails	0.6
Dowels	0.6
Glued connections	0.1

Nails are the most commonly used connections in timber construction and are available in many different sizes and with various different quality properties (Livingstone, 2016). Screws are especially suitable for steel-to-timber and panel-to-timber joints but are also used for timber-to-timber joints, and considering structural integrity, screws have a higher withdrawal capacity than nails (Livingstone, 2016). Oftentimes, processes of de-nailing or unscrewing at the end-of-life of the structure are carried out (Cruz Rios et al., 2019). However, these processes can damage the timber from which nails and screws are removed (Sakaguchi et al., 2017), e.g. by leaving visible holes undesirable for future use or compromising the potential to apply new connections, and are thus sometimes categorized as irreversible connections (Klinge et al., 2019).

Bolts are dowel-type fasteners with heads and nuts and are placed through pre-drilled holes which are about 1-2 mm oversized, after which the bolt and washer are tightened so the connection fits closely together (Livingstone, 2016). Nuts and bolts are very suitable connections for timber elements that also make assembly and disassembly of the timber construction system fairly straightforward (B. Zeisser, personal communication, May 14, 2021).

Dowels are circular rods of timber, steel, or carbon-reinforced plastics, which are driven into identically or slightly undersized holes (Livingstone, 2016). Dowel connections are not the most ideal connections since timber shrinks and swells, especially in the case of TFC, and should thus be designed properly so connections do not loosen (A. Verkuijlen, personal communication, May 19, 2021). The use of wooden dowels makes it slightly more difficult to disassemble timber elements than the use of nuts and bolts, but wooden dowels could also be sawn through (B. Zeisser, personal communication, May 14, 2021).

The most effective connection method mechanically speaking is gluing, which is often done in a controlled environment and thus excludes on-site gluing, reducing the flexibility of the application (Van der Lugt & Harsta, 2020). Nevertheless, glue is still used often as it is the quickest way of connecting elements (A. Verkuijlen, personal communication, May 19, 2021). However, glued connections are not beneficial when taking into account PCD 2 through 5, as the potentials for disassembly and reuse are highly impaired when applying glued connections. A more circular development in the future could be the use of a special treatment in the form of a specific type of hot glue which can be soaked off by applying heat to the element (M. Timmer, personal communication, May 10, 2021).

A possible future connection method is the click system. Currently, click systems are mostly applied to mineral materials such as bricks (Schut et al., 2015a; Van Dam & Van den Oever, 2019). Although this is currently not a highly implemented connection system, there is an interest in adopting these types of connection systems (V. de Beus, personal communication, May 26, 2021).

Prefabrication

Conflicting with PCD 7 (Materials passport), a downside to existing prefab elements is that it is often not documented which materials or connection methods were used (Nelissen et al., 2018), resulting in the prefab element not being reused in the same function: in some cases these prefab elements can be downcycled as particleboard, but oftentimes they are directly sent to incineration (A. Verkuijlen, personal communication, May 19, 2021). Additionally, conflicting with PCD 4 (Design for deconstruction), prefabrication is in practice almost never suitable for disassembly: insulation materials are glued to timber elements which complicates disassembly, or when PUR foam is stuck to timber elements this results in the element becoming chemical waste (A. Verkuijlen, personal communication, May 19, 2021), which negates the preconditions discussed in section 4.5.1.

Taking into account these downsides experienced with existing prefab elements, designs of dwellings using prefab elements should thus not only focus on easy construction, but also on easy disassembly after the end-of-life of a building has been reached or the function of a building or location has been changed, enforcing PCD 2 (Modular design), 3 (Adaptive design), and 4 (Design for deconstruction). This could be realized by prefabricating to the lower complexity levels and smaller scales as presented in Figure 9 (section 2.6.2), as producing less complex prefab elements will increase the disassembly potential of these elements (Bertram et al., 2019). When prefabrication is combined with the possibility for dis- and reassembly, using prefab elements can prove a very beneficial method to maximize the lifetime of timber elements, with many other accompanying benefits (see section 4.3.1). Timber construction is a market that lends itself well to digital design, preprocessing, and assembly (R. van Gurp, personal communication, May 20, 2021). Therefore, an important step in enabling disassembly of construction systems is good prefabrication: designing the connections of different elements digitally and drilling holes for connections beforehand, so the construction system can be brought to the construction site as one construction kit (B. Zeisser, personal communication, May 14, 2021).

Materials passport

For timber, there are currently no standard tables which present the different qualities of timber construction elements, which do exist for e.g. steel (B. Grootenboer, personal communication, June 2, 2021). As mentioned in section 2.3, the materials passport is an important PCD (7), which is a strategy that will allow for the maximization of the lifetime of timber elements by describing the exact wood type, strength category, connections, glue type (where applicable), and combinations with other materials used (B. Grootenboer, personal communication, June 2, 2021). Materials passports of residential dwellings facilitate efficient reuse and recycling of materials (Peschier, 2019), and should thus be a mandatory component of the design of new residential dwellings. However, several materials passport initiatives already exist with differing descriptions of proposed materials passport content, which means that there is a need for one clear definition of a materials passport (Stolk, 2019).

Regulations

Due to the continuous updating of the building decree *(Bouwbesluit)* and the energy performance regulations, timber elements that are used in dwellings constructed in the past may not be able to be used in the same form today, and elements used in dwellings constructed today may not be able to be used in the same form in the future. Stricter insulation requirements result in the need for thicker elements; stricter daylight requirements may result in the need for (prefab) elements with larger window openings; increasing story height requirements may result in the need for larger or longer timber elements (M. Timmer, personal communication, May 10, 2021). All these uncertainties are the opposite of what PCD 3 (Adaptive design) and 6 (Recycle for design) entail, which implies that there will very likely be practical objections to reusing timber elements in the same form as they were used in their first product life. In the design of dwellings, it should thus be taken into account that the elements may need to be updated (increased in width or length or changed in dimensions) according to updated regulations.

4.5.3 Strategies for disassembly

For the disassembly of building elements a different approach to demolition is required. The methods required for disassembly of elements are in essence reversed construction methods, the tools needed for disassembly are thus the same tools used in construction (A. Verkuijlen, personal communication, May 19, 2021). Experience does show that employees are educated differently: a traditional demolition employee is practically educated, whereas a disassembly employee needs more dexterity in order to disassemble the elements so they remain undamaged and suitable for reuse (A. Verkuijlen, personal communication, May 19, 2021).

It is important to note that existing dwellings are not designed for disassembly: where elements are glued together, it is difficult to disassemble these for reuse (A. Verkuijlen, personal communication, May 19, 2021). New techniques should thus become available that make the disassembly of certain combinations of materials, like plaster and wood, more efficient (M. Timmer, personal communication, May 10, 2021). It is speculated that this should be possible, for instance by using a type of chord which can be pulled between timber and glued insulation to separate these, or cut insulation layers off with a laser (O. Wiggers, personal communication, May 26, 2021).

4.5.4 Strategies for logistics development

Quality determination

As mentioned in section 4.5.2, there are currently no standards which present the different qualities of timber construction elements (B. Grootenboer, personal communication, June 2, 2021). Therefore, standards should be set on the most important timber quality parameters: dimension, shape, stiffness, vibration, load-bearing capacity, smell, and durability (Kliger, 2016). For reused timber, important additional quality parameters are defects (such as holes from nails or screws), glue remnants, and glues used (in the case of CLT and other laminated timbers) (B. Grootenboer, personal communication, June 2, 2021). As long as there are no guarantees for the different quality parameters, it may prove difficult to justify the implementation of reused timber as structural elements in buildings to architects, contractors, and other stakeholders (B. Grootenboer, personal communication, June 2, 2021).

Infrastructure

When there is not only virgin timber to take into account but also reused timber, this can pose some logistical issues. There are two ways to approach the production and use of virgin timber and the disassembly and reuse of secondary timber: a just-in-time (JIT) approach and a storage approach.

In a JIT approach, the amount of materials held in stock is minimal and elements are produced and delivered at the time they are required for construction (Victor, 2018), which avoids unnecessary storage and double handling of elements (Waugh Thistleton Architects, 2018). This limited timber storage potential does mean that when dwellings are demolished, there is a higher change of secondary timber being used for lower-value end uses or incineration with energy recovery. In practice, JIT planning is difficult to realize in residential dwelling construction (Metabolic & DR2 New Economy, 2018a).

In a storage approach, secondary timber elements that cannot be directly reused in new projects are stored until they are used. This reduces the chances of these timber elements being used for lower-value end uses or incineration, but storage space can be expensive and permits can be difficult to receive (Metabolic & DR2 New Economy, 2018a). Therefore, empty storage locations could be considered: a suggested potential storage location for timber is the previous locations for coal transshipment in Dutch harbors (Bronsvoort et al., 2020).

Another important aspect to take into account is transport of timber. In a JIT approach, the transport of timber is minimal (Konijnenberg, 2014): timber is transported from the disassembly location to a reprocessing location (when necessary), to the location of reuse, whereas in a storage approach, the transport could be far greater than in the case of a JIT approach depending on the storage location. This increased need for transport would also entail increased costs, labor, and emissions.

As both the JIT and the storage approach have benefits and downsides, an optimal balance between a JIT and storage approach is needed, where timber is reused directly where possible and stored where necessary.

Marketplace for supply and demand

Metabolic & DR2 New Economy (2018a) identified that for all stakeholders involved in the construction sector there is a clear need for a marketplace for reusable construction materials in general: there is a long way to go for matching supply and demand. In order for the reuse of timber to be efficient, an overview of the different flows of reusable timber should be strived for (Arnoldussen et al., 2020; Du Saar, 2021; Gemax B.V., 2020). The presence of such an overview will likely reduce material waste (Konijnenberg, 2014). This should not be organized by setting up different systems in parallel, but by collaborating to report and manage the data about released and required timber flows (Metabolic & DR2 New Economy, 2018a). This data should include quality parameters as discussed earlier in the paragraph on quality determination, as well as the quantities and location of the available timber.

4.5.5 Scenarios cascading potential

The key assumptions for reuse scenarios Primary, Mix, and Reuse are described in Table 18, where it is important to note that the developments of shares for timber reprocessing, lower-value reuse, incineration, and reuse were assumed to increase and decrease linearly between the indicated years. Furthermore, the storylines behind the assumptions are described below in Box 4 to Box 6. For these scenarios, assumptions were made regarding the strategies for disassembly and strategies for logistics: as these strategies are not yet implemented in practice, no quantification of the effectiveness of these strategies exists.

Table 18. Assumptions on quantities of reuse scenarios. Sources and assumptions described in notes.

Parameter in scenario	Time (year)	Reuse scenario					
		Primary		Mix		Reuse	
Shares of timber to reprocessing	2020	0%[1]		0%[1]		0%[1]	
	2050	0%		37.5%		100%[2]	
	2100	0%		100%		100%	
Shares timber to direct lower-value reuse and incineration		Lower-value	Incineration	Lower-value	Incineration	Lower-value	Incineration
	2020	46.0%[1]	54.0%[1]	46.0%[1]	54.0%[1]	46.0%[1]	54.0%[1]
	2050	46.0%	54.0%	28.8%	33.8%	0%[2]	0%[2]
	2100	46.0%	54.0%	0%	0%	0%	0%
Share reuse of TFC to CLT (waste)	2020	0%		0%		0%	
	2050	0%		5.3%		14.1%[3]	
	2100	0%		14.1%		14.1%	

[1] Shares of reuse, lower-value reuse and incineration (Metabolic & DR2 New Economy, 2018b).

[2] Goal for reuse (Rijksoverheid, 2016).

[3] Technical potential from downsizing standard sizes (Friesland Prefab, n.d.).

Primary

Scenario Primary functions as a reference scenario for the cascading potential, where the focus is still on using primary materials in construction. There are no quantitative data available on the reuse of timber elements from residential dwellings of the Netherlands as a whole (Gemax B.V., 2020), which is often regarded as a barrier for so-called urban mining demolition companies (Du Saar, 2021). Nevertheless, it is discussed that timber is for the largest share reused in the form of particleboard or wood chips and most often incinerated (with energy recovery) (Algemene Vereniging Inlands Hout et al., 2016; Peschier, 2019; Strengers et al., 2018). Direct reuse of timber elements is only done by small-scale initiatives (Metabolic & DR2 New Economy, 2018a). The storyline and assumptions of this scenario are described in Box 4.

Box 4. Primary scenario, values from Table 18.

Although the Dutch government has set targets for a more circular economy within the Netherlands, the investments in infrastructure required to allow for higher-value reuse of structural timber elements have not been made. Additionally, there is no general marketplace, only a selection of small marketplaces run by small-scale initiatives where a limited overview for available secondary construction materials is provided. Design for dis- and reassembly have only been implemented by architects who can design buildings in high-end price categories: the largest share of affordable new dwellings is designed using conventional methods for connections and material combinations. No investments have been made into innovative disassembly techniques, which makes disassembly of timber from existing dwellings laborious and costly. This lack of infrastructure for the reuse of existing timber elements and lack of incentives for dis- and reassembly results in practically no high-value reuse and consistent ratios for lower-value reuse (46%) and incineration with energy recovery (54%) until 2100.

Reuse

Scenario Reuse functions as a high estimate scenario for the cascading potential, where there is a strong focus on high-value reuse. It is based on the circularity regulations from the Dutch government, in which they state targets to be 100% circular by 2050 (Rijksoverheid, 2016). However, biotic materials such as wood and bioplastics are not covered by the policy's target (A. G. Prins & Rood, 2020), and biomass (including waste wood streams) is still counted under the ‘Stimulation Regulation Sustainable Energy Production’ (*Stimuleringsregeling Duurzame Energieproductie*) or SDE++ subsidy, which provides subsidies for the incineration of biomass as a renewable energy source (RVO, 2020b). Therefore, in these targets, timber is not considered to be 100% circular to the same extent as other materials such as steel or concrete (Rijksoverheid, 2016). The percentage of timber lost to downsizing to the next standard-sized element is based on the standard sizes discussed in 2.6.1, which results in a downsizing percentage of 14.1% for TFC elements and 8.8% for CLT elements. It is assumed this TFC percentage is reprocessed into CLT (flow E), and the CLT percentage is reprocessed into lower-value end uses (flow F2). The storyline and assumptions are described in Box 5.

Box 5. Reuse scenario, values from Table 18.

The circular economy targets from the Dutch government of being 100% circular do not include wood to the same extent as other materials, as waste wood was intended to fall under the SDE++ subsidy. However, the circularity targets have been pushed even further, encompassing all biomass in the target of being 100% circular including wood waste, which is not included under the SDE++ subsidy anymore. Investments into infrastructure, such as storage facilities and efficient transportation, are implemented with urgency. The market has shaped a marketplace where many different stakeholders provide their available secondary timber, creating an overview of what is available. Investments into the development of new disassembly techniques for existing residential dwellings allow for a more efficient disassembly process, where timber can be separated from other materials with ease. These measures allow the rates of reprocessing for reuse to increase linearly from 0 to 100% until 2050, and remain there until 2100. Reuse of TFC reprocessing waste into CLT is highly stimulated, thus increasing this percentage from 0% in 2020 to the maximum rate of 14.1% in 2050, where it remains until 2100. The rates for lower-value reuse (46%) and incineration (54%) decrease until 0% until 2050, and remain there until 2100, with the exception of lower-value reuse of reprocessed CLT, which decreases to the CLT reprocessing waste percentage of 8.8%[1] in 2050, where it remains until 2100.

[1] Percentage from De Groot Vroomshoop Gelijmde Houtconstructies B.V. (2017).

Mix

Scenario Mix functions as a middle-of-the-road estimate for the cascading potential, where there is a focus on increasing high-value reuse, but also using primary materials where it is convenient. This scenario is an average between scenarios Primary and Reuse, with the storyline and assumptions described in Box 6.

Box 6. Scenario Mix, values from Table 18.

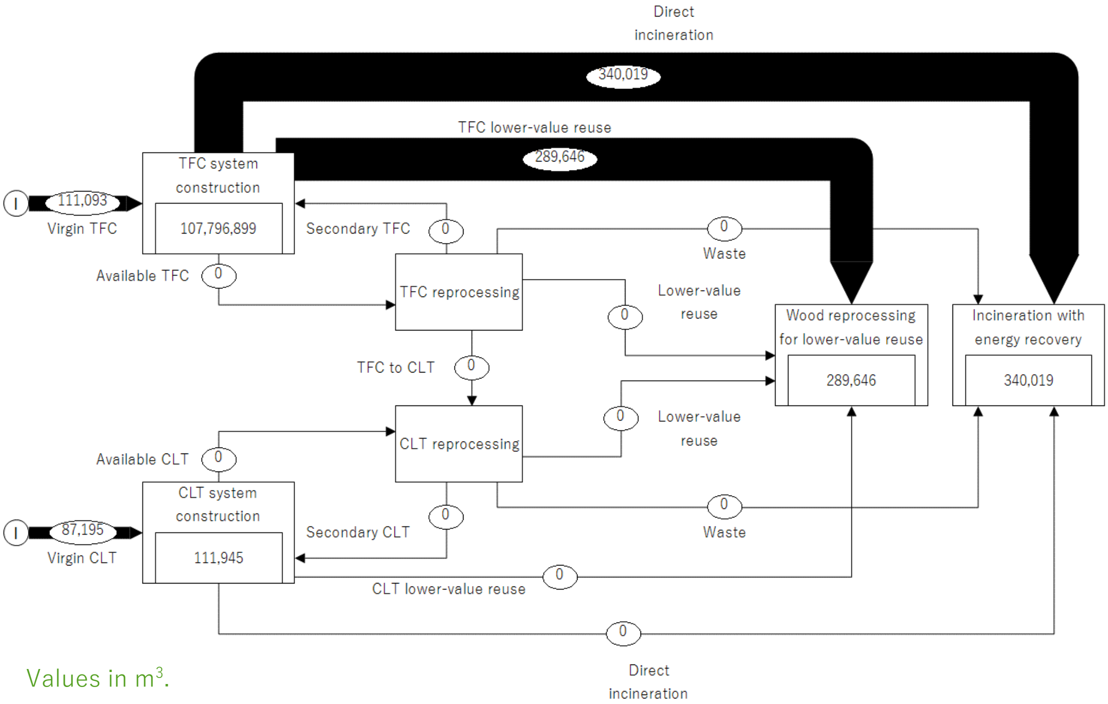
Compared to scenario Reuse, the circularity targets are pushed further than the targets set by the Dutch government in 2016, thus encompassing all biomass in the target of being 100%, including timber. However, this is done more slowly, phasing wood waste out of the SDE++ subsidies. Investments into infrastructure are made allowing high-value reuse, though this infrastructure is implemented at a lower speed than in scenario Reuse. Several marketplaces emerged where many different stakeholders provide their available secondary timber, though a cohesive overview of available materials is lacking. The development of new disassembly techniques for existing residential dwellings is slow, though techniques are found allowing timber to be separated from other materials with in specific circumstances. Therefore, the rates of high-value reuse increase more slowly: from 0 to 100% until 2100, and the rates for lower-value reuse (46%) and incineration (54%) decrease more slowly as well: until 0% until 2100, with the exception of lower-value reuse of reprocessed CLT, which decreases to the CLT reprocessing waste percentage of 8.8%[1] in 2100. Reuse of TFC reprocessing waste into CLT is stimulated somewhat, increasing this percentage from 0% in 2020 to the maximum rate of 14.1% in 2100.

[1] Percentage from De Groot Vroomshoop Gelijmde Houtconstructies B.V. (2017).

4.6 Sub-question 6: Quantities virgin and reused timber and associated carbon storage

4.6.1 Overview MFA

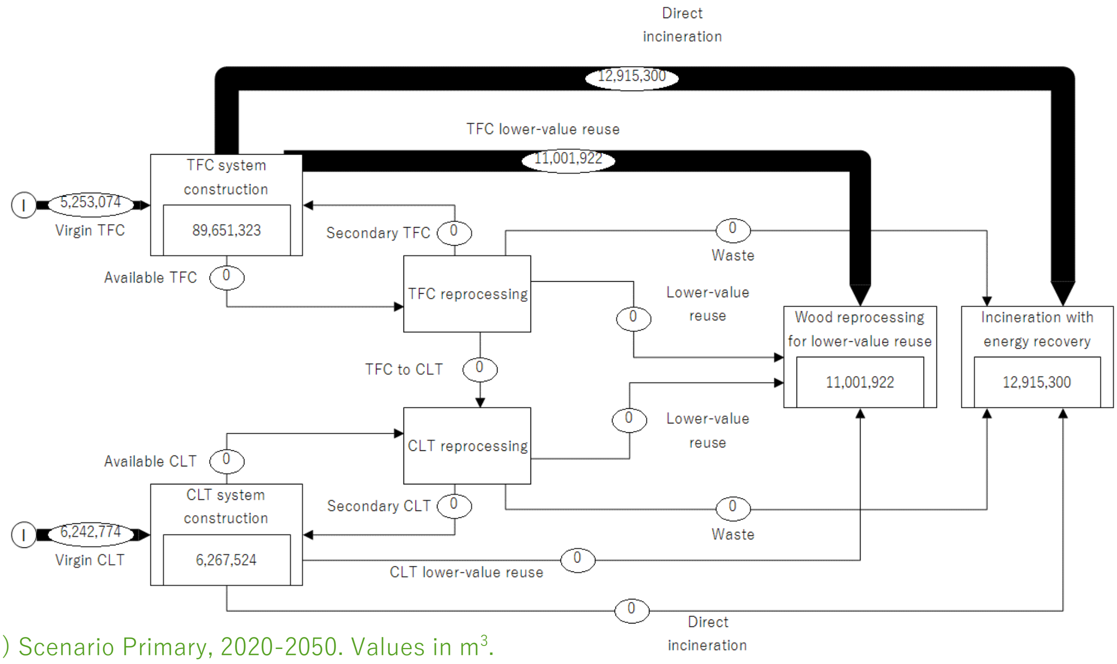
Due to the number of scenarios studied in this research, a selection of these scenarios was chosen to visualize in this section as Sankey diagrams. The diagrams in Figure 26 to Figure 29 below show the timber flows for scenario Middle pop., wood use scenario Moderate Timber, for 2020 (which is the same for all three reuse scenarios), and for 2020-2050 and 2020-2100 for the three reuse scenarios. The modelled stocks wood reprocessing for lower-value reuse and incineration with energy recovery are not stocks in real life, which is further discussed in section 5.1.4.



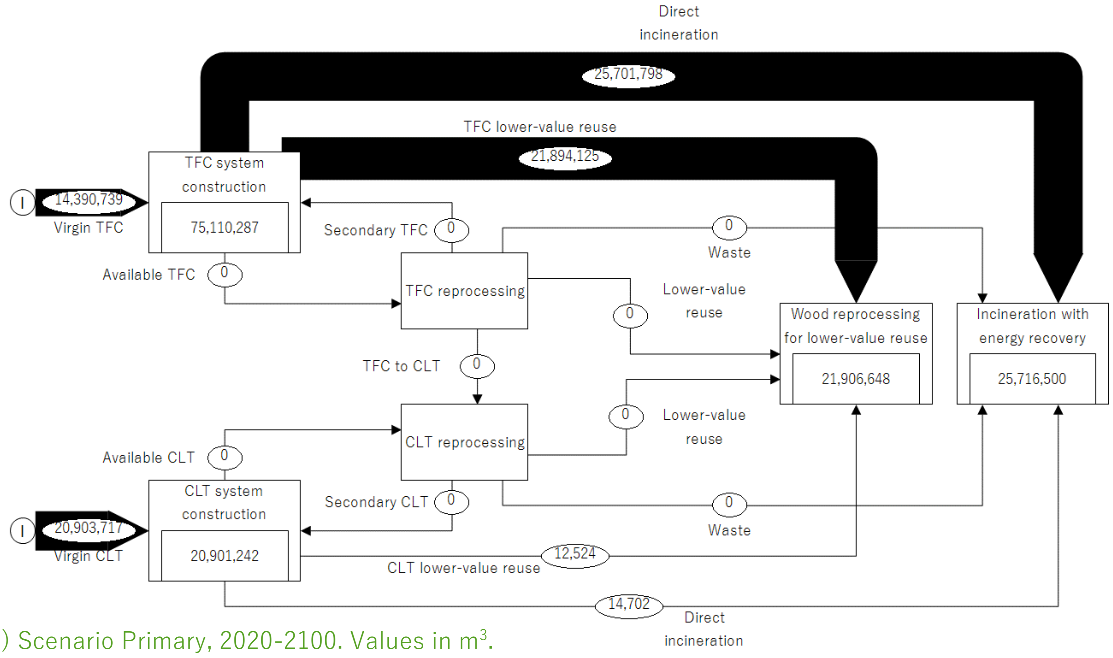
Values in m^3.

Figure 26. Overview stocks (rectangles) and material flows (arrows with circles) of timber (m^3) for scenario Middle pop., wood use scenario Moderate Timber, in 2020. These values are the same for reuse scenarios Primary, Mix, and Reuse.

Figure 26 visualizes that there is currently no infrastructure in place for the reuse of timber originating from residential dwellings. As a result, all available timber from the TFC systems is either processed for lower-value reuse or incinerated with energy recovery. More timber becomes available from the built environment than is used in residential dwellings, as the percentage of existing dwellings from timber is larger than the percentage of newly constructed residential dwellings from timber (see also Figure 22). As CLT systems have not been a part of the built environment of residential dwellings until recently, the timber from these systems does not become available until 2090-2100 according to the model calculations. It is important to note that Figure 26 visualizes the model results for timber flows in 2020 and does not reflect measured quantifications of flows.



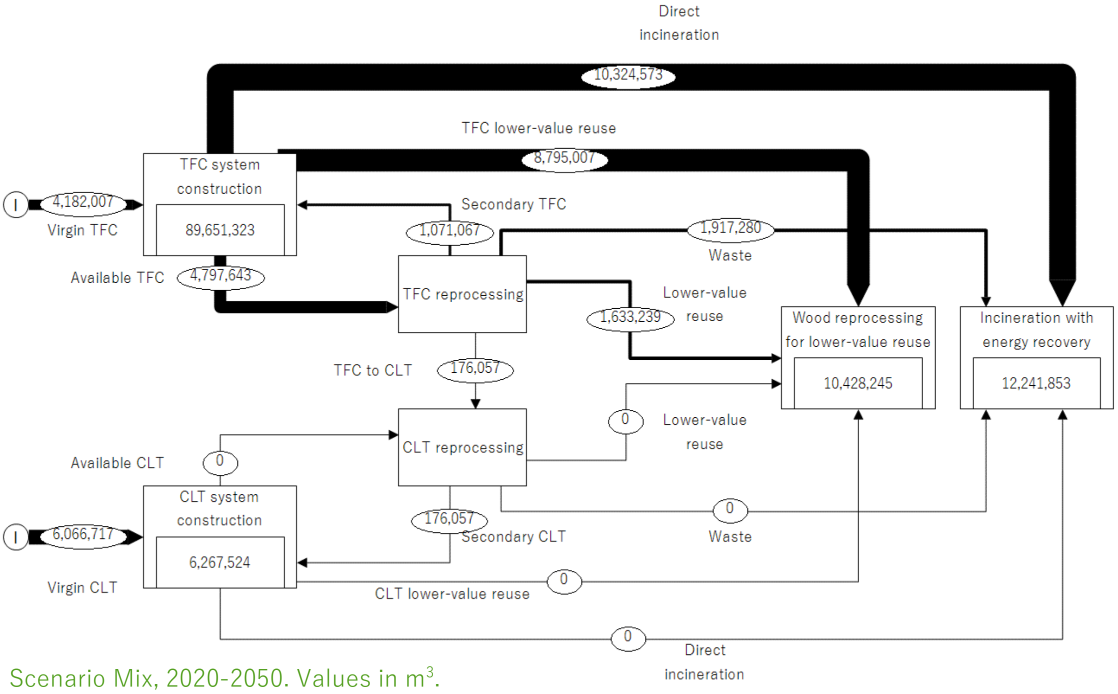
a) Scenario Primary, 2020-2050. Values in m^3.



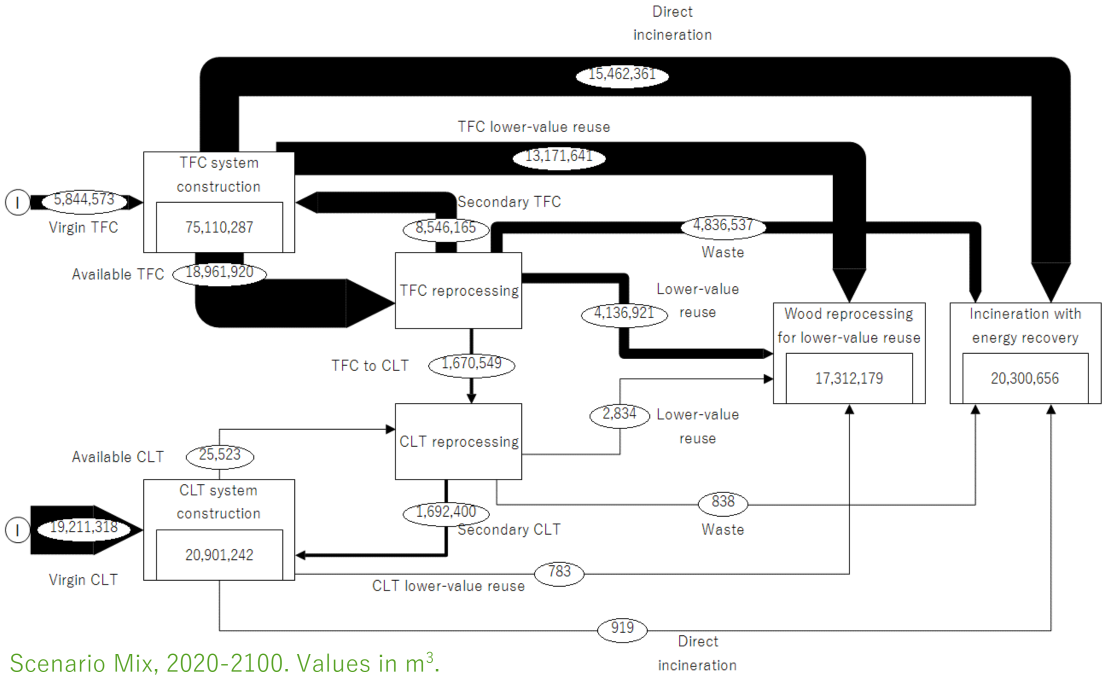
b) Scenario Primary, 2020-2100. Values in m^3.

Figure 27 a) and b). Overview stocks (rectangles) and material flows (arrows with circles) of timber (m^3) for scenario Middle pop., wood use scenario Moderate Timber, reuse scenario Primary, in a) 2020-2050 and b) 2020-2100. The flows represent the values over the entire period, the stocks represent the values in the final year of the period.

Figure 27 a) and b) visualize the flows that would occur if no efforts are made to implement an infrastructure for the reuse of timber originating from residential dwellings. More and more timber is either processed for lower-value reuse or incinerated with energy recovery. This lack of reuse also results in high virgin timber demands for TFC and CLT systems.



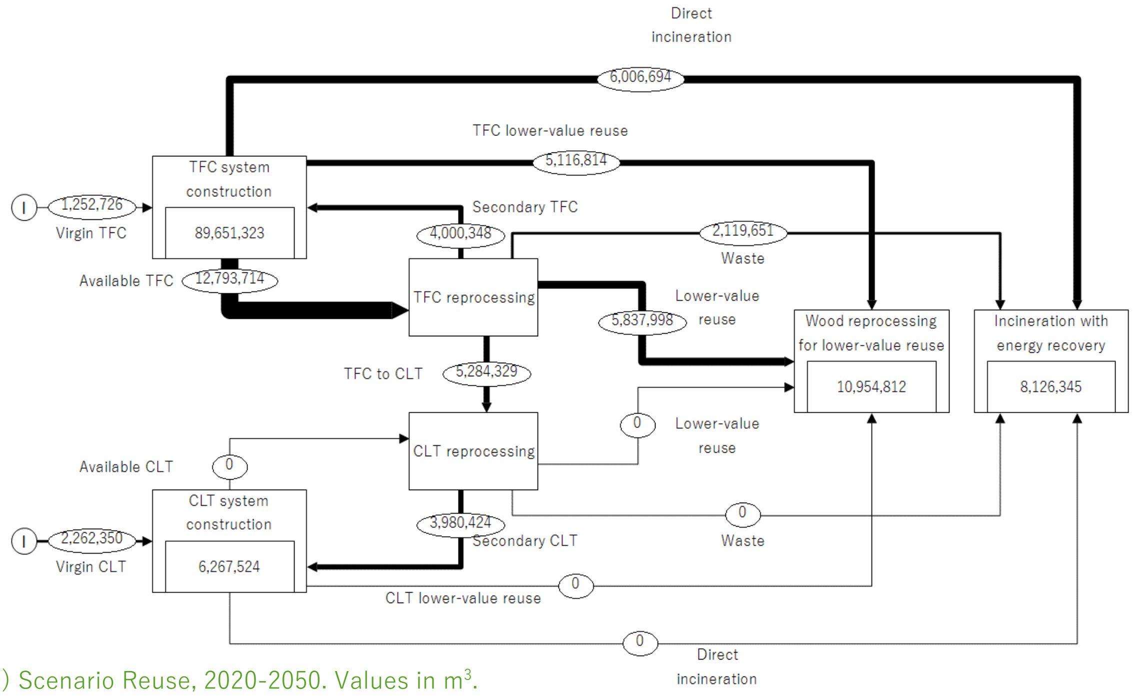
a) Scenario Mix, 2020-2050. Values in m^3.



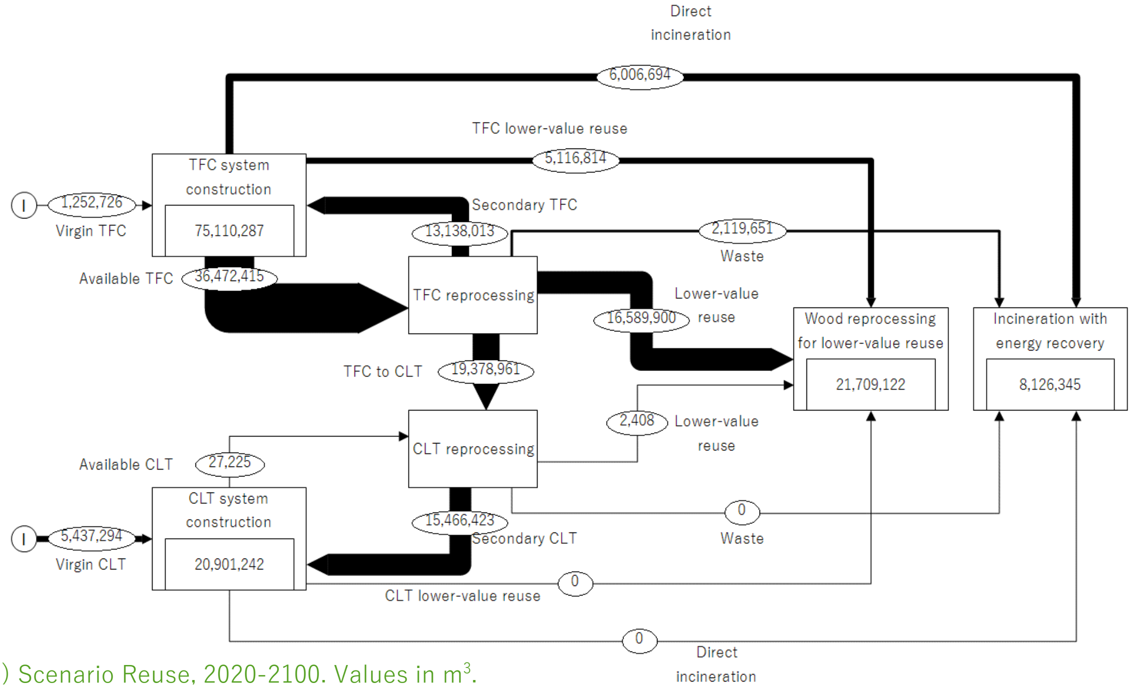
b) Scenario Mix, 2020-2100. Values in m^3.

Figure 28 a) and b). Overview stocks (rectangles) and material flows (arrows with circles) of timber (m^3) for scenario Middle pop., wood use scenario Moderate Timber, reuse scenario Mix, in a) 2020-2050 and b) 2020-2100. The flows represent the values over the entire period, the stocks represent the values in the final year of the period.

Comparing Figure 28 a) and b) to Figure 27 shows that in scenario Mix, a share of the available TFC from the built environment is reprocessed into TFC and after this also into CLT. As CLT is made from cross-laminating smaller sections of wood into one element, an increasing share of the waste from TFC can be reused in CLT elements (see Table 18). Still, in scenario Mix, a share of the available timber is directly and indirectly reused in lower-value end products or incinerated with energy recovery. Nevertheless, less timber is used in lower-value end products and incinerated, and less virgin timber is required in scenario Mix than in scenario Primary, though for CLT the lower virgin timber requirement is only marginal.



a) Scenario Reuse, 2020-2050. Values in m^3.



b) Scenario Reuse, 2020-2100. Values in m^3.

Figure 29 a) and b). Overview stocks (rectangles) and material flows (arrows with circles) of timber (m^3) for scenario Middle pop., wood use scenario Moderate Timber, reuse scenario Reuse, in a) 2020-2050 and b) 2020-2100. The flows represent the values over the entire period, the stocks represent the values in the final year of the period.

Comparing Figure 29 a) and b) to Figure 27 and Figure 28, it becomes apparent that in scenario Reuse, the largest share of post-consumer timber from the TFC systems is reprocessed. This results in high secondary timber shares for the construction of new TFC and CLT systems, as well as a lower virgin timber requirements for both systems. Less timber is directly reprocessed into lower-value end products or incinerated in scenario Reuse than in scenarios Primary and Mix. However, in scenario Reuse, more timber ends up being reused in lower-value end products than in scenario Mix, because in the second half of the century, more secondary timber is available than can be used in TFC systems or is assumed to be reprocessed for CLT, which means that the virgin timber input in this period is 0. Therefore, taking into account the levels of cascading, timber is reused in lower-value end products rather than having it incinerated with energy recovery.

4.6.2 Quantities virgin and reused timber

Using MFA, all flows and stocks were calculated for the different combinations of population, wood use, and reuse scenarios. The quantities of annual virgin timber used in residential dwellings are presented in Figure 30 and the quantities of timber reused as structural elements in residential dwellings are presented in Figure 31. The cumulative quantities of virgin and reused timber used in residential dwellings are presented in Figure 32 (use over the period 2020-2050) and Figure 33 (use over the period 2020-2100).

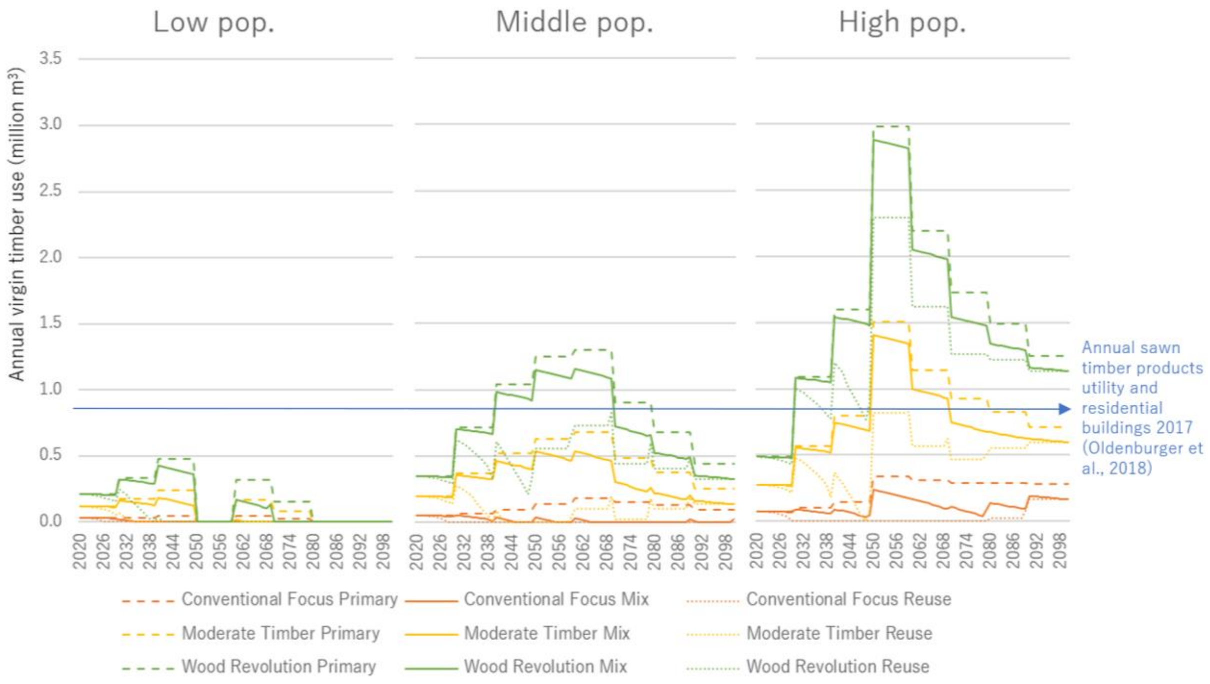


Figure 30. Annual virgin timber use (m^3) for Dutch residential dwellings for scenarios Low pop. (left), Middle pop. (middle), and High pop. (right) (2020-2100).

Figure 30 shows that the annual virgin timber use for Dutch residential dwellings varies greatly for the three population scenarios, especially when considering wood use scenario Wood Revolution (green lines). The blue line represents the annual sawn timber product use of utility and residential buildings in the Netherlands in 2017 of approximately 857,000 m^3 (Oldenburger et al., 2018), which is visualized to put the annual timber use for the different scenarios in perspective. In scenario Low pop., this number is not exceeded; in scenario Middle pop., this number is exceeded by wood use scenario Wood Revolution, reuse scenarios Primary and Mix; in scenario High pop., this number is exceeded by wood use scenario Wood Revolution (all reuse scenarios) and Moderate Timber, reuse scenarios Primary and Mix.

The available volume of roundwood in Europe is expected to increase from about 520 million m^3 rwe in 2016 to about 600-650 million m^3 rwe in 2030 (Nabuurs et al., 2016). A quantity of 600 million m^3 rwe translates to approximately 444 million m^3 sawn timber product (Oldenburger et al., 2018). If the available roundwood in Europe in 2030 remains at this level for the rest of the century, the peak seen in Figure 30 for scenario High pop., wood use scenario Wood Revolution, reuse scenario Primary would account for about 0.65% of the total available European sawn timber products.

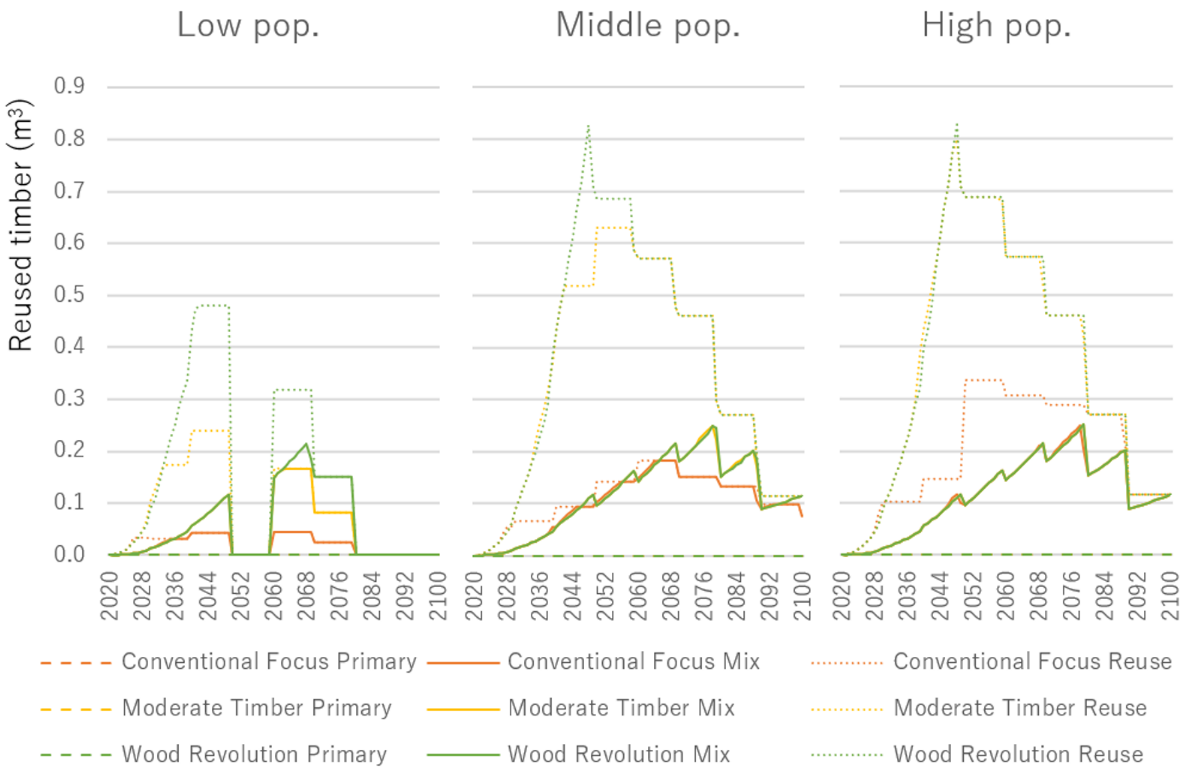


Figure 31. Annual volumes of timber reused as structural elements (m^3) in Dutch residential dwellings for scenarios Low pop. (left), Middle pop. (middle), and High pop. (right) (2020-2100).

Figure 31 shows that the annual potential for reuse of timber as structural elements varies greatly over time. The peaks of reuse are seen in the year 2048, for scenario Middle pop. – Wood Revolution Reuse, High pop. – Moderate Timber Reuse, and High pop. – Wood Revolution Reuse. It first takes time for the potential for reuse to increase, as the length of use maximization strategies discussed in section 4.5 take time to implement. After the peak, the potential for reuse of timber gradually declines, as less timber becomes available from existing residential dwellings (see Figure 23). For reuse scenario Mix, in which the measures that increase the potential for reuse are implemented slower, the peak for reuse is reached later, and is also far lower than seen in reuse scenario Reuse.

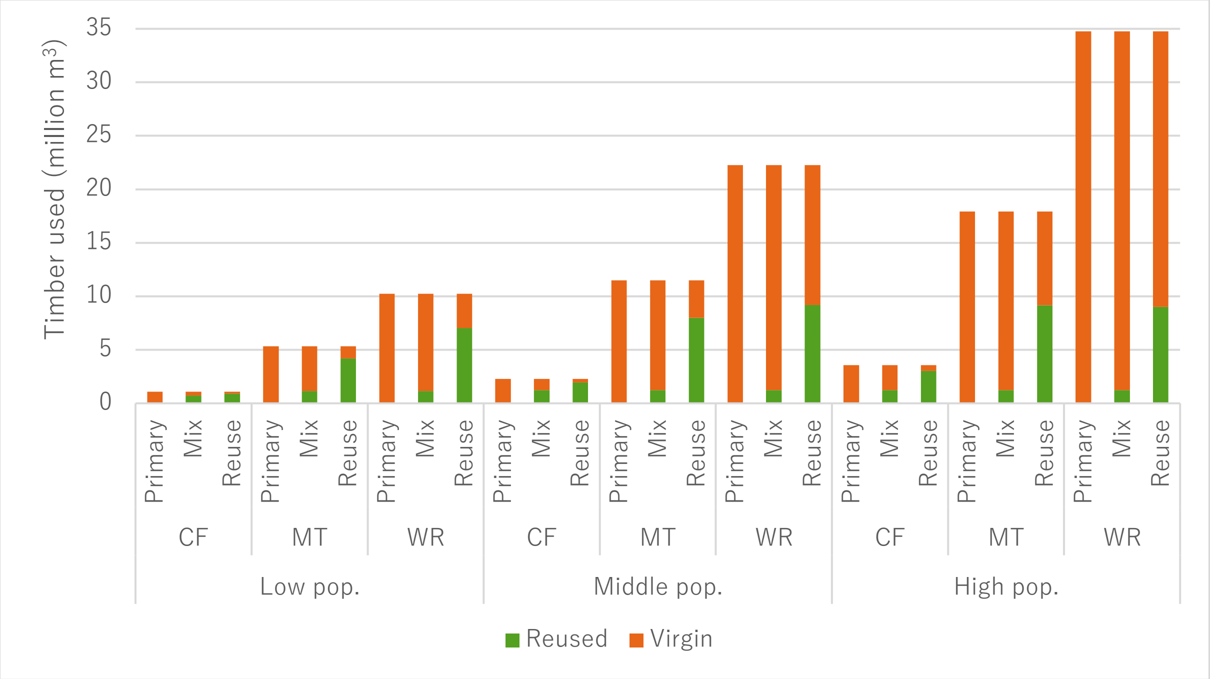


Figure 32. Total cumulative reused and virgin timber used (m^3) in residential dwellings in the Netherlands from 2020-2050, under various population growth, wood use, and reuse scenarios.

Figure 32 shows that the total quantities of timber used do not vary for the different reuse scenarios, as these are determined by the demand for new dwellings. It also shows that over the period 2020-2050, there is a maximum potential for the reuse of timber of approximately 9.2 million m^3. This can be seen in scenario Reuse for scenario Middle pop. – Wood Revolution, High pop. – Moderate Timber, and High pop. – Wood Revolution. This is due to the limited availability of timber from the built environment, as well as time limitations in scaling up the infrastructure required to process existing timber elements for reuse. The highest ratios of reused timber to virgin timber can be seen in reuse scenario Reuse, wood use scenario Conventional Focus, scenarios Low pop., Middle pop., and High pop., with ratios of 6.4, 6.1, and 5.7, respectively.

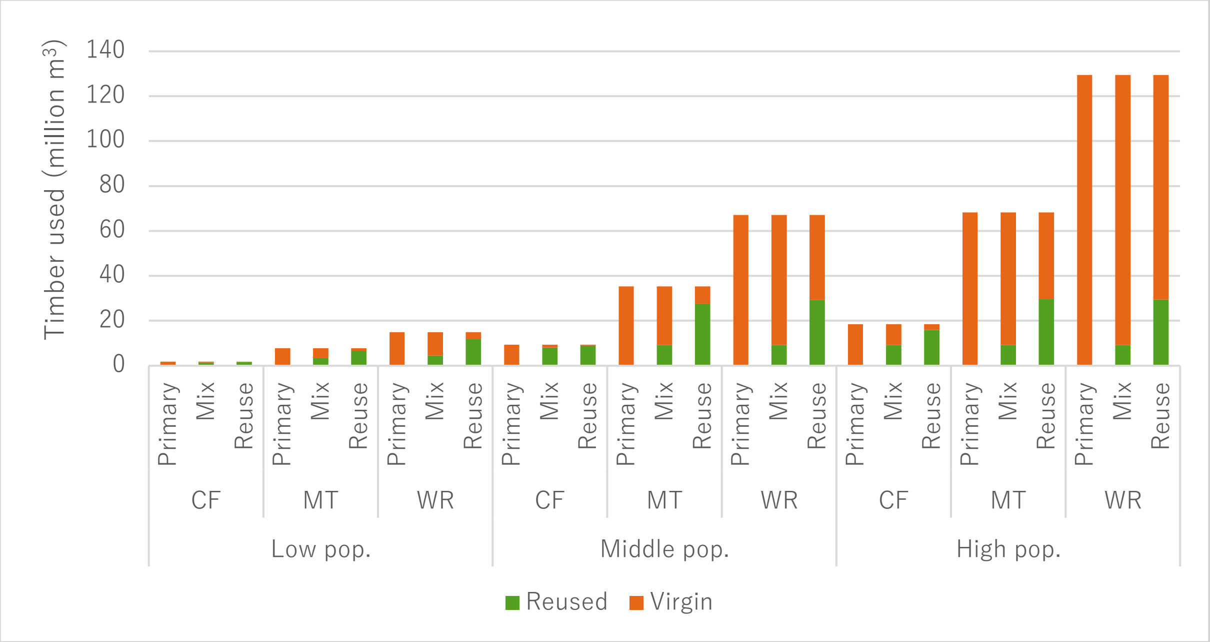


Figure 33. Total cumulative reused and virgin timber used (m^3) in residential dwellings in the Netherlands from 2020-2100, under various population growth, wood use, and reuse scenarios.

Figure 33 shows that over the period 2020-2100, the maximum potential for the reuse of timber is approximately 29.4 million m^3. This can be seen in scenario Reuse for scenario Middle pop. – Wood Revolution, High pop. – Moderate Timber, and High pop. – Wood Revolution. The highest ratios of reused timber to virgin timber are seen in different scenarios than over the period 2020-2050, namely in scenario Low pop., wood use scenario Conventional Focus, reuse scenario Reuse (ratio 11.2), and in wood use scenario Conventional Focus, scenario Middle pop., reuse scenarios Reuse (ratio 24.5).

The results from Figure 32 and Figure 33 highlight that the more timber is used for residential dwellings (e.g., the most timber is used in scenario High pop., where the most dwellings are required, and in wood use scenario Wood Revolution, where the highest percentages of dwellings are constructed from timber), the lower the relative potential will be to implement reused timber that becomes available from demolished buildings, as the current built environment only provides limited quantities of secondary timber. However, when more timber is used in residential dwellings, the absolute potential to implement reused timber is higher than when less timber is used. This also means that the highest absolute virgin timber savings are realized in the scenarios with the highest reused timber use, as in these scenarios reused timber replaces virgin timber.

Comparing reuse scenarios Mix and Reuse to reuse scenario Primary shows how much virgin timber can be saved for each population and wood use scenario (Figure 34).

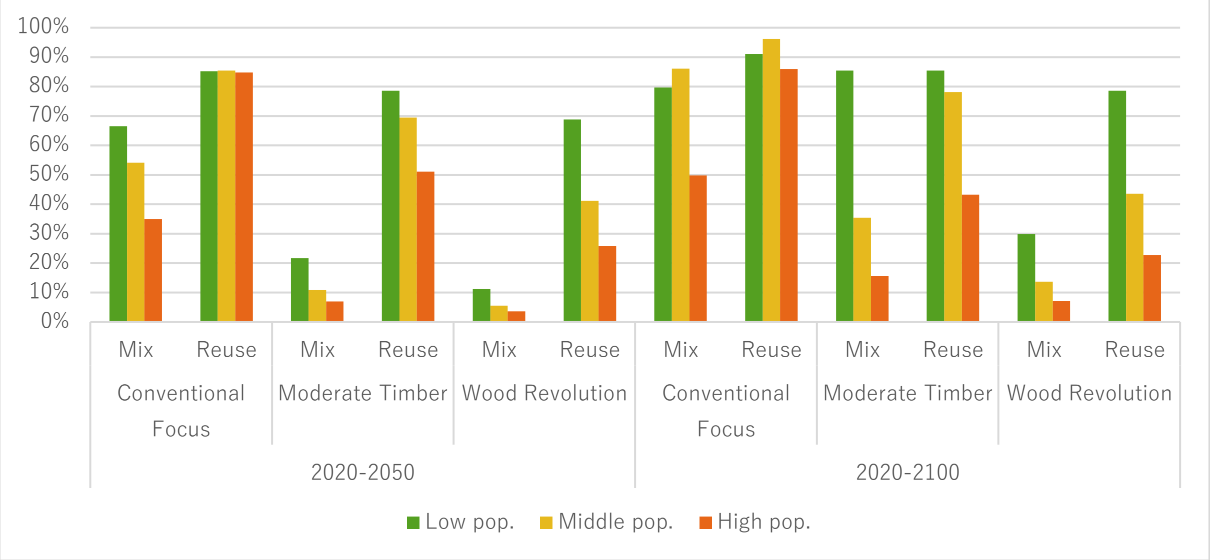


Figure 34. Savings in virgin timber demand (%) for the scenarios Low, Middle, and High, comparing the scenario Mix to the scenario Primary, and comparing the scenario Reuse to the scenario Primary.

The results from Figure 34 highlight that the less timber is used in residential buildings (e.g., the least timber is used in scenario Low pop., where the least dwellings are required, and in wood use scenario Conventional Focus, where the lowest percentages of dwellings are constructed from timber), the higher the potential to implement reused timber in dwellings, thus resulting in the highest relative virgin timber savings.

It is also possible to take into account the relative virgin timber savings when comparing reuse scenario Reuse to reuse scenario Mix, which shows relatively how much additional timber is saved were scenario Reuse to occur instead of scenario Mix. In 2020-2050, the highest ratios for timber saved by scenario Reuse compared to timber saved by scenario Mix are reached by wood use scenario Moderate Timber, scenario High pop. with 7.4 and by wood use scenario Wood Revolution, scenarios Middle pop. and High pop. with 7.4 and 7.3, respectively. In 2020-2100, the highest ratios are reached by wood use scenario Moderate Timber, scenario High pop. with 3.2 and by wood use scenario Wood Revolution, scenarios Middle pop. and High pop. with 3.2. The highest additional benefits for increasing the reuse rate on the shorter term are thus present when the construction of new dwellings is high (scenario High pop.) and when the rate of timber use is high (wood use scenario Wood Revolution).

4.6.3 Carbon storage associated with timber use

From the quantities of virgin and reused timber used in residential dwellings, the carbon storage associated with these quantities was calculated, along with the carbon stock present in the existing building stock, using Equation 9. The results are presented for scenario Middle pop. wood use scenarios Conventional Focus (Figure 35), Moderate Timber (Figure 36), and Wood Revolution (Figure 37).

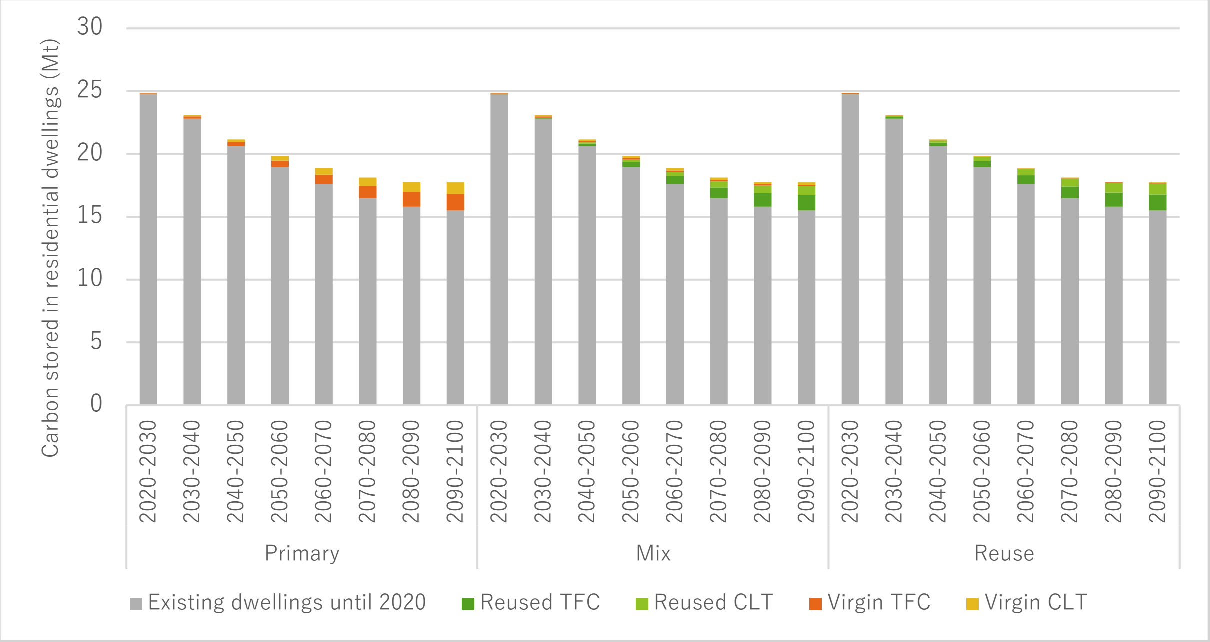


Figure 35. Carbon stored (Mt) in residential dwellings in the Netherlands over the period 2020-2100, scenario Middle pop., wood use scenario Conventional Focus, for various reuse scenarios. The carbon stock for existing dwellings is for the dwellings constructed until 2020, the other categories consist of carbon stored from 2020 onwards.

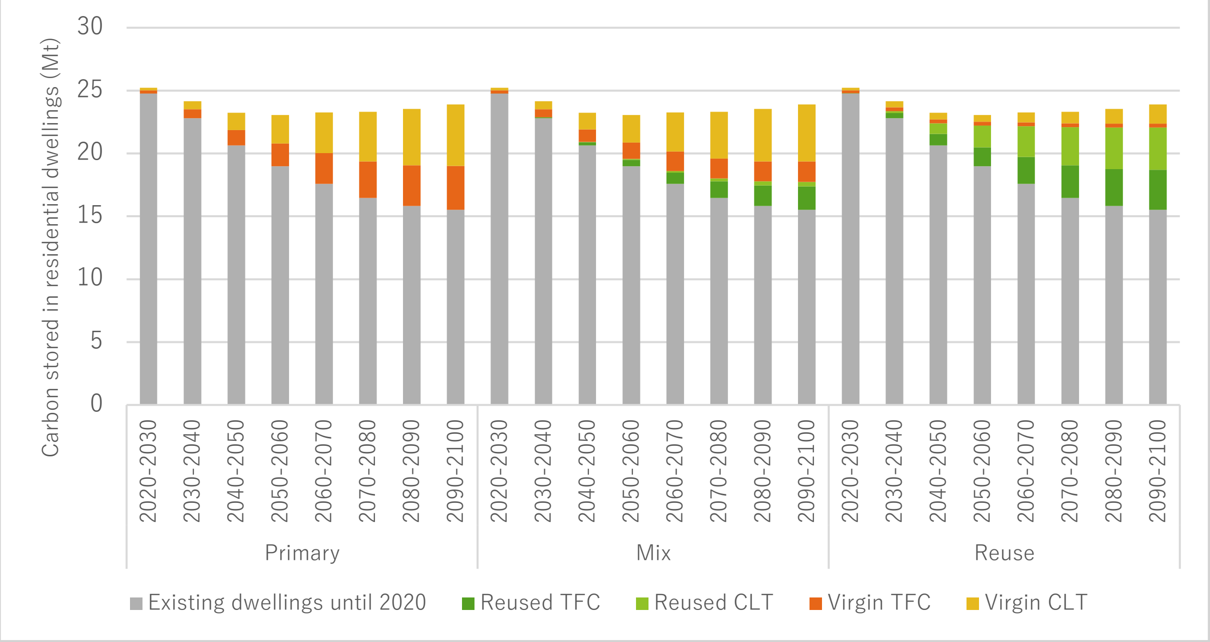


Figure 36. Carbon stored (Mt) in residential dwellings in the Netherlands over the period 2020-2100, scenario Middle pop., wood use scenario Moderate Timber, for various reuse scenarios. The carbon stock for existing dwellings is for the dwellings constructed until 2020, the other categories consist of carbon stored from 2020 onwards.

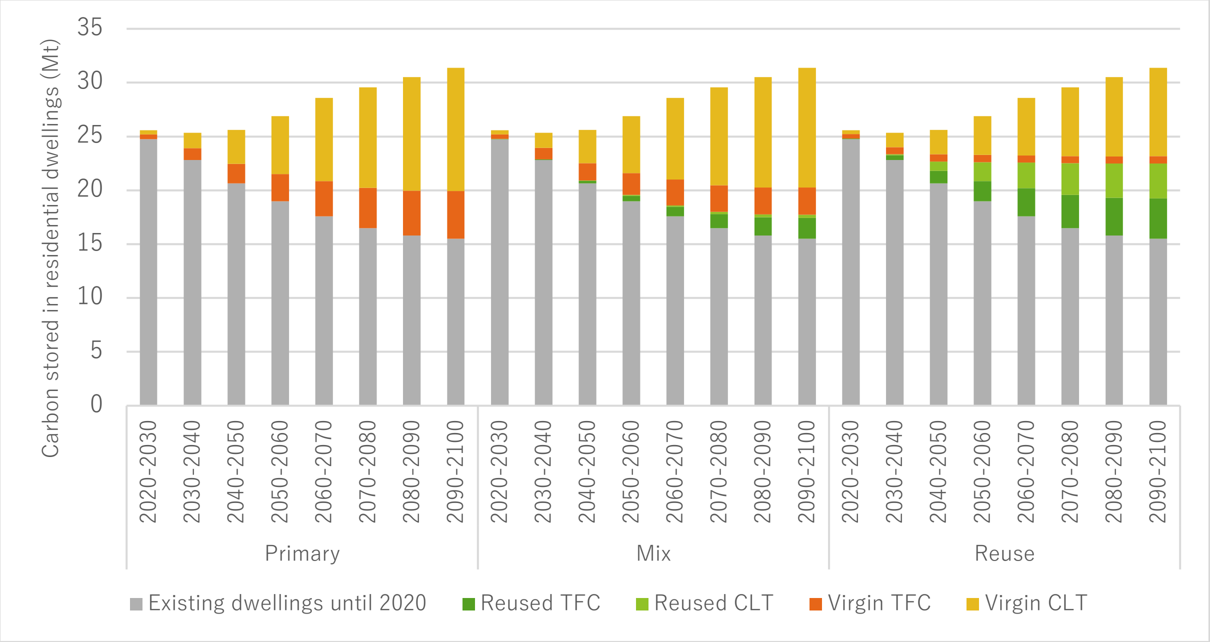


Figure 37. Carbon stored (Mt) in residential dwellings in the Netherlands over the period 2020-2100, scenario Middle pop., wood use scenario Wood Revolution, for various reuse scenarios. The carbon stock for existing dwellings is for the dwellings constructed until 2020, the other categories consist of carbon stored from 2020 onwards.

From Figure 35 to Figure 37, it can be seen that for scenario Middle pop., the total carbon stock of structural timber in residential dwellings keeps decreasing for scenario Conventional Focus and decreases at first for scenario Moderate Timber, after which it increases slightly. In scenario Wood Revolution, the carbon stock exceeds the original stock from the decade of 2040-2050 onwards, indicating the need to apply large quantities of timber in residential dwellings in order to restore the original carbon stock of residential dwellings. Here, the role that CLT can play in increasing carbon storage also becomes clear, which is partly due to the extent to which CLT can be implemented in the construction of apartments/flats (Table 15).

Furthermore, the maximum amount of additional carbon stored by reused timber until 2050 is approximately 2.0 Mt (average annual carbon storage of about 68 kt), which is reached in scenario Wood Revolution, reuse scenario Reuse (Figure 37). An amount of additional carbon storage of 1.7 Mt is reached in scenario Moderate Timber, reuse scenario Reuse (Figure 36). The maximum amount of additional carbon stored by reused timber until 2100 is approximately 7.0 Mt (average annual carbon storage of about 87 kt), which is reached in scenario Wood Revolution, reuse scenario Reuse (Figure 37). An amount of additional carbon storage of 6.5 Mt is reached in scenario Moderate Timber, reuse scenario Reuse (Figure 36).

The results from Figure 35 to Figure 37 highlight that the more timber is used in residential dwellings, the lower the relative potential is to store carbon in residential buildings in the form of reused timber, as the current built environment only provides limited quantities of secondary timber. The absolute potential for storing carbon is however the highest when more timber is used in residential dwellings.

4.6.4 Carbon storage associated with lower-value end uses

The carbon storage associated with reuse of timber elements in residential dwellings can be compared to the carbon outflow to lower-value end uses. The carbon storage within lower-value end products was not modelled, but rather modelled as a stock to which the carbon which was stored in the built environment exits. This is further elaborated on in section 5.1.4. As use in lower-value end products is a less desirable form of reuse, it is important to quantify the carbon outflow associated with lower-value end products, which was also done using Equation 9. The results for the carbon outflow to lower-value end uses are presented below (Figure 38).

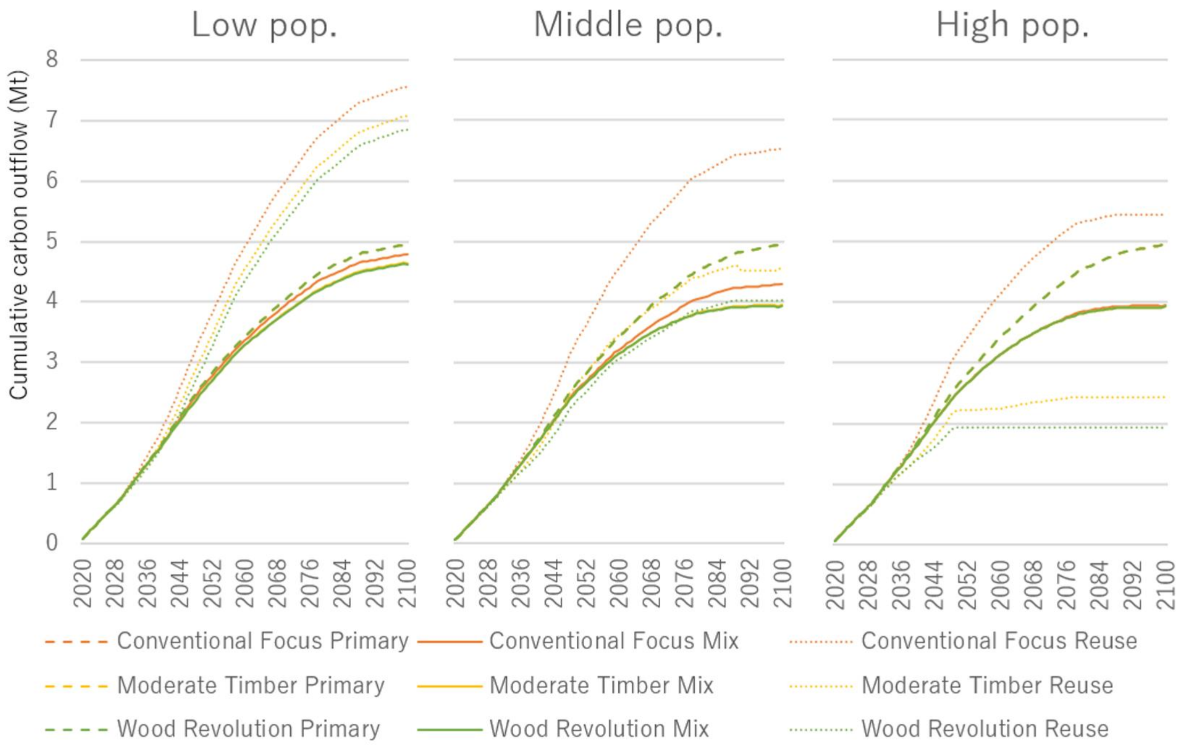


Figure 38. Cumulative carbon outflow to lower-value end products (Mt), for various population growth, wood use, and reuse scenarios.

As the carbon storage for reused timber can be limited by the amount of timber used in new residential dwellings, the available timber from demolished dwellings that is not reused at high-value end use partially goes to lower-value end uses. This is illustrated in Figure 38 by the fact that scenario Low pop. (low need for new residential dwellings) shows higher quantities of cumulative carbon outflow to lower-value end products compared to the other populations scenarios, as the virgin timber requirement in scenario Low pop. is very low (and even 0 from 2050-2060 and 2080-2100), especially for reuse scenario Reuse (see Figure 30). Additionally, wood use scenario Conventional Focus (low use of timber in residential buildings) shows higher quantities of cumulative carbon outflow to lower-value end products compared to the other wood use scenarios.

Figure 38 shows that there is only a relatively small difference in cumulative carbon outflow of the different populations scenarios for reuse scenario Mix. Reuse scenario Reuse shows very differing quantities of low-value end product cumulative carbon outflow in 2100 depending on the population scenario: ranging from approximately 6.8 to 7.6 Mt for scenario Low pop., from 4.0 to 6.5 Mt for scenario Middle pop., and from 1.9 to 5.4 Mt for scenario High. This larger spread in range for scenario High pop. is due to the fact that for wood use scenario Wood Revolution, large quantities of timber are required. Combined with reuse scenario Reuse, this causes for an increasing share of all available timber from existing residential dwellings to be reused instead of used in lower-value end products. On the other hand, in wood use scenario Conventional Focus low quantities of timber are required. Even when combined with reuse scenario Reuse, not all timber available from existing residential dwellings can be reused due to the low timber demand for residential dwellings (see also Figure 33), thus a certain outflow to lower-value end products is always present.

For reuse scenario Primary, the cumulative carbon outflow to lower-value end products in 2100 is the same for each wood use and population scenario, namely 5.0 Mt. This is due to the fact that in this scenario, no timber is reused in residential dwellings, and the shares of timber to lower-value end products and incineration remain constant over time (see also Table 18).

4.6.5 Average lifetime carbon in system

An important metric for determining the impact of reuse on increasing the length of use of structural timber elements in the system is the average lifetime (in years) of carbon entering the building stock of the system (as defined in Figure 18). This was calculated following Equation 11 to Equation 13 for carbon entering the building stock over the period 2020-2050 and over the period 2020-2100. The results are presented in Table 19 below. As was mentioned in section 3.7.3, the lifetime of carbon is defined as the time that carbon has resided (for reused elements) and will reside during the entire element use phase(s) within the timber elements entering the building stock within the specified period. Reused timber elements are, after an assumed lifetime of 75 years, either reprocessed and reused, extending the lifetime to 150 years, or recycled into lower-value end products or incinerated, ending the lifetime of carbon in the system. The lifetime of carbon within lower-value end products is not considered, though this point is discussed further in section 5.1.4.

Table 19. Average lifetime (in years) of carbon entering the building stock over the period 2020-2050 and 2020-2100.

Population scenario	Wood use scenario	Average lifetime carbon entering building stock in 2020-2050 (years)			Average lifetime carbon entering building stock in 2020-2100 (years)		
		Reuse scenario					
		Primary	Mix	Reuse	Primary	Mix	Reuse
Low pop.	**Conventional Focus**	75	122	138	75	133	143
	Moderate Timber	75	87	126	75	112	136
	Wood Revolution	75	81	115	75	99	129
Middle pop.	**Conventional Focus**	75	108	135	75	132	144
	Moderate Timber	75	81	115	75	92	122
	Wood Revolution	75	78	94	75	84	95
High pop.	**Conventional Focus**	75	95	132	75	106	136
	Moderate Timber	75	79	102	75	83	101
	Wood Revolution	75	77	88	75	79	88

In Table 19, it can be seen that for all scenarios under reuse scenario Primary, the lifetime of carbon entering the building stock in 2020-2050 and in 2020-2100 is 75 years, as this reuse scenario does not have any reuse, which leads to timber elements being used in lower-value end products or incinerated after the assumed dwelling lifetime of 75 years. The lifetimes found in Table 19 can exceed the specified period, as the lifetime of carbon is defined as the time that carbon has resided (for reused elements) and will reside during the entire element use phase(s) within the timber elements entering the building stock within the specified period. The time after 2050 and 2100 in which carbon is stored within timber elements entering the building stock in 2020-2050 and 2020-2100 is thus also counted towards the average lifetime of carbon: the end of the use phase of (a share of) timber elements is only after the years 2050 and 2100, respectively.

Table 19 also shows that the carbon entering the building stock in the period 2020-2050 has longer average lifetimes in reuse scenario Mix and Reuse than in reuse scenario Primary. The differences are larger in the wood use scenarios where less timber is used in residential dwellings, with the largest differences seen in Conventional Focus. This is due to the fact that in scenario Conventional Focus, larger relative volumes of reused timber are implemented, thus requiring less virgin timber (see Figure 34) For the carbon within the building stock in the period 2020-2100, Table 19 shows longer average lifetimes in reuse scenarios Mix and Reuse than in reuse scenario Primary as well. In the period 2020-2100, the differences between the reuse scenarios are larger than in the period 2020-2050, as the average higher-value reuse percentages over the period 2020-2100 period are higher.

Ultimately, the longest average lifetimes of carbon within the building stock for timber entering the building stock in 2020-2050 are found in wood use scenario Conventional Focus, reuse scenario Reuse, Low pop. (138 years), Middle pop. (135 years), and High pop. (132 years). For timber entering the building stock in 2020-2100 the longest average lifetimes of carbon are also found wood use scenario Conventional Focus, reuse scenario Reuse, Low pop. (143 years), Middle pop. (144 years), and High pop. (136 years). This combination of scenarios a low timber use in new dwellings (Conventional Focus), which combined with a high reuse rate (Reuse) leads to a low demand for virgin timber. Although this means small quantities of timber are used, high percentages of timber used in residential dwellings can consist of reused timber.

4.6.6 CO_2 emissions from incineration

Following Equation 10, the CO_2 emissions resulting from timber incineration over the period 2020-2100 were calculated. The CO_2 emissions are largely dependent on the reuse scenarios and only in small part on the population and wood use scenarios, as the amount of timber incinerated is largely determined by the different rates defined in Table 13 in section 3.7.1. The resulting CO_2 emissions calculated are thus the emissions found for reuse scenarios Primary, Mix, and Reuse (Figure 39). These results should be viewed taking into account two important notes. Firstly, within the global warming reports of the IPCC on lowering emissions, emissions from the combustion of biomass are regarded as short-cycle emissions and are therefore reported as zero, so these CO_2 emissions are not incorporated in the IPCC targets (IPCC, 2018). Secondly, as was mentioned in section 1.1, wood incineration with energy recovery currently replaces fossil fuels as an energy carrier in the Netherlands, which can thus be considered favorable. Depending on the rate at which the Dutch energy mix shifts to a more renewable one, this will remain the case for at least the coming decades.

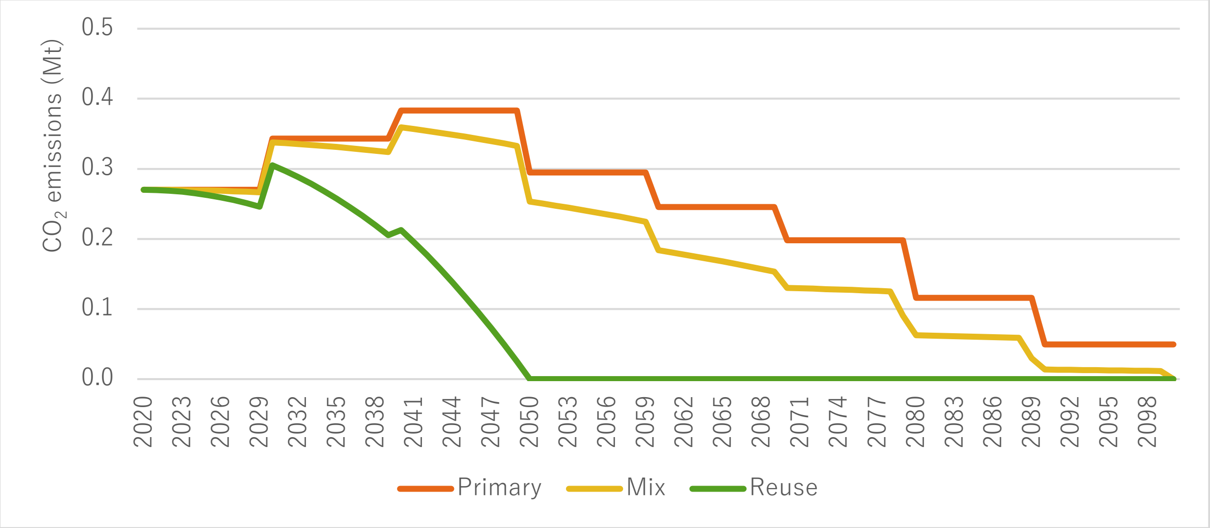


Figure 39. Annual CO_2 emissions (Mt) from incineration for the scenarios Primary, Mix, and Reuse.

Figure 39 shows that the CO_2 emissions from incineration become 0 in 2050 for scenario Reuse and in 2100 for scenario Mix. This does not necessarily indicate that all timber is reused: shares of timber are still recycled in lower-value end products (see Figure 38). Figure 39 also clearly shows that the CO_2 emissions seen in scenario Mix are relatively closer to the CO_2 emissions seen in scenario Primary than in scenario Reuse. The values seen for scenario Primary show clear stagnant 10-year periods, which are also present to a lesser extent in scenario Reuse. This is due to the fact that the data used on available timber from demolition is expressed in average annual timber availability for each decade (see section 4.2.2).

Derived from the annual CO_2 emissions, the cumulative CO_2 emissions are presented in Table 20, in which the avoided CO_2 emissions from incineration by reuse scenarios Mix and Reuse are also presented. Here it is important to note that depending on the rate at which the Dutch energy mix shifts to a more renewable one, phasing out biomass as an energy carrier will result in an increased need for fossil fuels.

Table 20. Cumulative CO_2 emissions from incineration (Mt) and avoided CO_2 emissions from incineration (Mt and %) for scenarios Mix and Reuse compared to scenario Primary.

Reuse scenario	**Primary**	**Mix**			**Reuse**		
Period	**CO_2 emissions (Mt)**	**CO_2 emissions (Mt)**	**Avoided**		**CO_2 emissions (Mt)**	**Avoided**	
			(Mt)	**%**		**(Mt)**	**%**
2020-2050	10.3	9.8	0.5	4.5%	6.5	3.8	37.1%
2020-2100	19.1	16.3	2.8	14.6%	6.5	12.6	66.1%

Table 20 shows the CO_2 emissions for the reuse scenarios, as well as the resulting CO_2 savings that reuse scenarios Mix and Reuse result in when compared to scenario Primary. Here it also becomes clear that scenario Reuse results in much lower CO_2 emissions than scenarios Mix and Primary.

5. Discussion

5.1 Limitations of research

During the course of this research, some limitations were encountered regarding data availability, the scope of this research, and simplifications for the model used. This section discusses the limitations regarding the assumptions made in this research, the way uncertainty was handled, two sensitivity analyses, limitations regarding the scope of this research, and modelling improvements that could be made.

5.1.1 Assumptions and uncertainty

The focus of this research is on TFC and CLT systems as they are regarded the most dominant and most likely to increase significantly, respectively. This has been further elaborated on in section 1.4. Focusing on carbon storage within TFC and CLT is done by other researchers (Hafner & Rüter, 2018; Keijzer et al., 2021; Luijkx et al., 2021), whereas others do not specify the construction system or wood types assumed (Breton et al., 2018; Churkina et al., 2020; Kalt, 2018), focus solely on TFC systems (Heräjärvi, 2019), focus on several different elements used in timber construction (Head et al., 2021), or conduct a review of several papers quantifying carbon storage which thus encompass several different construction systems (Amiri et al., 2020; Geng et al., 2017). Aside from TFC and CLT, other types of timber construction systems exist and are constructed that were not considered in this research, such as other laminated structure types like glulam or laminated veneer lumber (LVL) (Hough, 2019), log cabin construction (O. Wiggers, personal communication, May 26, 2021), and hybrid systems, which consist of combinations of timber with other materials such as concrete or steel (M. Timmer, personal communication, May 10, 2021; Van der Lugt & Harsta, 2020).

The timber content of existing buildings was based on estimations. As mentioned in section 4.5.2, it is often not documented which materials or connection methods are used in prefab elements (Nelissen et al., 2018). For existing dwellings, there is often no documentation of the materials used, which is a problem that is often encountered (not just for timber but for all construction materials) and is one of the reasons why there is an increase in initiatives that aim to work with materials passports for buildings, such as Madaster and BIM (Stolk, 2019). These estimations form the basis for the quantities of timber available for reuse, thus the best fitting data were used as the basis for these estimations. A paper by Vringer & Blok (1993) provides an extensive overview of materials used in cement-based residential dwellings in the Netherlands. Compared to the material intensity of dwellings (kg/m^2) assumed in this research, the material intensity found in their research is about 85% higher. Although their research focuses on cement-based dwellings and may not provide an accurate representation of available timber from existing residential dwellings, the timber available for reuse may be higher if the material intensity in existing dwellings is higher than assumed in this research.

This research aims to provide insight into the technical potential of timber in residential buildings, reuse of structural timber elements, and the associated carbon storage until 2050 and 2100. As the results of this research are about future developments, these two timeframes, and especially the long-term temporal scope (2020-2100), are inherently accompanied by uncertainties. By creating scenarios for the most important developments, namely the number of dwellings constructed, the extent to which timber is applied, and the extent to which timber is reused, ranges for all results were created. This way, uncertainties around these important developments are accounted for.

Information obtained from expert interviews was sometimes conflicting, which may originate from differences in their own interests and experiences. This highlights the need for shared knowledge and a highly collaborative approach for the transformation to a residential building sector where building with timber and cascading are increased. This can also be found in literature, where it is often concluded that there is the need for a collaborative knowledge platform on timber construction and the circular use of materials (Arnoldussen et al., 2020; Bronsvoort et al., 2020; Nelissen et al., 2018; Rijksoverheid, 2016; Schut et al., 2015a; Studio Marco Vermeulen, 2020).

5.1.2 Sensitivity analysis

Aside from model uncertainties, the sensitivity of model parameters is an important aspect to take into account. This section handles the sensitivity of the parameter for the percentage of residential dwellings (types detached, semi-detached, and terraced) from TFC and CLT, and the parameter of dwelling lifetime, as this could vary following a normal distribution and sensitivity analysis on the parameter of dwelling lifetime is often performed (E. Müller et al., 2014).

As was discussed in section 4.3.2, TFC dwellings are often considered more favorable for low-rise buildings than CLT, as low-rise buildings do not require the structural properties that TFC can provide and TFC systems require less timber than CLT systems. Therefore, the 50-50 divide of TFC and CLT dwellings of the types detached, semi-detached, and terraced may be too optimistic in the application of CLT. Therefore, a sensitivity analysis was conducted, including a 75-25 and a 100-0 divide in the place where a 50-50 divide was used in the model parameters discussed in Table 15. The results for this sensitivity analysis are visualized below (Figure 40).

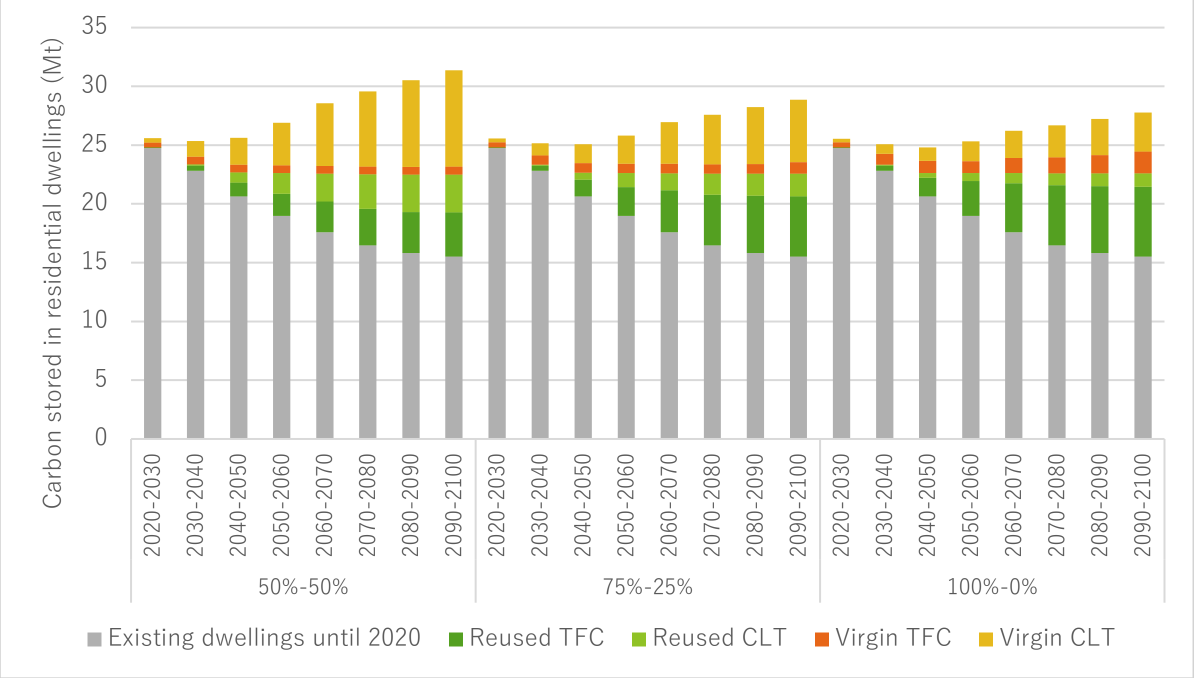


Figure 40. Carbon stored (Mt) in residential dwellings in the Netherlands over the period 2020-2100, scenario Middle pop., wood use scenario Wood Revolution, reuse scenario Reuse, for different divisions of TFC and CLT for the dwelling types detached, semi-detached, and terraced house. The carbon stock for existing dwellings is for the dwellings constructed until 2020, the other categories consist of carbon stored from 2020 onwards.

Figure 40 shows that for scenarios Middle pop., Wood Revolution, Reuse, the ratios of dwellings from TFC and CLT has an impact on the additional carbon storage potential of timber elements in residential dwellings (the carbon in existing dwellings is disregarded as this remains the same throughout the sensitivity analysis). When the divide of TFC of CLT is 50%-50% in 2050 (and from then until 2100), as was the case in the results of this research, the maximum additional carbon storage potential is 5.0 Mt in 2050 and 15.9 Mt in 2100. In the case that this divide is 75%-25%, the maximum carbon storage potential is 4.4 Mt in 2050 (a decrease of 11.3% compared to original results) and 12.4 Mt in 2100 (decrease of 21.7%). When this divide is 100%-0%, the maximum carbon storage potential is 4.2 Mt in 2050 (a decrease of 16.3% compared to original results) and 12.3 Mt in 2100 (decrease of 22.7%). The implementation of CLT in residential dwellings would thus have a higher impact on carbon storage potential on the long term, which is due to the fact that the percentage of CLT is currently low and would need to increase to 50% gradually, though constructing either 25% of dwellings (types detached, semi-detached, and terraced) or 0% from CLT makes a larger difference on the shorter term (until 2050) than on the longer term (until 2100).

One of the parameters often tested for sensitivity is the assumed dwelling lifetime (E. Müller et al., 2014). This research assumed a dwelling lifetime of 75 years, but shorter and longer lifetimes are possible. Therefore, this sensitivity analysis compares the results for average lifetime of carbon in timber entering the building stock in 2020-2100 for a dwelling lifetime of 60 years, 75 years, and 90 years (Figure 41).

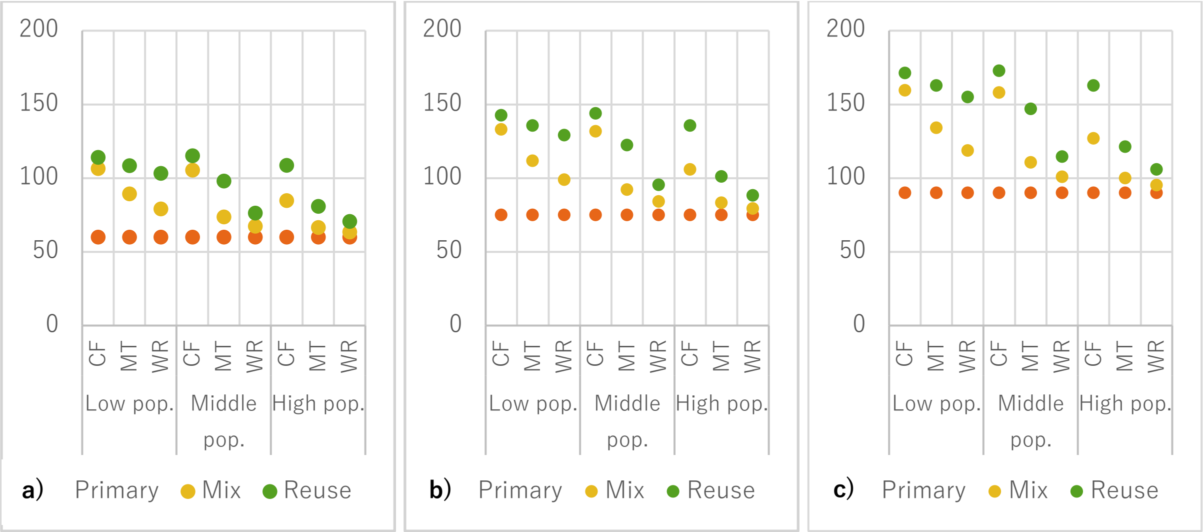


Figure 41. Dispersion of average carbon lifetimes in timber entering the built environment in 2020-2100 for a) a dwelling lifetime of 60 years, b) a dwelling lifetime of 75 years, and c) a dwelling lifetime of 90 years.

Figure 41 shows that for a dwelling lifetime of 60 years, the average lifetimes of carbon in the system are more similar than for a dwelling lifetime of 75 years. For a dwelling lifetime of 90 years, the lifetimes of carbon in the system are more spread out than for a dwelling lifetime of 75 years. However, choosing only one dwelling lifetime results in a similar pattern of average lifetimes for the different scenario combinations. In section 5.1.4, improving the approach for dwelling lifetime through applying a normal distribution is discussed.

5.1.3 Scope of research

The sourcing of wood in practice is left out of the scope of this research. However, an important precondition is that the timber used in residential dwellings in the Netherlands is sourced from sustainably managed forests (Geng et al., 2017; Oldenburger, Reichgelt, et al., 2020). Sustainable forest management is defined by the Food and Agriculture Organization (FAO) of the UN as a “dynamic and evolving concept, which aims to maintain and enhance the economic, social and environmental values of all types of forests, for the benefit of present and future generations” (FAO, 2020), and thus depends on many different indicators related to the 3P’s of sustainability: Planet, People, and Profit. Many indicators are related to Planet, for example the harvest to growth ratio, annual carbon sequestration of forests, and water balance (Nabuurs et al., 2016). Additionally, other indicators such as job opportunities (People) and added value for the wood and forestry sector (Profit) are deemed important (Nabuurs et al., 2016). In practice, not all timber is sustainably sourced yet: in 2015 over 83% of all Dutch timber products were either PEFC (Programme for Endorsement of Forest Certification Schemes) or FSC (Forest Stewardship Council) certified (Oldenburger et al., 2016).

Related to the sourcing of wood, the feasibility of the supply of the calculated timber use quantities in residential buildings is outside the scope of this research. Although this feasibility is not the focus of this research, it is important to acknowledge that the available volume of roundwood in Europe will not remain stagnant, but is expected to increase from about 520 million m^3 rwe in 2016 to about 600-650 million m^3 rwe in 2030, and planting long- or short-rotation forest on abandoned agricultural lands could result in an additional yield of 100 million m^3 rwe per year on the longer term (Nabuurs et al., 2016). As was mentioned in section 4.6.2, if the available roundwood in Europe remains at the 2030 level for the rest of the century, the scenario in this research that requires the largest amounts of virgin timber annually would account for about 0.65% of the total available European sawn timber products.

The design strategies to maximize the length of use of timber elements identified in section 4.5.2 will only become relevant after the buildings designed with these strategies are demolished. The current cascading potential is thus mostly reliant on the quality of timber that becomes available from disassembled buildings, strategies for disassembly (section 4.5.3), strategies for logistics development (section 4.5.4), and future development of regulations regarding circularity and energy from biomass.

5.1.4 Improvements for modelling timber and carbon flows

Some of the data, such as the data provided by the Vesta model, were not provided annually but per decade. To improve the model, these data could be smoothed, from which annual data are derived. Incorporating smoothing could prevent the model outcomes from displaying abrupt changes (see for example Figure 30), however, it should be made clear where smoothing of data is implemented.

This research assumed a dwelling lifetime of 75 years, as this simplified the modelling calculations. To allow for a more accurate representation of dwelling lifetime and thus the available timber in each year, the calculations could incorporate a normal distribution of dwelling lifetime instead of assumption 75 years, as was determined by e.g. research by (D. B. Müller, 2006).

As mentioned in section 3.7.1, the outflow of carbon to lower-value end products was modelled as a stock. This also means that the time that carbon is stored these end products was not included in the results on average lifetime of carbon presented in Table 19. The model could be expanded by adding the carbon storage of lower-value end products, after which they are either reused as lower-value end products or incinerated. As lower-value end products can also have lifetimes of several decades, e.g. particleboard can have a lifetime of 25 years (INSIDE/INSIDE, 2020), this could increase the average lifetime of carbon in timber products by 25 years, and even longer if these end products are reused.

This research does not take into account the import (or export) of timber elements and lower-value end products, and by limiting the spatial boundaries to the Netherlands effectively assumes that the Netherlands is a type of island. However, flows to and from neighboring countries are also present: wood is largely imported (88%) (NIBE Research, 2019), CLT is most likely to originate from Austria, Germany, Switzerland, the Czech Republic, or Italy (Jauk, 2020), and waste wood from construction can be exported to Germany or Belgium (Van Bruggen & Van der Zwaag, 2017). As mentioned in section 3.7.1, timber outflow to lower-value end products and timber outflow to incineration are modelled as stocks for simplicity of the model calculations. Expansion of the system by including imports and exports, and with that the system components associated with lower-value end products and those associated with incineration, could allow for a more complete material flow analysis of timber use in the Netherlands including imports and exports. In that case, new system boundaries would need to be defined.

To simplify the model calculations, a JIT planning was assumed in the MFA, meaning that there was no storage of timber elements that 1) become available, 2) are reprocessed, and 3) are not directly reused (Victor, 2018), as the model rarely showed a higher supply than demand. Nevertheless, this is an important element of infrastructure that should be implemented, as was discussed in section 4.5.4. If storage of timber elements was included in the model calculations, it is likely that higher quantities of timber would be directly and indirectly reused, higher quantities of timber would be used in lower-value end products, less virgin wood would be required, and lower quantities of timber incinerated with energy recovery could be reached. The cumulative amount of timber that is now modelled to go to lower-value end uses or incineration over 2020-2100 which could have been used if the demand was higher and could thus be stored ranges from about 0.3 million m^3 (scenarios High pop., Moderate Timber, Reuse) to 27.1 million m^3 (scenario Low pop., Conventional Focus, Reuse). The highest annual amount of timber that could be stored is about 0.72 million m^3 (scenario Low pop., Conventional Focus, Reuse) and is reached in 2048 (see also Figure 47 in Appendix VI). However, the amount of timber that can be stored in practice depends on the development of the capacity of storage locations.

The average lifetime of carbon in the building stock of the system is only calculated for the period 2020-2100, as after this the uncertainties of the number of dwellings constructed, amount of timber used, and rates of reuse are considered too high to extrapolate further: the assumed quantities for these developed scenarios already vary greatly. If this were extrapolated further, then potential third (or more) lifetimes of timber elements could also be taken into account, thus also including timber elements storing carbon for 225 years (or more).

5.2 Theoretical implications and recommendations for further research

This section discusses a comparison of the results from this research with other research on carbon storage within timber elements and on cascading potential of timber elements, elaborates on how this research extends current theoretical insights by discussing the addressed knowledge gaps, and provides recommendations for further research.

5.2.1 Comparison existing research

Churkina et al. (2020) found a global carbon storage potential for new timber dwellings of 0.01 – 0.68 Gt per year until 2050 depending on the scenario in their research, which would increase the existing carbon sink of timber elements. This research has determined that the potential for carbon storage within timber dwellings can be about 68 kt per year until 2050, which is 0.01% of the upper estimate for global annual carbon storage found by (Churkina et al., 2020). To give an indication of the scale, the Netherlands was responsible for about 0.4% of the global CO_2 emissions in 2018 (Climate Watch, 2020). Though relating this to CO_2 emissions is not a perfect comparison, this comparison would indicate that the estimates for the Netherlands and globally differ by a factor 40. Churkina et al. (2020) also indicate that the existing carbon stock in the built environment could be increased by 25-170% by 2050, whereas this research found a maximum increase in carbon stock in 2050 of 7.8% (High pop., Wood Revolution), which increases to 62% in 2100. These differences may indicate that the scenarios in this research are too pessimistic, but could also indicate that the carbon storage potential outside of the Netherlands is larger than in the Netherlands.

Kalt (2018) defined the existing carbon stock of Austrian timber residential dwellings at 7.8 Mt in 2015, and found a maximum carbon storage potential for timber in dwellings in Austria of over 31 Mt in 2100. In this research, the carbon stock of Dutch timber residential dwellings was defined as 24.8 Mt in 2020, with a maximum carbon storage potential of 31.4 Mt in 2100 (High pop., Wood Revolution). In all scenarios regarded in his research, the carbon stock of timber in residential dwellings increases over time (Kalt, 2018), which is not the case in this research. This can explained by the fact that in the Netherlands, in 2019 only 2% (mass-based) of materials used in dwellings was wood and has been decreasing over time (Figure 22), whereas in Austria this has been increasing from 9% in 1998 to 21% in 2013 (Kalt, 2018). Additionally, Kalt (2018) assumed the amounts of timber from demolition would increase until 2100, whereas in this research, the amount of timber from demolition is projected to increase until 2050, and then decrease from after 2050 (Figure 23). Although Kalt (2018) did not look into reuse, if the availability of timber from existing residential dwellings would increase in the Netherlands, the potential for reuse of timber from existing dwellings could increase and be less limited to the available timber found in this research (Figure 33).

In their research on cascading wood from demolished buildings in Finland, Sakaguchi et al. (2017) found that the potential cascading flows and applications are dominated by the location in the building and demolition method, rather than the dimensions of the timber element. The location in the buildings was of importance, as for specific elements the demolition process would need to be more gentle to avoid damage to these elements (Sakaguchi et al., 2017). In this research, improving disassembly methods is also indicated as a key aspect to the reuse potential for timber elements, though this research did not take into account differences regarding the location of an element within buildings. Sakaguchi et al.

(2017) also found that improvements in connection methods and reducing the amounts of materials attached directly to the element would provide a better starting condition of the element for the cascading chain. Although this research listed several ways to improve the design of timber elements (see section 4.5.2), it was found that these strategies will only improve reusability of timber elements in the long term, as the dwellings that are constructed now will only be demolished decades later.

5.2.2 Filling of knowledge gaps

The first identified knowledge gap was that no scenarios on the timber demand for residential dwellings in the Netherlands and the associated biogenic carbon storage potential had been developed for timeframes until 2050 and until 2100 (Leguijt et al., 2020). This research has derived population scenarios from the existing WLO scenarios (Van Gemeren et al., 2016) by adding an additional scenario (Middle pop.) and extrapolating the scenarios further until 2100. Together with the population scenarios, the wood use scenarios created in this research describe different possibilities for the development of timber demand for residential dwellings in the Netherlands. Additionally, the reuse scenarios created in this research indicate to what extent the timber demand can consist of virgin and reused timber. By conducting an MFA, this research shows the associated biogenic carbon storage potential for the different scenarios. It was also mentioned in section 1.3 that the assessment period of 2020-2100 is very relevant in addition to the shorter timeframe 2020-2050. This has proven to be the case not only because structural timber elements have lifetimes of many decades, but also because it takes time to increase the timber use in residential dwellings and to increase the rate of higher-value reuse.

Another identified knowledge gap was the need to investigate strategies that can enhance the length of carbon storage within timber elements. Existing research on carbon storage in dwellings does not take into account the effects of cascading (Amiri et al., 2020; Breton et al., 2018; Churkina et al., 2020; Geng et al., 2017; Head et al., 2021; Heräjärvi, 2019; Kalt, 2018; Keijzer et al., 2021; NIBE Research, 2019), although cascading is necessary in order to lengthen the use of timber elements. This research identified many different strategies for increasing the length of use of timber elements (and therefore the length of carbon storage) in section 4.5 and aimed to quantify these by creating several reuse scenarios.

The practical reuse potential of standardized and prefabricated elements was another identified knowledge gap. This research shows that the quality of timber is not a limiting factor for the potential for reuse. However, standardization of elements does mean that in the case of defects or if an element needs to be downsized, the element needs to be downsized to the next standard size. However, smaller pieces of timber could be used to make new CLT elements. Existing prefabricated elements can be reused under a few conditions (see section 4.5.2): the level of complexity of prefabrication is low; the materials the element is made from are known; the element is composed of materials that are easy to disassemble.

The last knowledge gap mentioned in section 1.3 was that it is unknown to what extent cascading and possible other methods enhance the length of carbon storage in structural timber elements. The methods to enhance the length of carbon storage discussed in section 4.5 formed the basis for the quantification of their impacts on the length of carbon storage. By combining the developed scenarios with the MFA conducted in this research, it was possible to derive the average lifetime of carbon in structural timber elements in the building stock, which was found to be enhanced the more reuse is facilitated (see section 4.6.5 for results).

5.2.3 Recommendations for further research

As was mentioned in section 2.1, there are discussions within the scientific community revolving around the extent to which a counterfactual scenario of forest growth, in which more carbon is sequestered during their growth period, would yield larger climate benefits than using timber in buildings (Coomes et al., 2014; Den Ouden et al., 2020; Lippke et al., 2011; Lundmark et al., 2014; Stockmans, 2020). Den Ouden et al. (2020) researched whether postponing wood harvest can contribute to CO_2 mitigation, in which they conclude that in the short term, a significant amount of additional carbon can be sequestered in forest biomass by postponing wood harvest. Lu et al. (2018) found similar results, also indicating that postponing harvest, thereby creating longer periods between harvests, results in avoided emissions associated with the harvesting process. It is recognized that rainfall, species diversity, and mean tree size have impact on wood productivity and thus on the capacity of forests to function as carbon sinks (Coomes et al., 2014). Additionally, forests may be impacted severely through the impacts of invasive pests or pathogens, illustrated for example by the wide-spread perishing of spruce forests in Germany due to the recent bark beetles infestation (Oldenburger, Reichgelt, et al., 2020), and by droughts or heatwaves (Allen et al., 2010; Anderegg et al., 2013). Nevertheless, it is uncertain to what extent climate change may impact these different parameters that influence the capacity for forests to function as a carbon sink (Coomes et al., 2014). This research quantifies the carbon storage potential, and with that the potential for delayed emissions, of using timber in residential dwellings in the Netherlands. Therefore, further research in which different counterfactual scenarios encompassing different forest management techniques are explored could provide a comparison between the climate impact of carbon storage within timber residential dwellings and carbon storage within forests. A potential option for this could be the integration of the model from the research by Den Ouden et al. (2020) and the model of this research.

This research does not take into account the economic feasibility of the extent to which timber is used in residential dwellings, or the extent to which timber is reused: the results of this research purely consider technological feasibility. Therefore, an economic feasibility analysis of the timber used in dwellings and the rate of timber reuse would be an important next step in research. In the last year, wood prices have increased drastically worldwide, which is not due to a low availability of wood but due to the low production capacity of sawmills (M. Timmer, personal communication, May 10, 2021; WUR, 2021). On the one hand, this increase in price may lead to a higher demand for reused timber over virgin timber (D. Grootenboer, personal communication, June 2, 2021), but on the other hand, the low availability of timber may also make producers and clients more reluctant to apply timber in dwellings (M. Timmer, personal communication, May 10, 2021).

As the different scenarios explored in this research are predictive what-if scenarios, explorative strategic scenarios, a normative transforming scenario, and backcasting scenarios (see sections 3.5.2 and 3.6.2 for the specifications of scenarios), none of the scenarios were necessarily considered as more likely than others (Börjeson et al., 2006). Therefore, an analysis of which of these scenarios is the most likely, by taking into account for instance economic feasibility, the feasibility of rate of change regarding reuse parameters such as infrastructure, and the implementation of different policies could give insight into which of the scenarios developed in this research would be more likely than others, and thus which areas of the ranges of results would be the most likely.

5.3 Policy implications

Following the results of this research and the points of discussion above, this section aims to give advice to policymakers on increasing construction of timber residential dwellings and increasing reuse of structural timber elements. The scenarios developed in this research result in quantified ranges of potential for carbon storage, reuse of structural timber elements, and avoided CO_2 emissions from incineration, which are presented in Table 21.

Table 21. Results for potential for carbon storage, maximum potential for reused structural timber elements, and maximum potential for avoided CO_2 emissions from incineration.

Description potential (unit)		2020-2050	2020-2100
Carbon storage	Average annual potential (kt)	8.8 – 272	5.5 – 373
	Cumulative potential (Mt)	0.3 – 8.2	0.4 – 29.9
Reused timber	Maximum cumulative potential (m^3)	9,250,000	29,400,000
Avoided CO_2 incineration	Maximum annual average potential (kt)	127	157
	Maximum cumulative potential (Mt)	3.8	12.6

Taking into account the goal of the Dutch government to reduce GHG emissions by 3.4 Mt CO_2-eq by 2030 and the fact that timber demand is projected to increase significantly already until 2030 (Algemene Vereniging Inlands Hout et al., 2016), the results in Table 21 indicate that there could be a significant contribution to lowering atmospheric CO_2 emissions by delaying emissions through carbon storage, by avoiding emissions from incineration, and by reducing the demand for primary timber. However, it is important to stress that these emissions are not counted towards the targets set by the IPCC, and if incineration with energy recovery from biomass is avoided, other energy carriers (currently largely fossil fuels) will need to replace biomass. Strengers et al. (2018) estimated the annual CO_2 storage potential for timber in civil engineering projects in the Netherlands at about 0.3 Mt in 2030 and 0.6 Mt in 2050. Extrapolating the trend, this would be an annual CO_2 storage potential of about 1.35 Mt in 2100. Converting this to stored C, these estimates would be about 164 kt C/yr in 2050 and about 368 kt C/yr in 2100. This research finds higher potential carbon storage for timber in residential dwellings in 2050 than Strengers et al. (2018) found for civil engineering, but a similar carbon storage potential in 2100. Given the potential for the use and reuse of timber, and with that the potential for carbon storage and avoided CO_2 emissions, stimulating the reuse of timber building elements could be achieved through several measures.

As mentioned in section 5.1.3, the design strategies to maximize the length of use of timber elements only become relevant after the buildings designed with these strategies are demolished. Therefore, the most important aspects to implement to increase the reuse of timber elements are developing new disassembly techniques for existing dwellings (section 4.5.3) and developing quality standards for (reused) timber elements, improving the infrastructure for reuse of elements and materials, and creating a marketplace with an overview of supply and demand of secondary materials (section 4.5.4).

A component of reassembly potential could be added to tenders for residential building projects, as well as tenders in general. This could encompass the different aspects surrounding circular design discussed in section 4.5.2, following the PCDs discussed in section 2.3. An updated measuring method for disassembly potential was published this year (Van Vliet et al., 2021) and could form the basis for including this in designs. Adding a reassembly potential component to tenders can prove important: if the demand for buildings that incorporate reassembly potential is low, design for reassembly may only be implemented on small scales (B. Zeisser, personal communication, May 14, 2021). Similarly, a component in demolition of mandatory harvesting of materials rather than demolition of a building could be stimulated. Circular demolition specifications exist and are used (Gemax B.V., 2020; Metabolic & DR2 New Economy, 2018a). However, in practice it does occur that certain specified materials are deemed unsuitable for reuse at the demolition site and are thus disposed of anyway, so it is important to monitor that the circular demolition specifications are upheld (A. Verkuijlen, personal communication, May 19, 2021).

A way to encourage more sustainable and circular construction, which includes building with timber and increasing reuse, is taxation of CO_2 in the construction sector (V. de Beus, personal communication, May 21, 2021; Gustavsson & Sathre, 2011; Oldenburger, Van Den Briel, et al., 2020; R. van Gurp, personal communication, May 20, 2021; A. Verkuijlen, personal communication, May 19, 2021). As long as building with timber and using reused elements are more expensive than traditional construction, oftentimes construction companies and contractors revert back to what is standard, because changing conventional methods of construction is accompanied by risks (as was mentioned in section 4.3.2).

To convince contractors of the benefits of timber construction systems and of reassembly design aspects, it is important to display example projects (D. Grootenboer, personal communication, June 2, 2021). However, to realize these projects investments are needed: implementing standardized regulations surrounding proof-of-concept could facilitate the construction of example projects of timber residential dwellings (V. de Beus, personal communication, May 21, 2021) and incorporate reassembly design aspects.

The *Bouwbesluit* includes specific requirements, on for instance ceiling height or door formats (O. Wiggers, personal communication, May 26, 2021), that are ever-changing which makes circular construction complicated (A. Verkuijlen, personal communication, May 19, 2021). To stimulate reuse of timber elements and building materials in general, it is important to investigate how to include these changing requirements in the design of buildings so that buildings elements can be reused in some way (e.g. by being altered, converting to CLT, by combining elements) and are not inferior to new building elements.

This research shows that by implementing timber in Dutch residential dwellings, the carbon stock of Dutch residential dwellings could increase on the long term (Figure 37) and could thus contribute to the goals set by the Dutch government to reduce CO_2 emissions by delaying emissions through carbon storage. Although the MPG has already been altered slightly on July 1, 2021, it could be improved even further by including carbon storage potential of timber, which would more accurately represent the environmental impacts of timber as a construction material and would thus create a level playing field for timber in the construction sector. The demand for secondary construction materials has increased due to the MPG (A. Verkuijlen, personal communication, May 19, 2021), so altering it further could facilitate the shift towards more reuse of these materials.

6. Conclusion

The aim of this research was to identify strategies that enable high-quality reuse of timber from residential dwellings by providing an overview of the potential for carbon storage in structural timber elements in residential dwellings in the Netherlands until 2050 and 2100, taking into account strategies to maximize the length of use of timber components. This overview was created by combining existing data on residential dwellings with scenarios on new and demolished dwellings and carbon storage length maximization practices, and an MFA of wood and carbon flows, including cascading potential, which enabled the comparison of the potential for reducing virgin wood use for different scenarios.

By creating scenarios on the number of residential dwellings constructed, the use of timber in dwellings, and the rates of reuse based on the identified maximization strategies, ranges were provided for the virgin and reused timber use, associated carbon storage and thus delayed emissions, and the avoided CO_2 emissions from incineration. As timber structural elements have long lifetimes, the most important maximization strategies to increase the length of use of timber structural elements until 2050 and 2100 are developing new disassembly techniques for existing dwellings, developing quality standards for (reused) timber elements, improving the infrastructure for reuse of elements and materials, and creating a marketplace with an overview of supply and demand of secondary materials. To increase the length of use of structural timber elements on the longer term, it is also important to take into account design strategies that allow for easy dis- and reassembly.

Following from the different scenarios, the resulting ranges for carbon storage potential over the period 2020-2050 are an annual average potential of 8.8 to 272 kt and a cumulative potential of 0.3 to 8.2 Mt, and over the period 2020-2100 are an annual average potential of 5.5 to 373 kt and a cumulative potential of 0.4 to 29.9 Mt. The resulting maximum potential for the use of reused timber, and thereby the mitigated quantities of virgin timber is a cumulative potential of 9.25 million m^3 over the period 2020-2050 and a cumulative potential of 29.4 million m^3 over the period 2020-2100. The resulting maximum potential for the avoided CO_2 emissions from incineration over the period 2020-2050 is an annual average potential of 127 kt and a cumulative potential of 3.8 Mt, and over the period 2020-2100 is an annual average potential 157 kt and a cumulative potential of 12.6 Mt.

Maximizing overall timber use increases the total carbon storage in residential dwellings, but can also create a large demand for primary timber, especially when large numbers of dwellings are required, which may prove difficult to meet. When constructing with as much timber as possible, which occurs in the higher wood use scenarios, it becomes clear that the potential for building residential dwellings with reused timber is limited. This creates a clear distinction between on the one hand maximizing the use of timber in dwellings, thereby storing carbon and delaying emissions, and on the other hand maximizing the use of reused timber in dwellings, thereby preventing incineration and thus CO_2 emissions. This means that the efforts to increase timber use in dwellings and increase reuse should be carefully weighed to find an optimal balance between maximizing the length of carbon storage in structural timber elements by implementing cascading while being able to fulfill the demand for primary timber. This research provides several recommendations for policymakers that could facilitate increased use of timber in residential dwellings, which increases carbon storage within the built environment, and increased cascading and therefore higher-value reuse of structural timber elements, which lowers the demand for virgin timber and the quantities of high-quality timber incinerated with energy recovery.

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Appendix I. Input values MFA parameters

Table 22 presents the input values for the parameters mentioned in section 3.7.1. These values are based on the timber demand calculated in section 3.5.4 (Figure 25). It is important to note that the values for the parameters presented in Table 22 are the average annual values over the course of the relevant time period.

Table 22. Input values for parameters in the MFA model: name, population and wood scenario where applicable, time period, value (m^3).

Parameter	Population scenario	Wood use scenario	Period	Value (m^3/year)
TFC$_{available}$	-	-	2020-2050	774,344
	-	-	2020-2100	550,697
CLT$_{available}$	-	-	2020-2050	0
	-	-	2020-2100	3,094
TFC$_{in}$	Low pop.	Conventional Focus	2020-2050	20,891
			2020-2100	12,907
		Moderate Timber	2020-2050	82,407
			2020-2100	42,678
		Wood Revolution	2020-2050	124,431
			2020-2100	60,220
	Middle pop.	Conventional Focus	2020-2050	41,834
			2020-2100	67,164
		Moderate Timber	2020-2050	167,044
			2020-2100	178,675
		Wood Revolution	2020-2050	250,632
			2020-2100	226,809
	High pop.	Conventional Focus	2020-2050	62,778
			2020-2100	133,355
		Moderate Timber	2020-2050	251,680
			2020-2100	339,815
		Wood Revolution	2020-2050	376,832
			2020-2100	421,769
CLT$_{in}$	Low pop.	Conventional Focus	2020-2050	15,000
			2020-2100	9,288
		Moderate Timber	2020-2050	95,057
			2020-2100	54,672
		Wood Revolution	2020-2050	217,017
			2020-2100	126,346
	Middle pop.	Conventional Focus	2020-2050	29,919
			2020-2100	47,956
		Moderate Timber	2020-2050	195,162
			2020-2100	259,356
		Wood Revolution	2020-2050	449,871
			2020-2100	606,989
	High pop.	Conventional Focus	2020-2050	44,837
			2020-2100	94,978
		Moderate Timber	2020-2050	295,267
			2020-2100	503,892
		Wood Revolution	2020-2050	682,724
			2020-2100	1,180,411

Appendix II. Wood types in existing residential dwellings

In literature, there are no data available on the types of wood in existing residential dwellings or conclusive quantitative data on the types of timber used in TFC systems. For CLT systems, Muszynski et al. (2017) conducted market research in which they found that the largest share of CLT systems in Europe is constructed from spruce wood and other types of wood are also used on smaller shares (Table 23). For TFC systems, it is widely published that the largest share is constructed from spruce (Oldenburger, Van Den Briel, et al., 2020; Pontmeyer, 2021; M. Timmer, personal communication, May 10, 2021; A. Verkuijlen, personal communication, May 19, 2021), though the wood types pine, larch, and douglas are also used (Centrum Hout, 2005; Jeffree, 2020; Oldenburger, Van Den Briel, et al., 2020; Van Dam & Van den Oever, 2019). Based on the limited data available, assumptions for the shares of wood types used in TFC systems are listed in Table 23.

Table 23. Wood types used in TFC and CLT systems and their specific weights. Sources listed in table, use in TFC systems based on assumptions.

Wood type ***(latin name)***	**Specific weight (kg/m^3)**	**Sources specific weight**	**Use in TFC systems**	**Use in CLT systems (Muszynski et al., 2017)**
Spruce (*Picea abies*)	460	(Van Dam & Van den Oever, 2019)	75%	88%
Pine (*Pinus sylvestris*)	510		10%	6%
Larch *(Larix spec. div.)*	590		10%	0.31%
Douglas *(Pseudotsuga menziessii)*	530		5%	-
Fir *(Abies alba)*	460	(Centrum Hout, n.d.-a)	-	5%

Taking into account the data provided in Table 23, the average specific weight for dwellings using a TFC system is 482 kg/m^3, and the average specific weight for dwellings using a CLT system is 463 kg/m^3.

Appendix III. Population and household scenarios

For sub-question 1, different prognoses on population growth and number of households were calculated, which are presented below (Figure 42 and Figure 43).

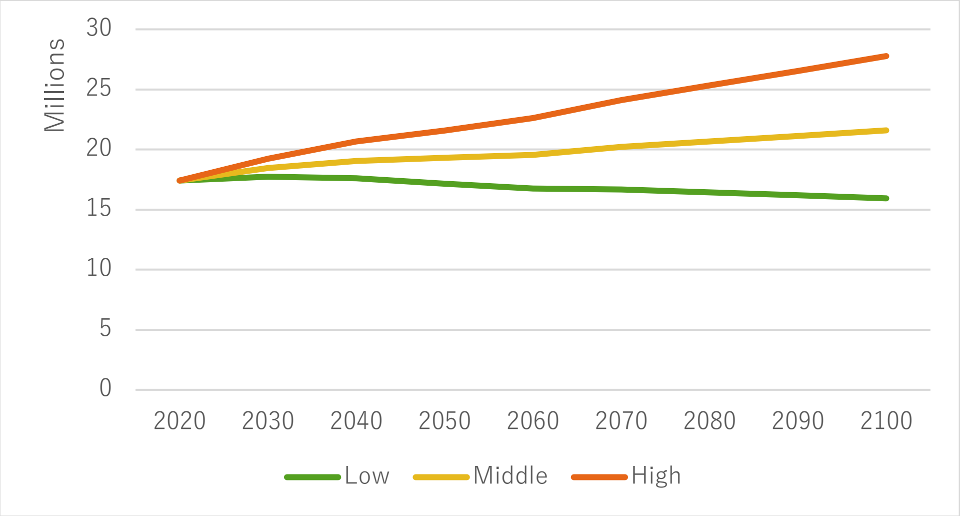

Figure 42. Population of the Netherlands, extrapolated from CBS (2019).

Figure 42 shows that in scenario Low pop., it is expected that after a slight peak around 2030, the population size is projected to decrease. In scenarios Middle pop. and High pop., the population size is projected to increase, albeit a more gradual increase for the former and a steeper increase for the latter.

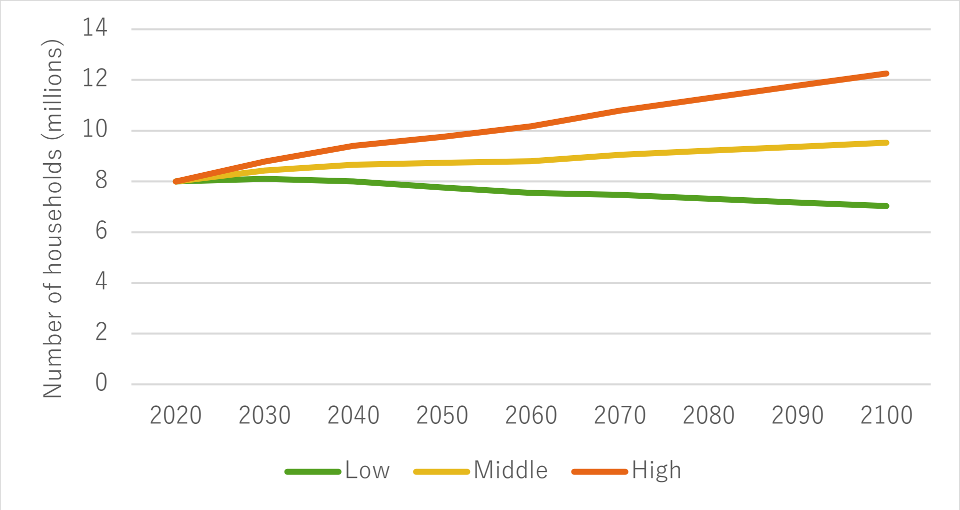

Figure 43. Prognosis of number of households in the Netherlands. Based on population prognoses and prognosis of number of persons per household.

The developments in Figure 43 follow a similar trend to the trend seen the projected population development (Figure 42), but due to the slightly increasing number of persons per household, the projected increases in number of households for scenarios Middle pop. and High pop. are less strong than the projected increases in population.

Appendix IV. New dwellings

The results from section 4.1.3 on the new dwellings for each population scenario until 2050 are presented below (Figure 44).

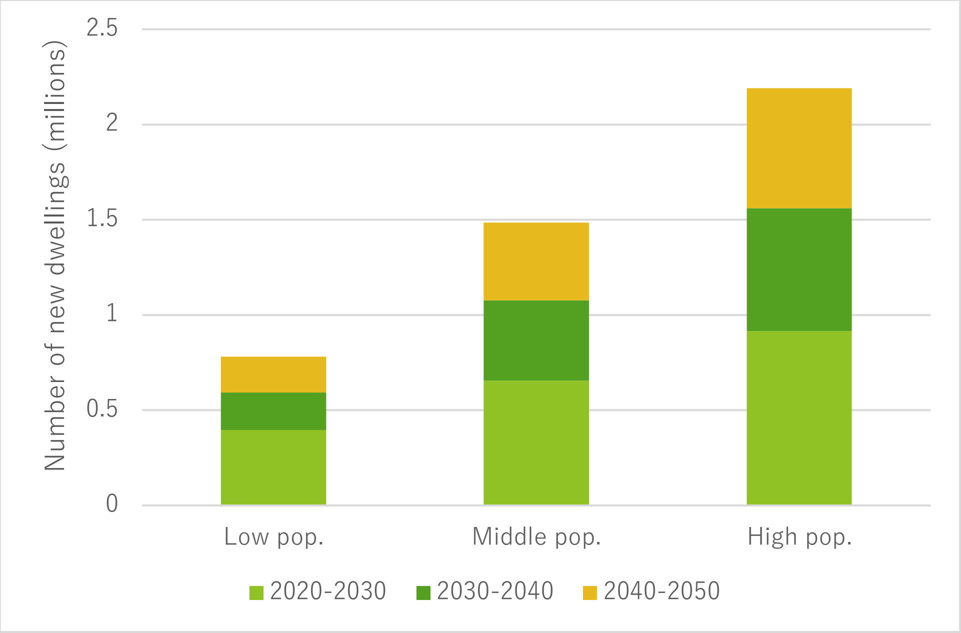

Figure 44. Number of new dwellings according to scenarios Low pop., Middle pop., and High pop., until 2050.

Appendix V. Potential dwellings from timber – scenarios Low pop. and High pop.

The results for the technical potential of the number of dwellings from timber in population scenario Low pop. are presented in Figure 45.

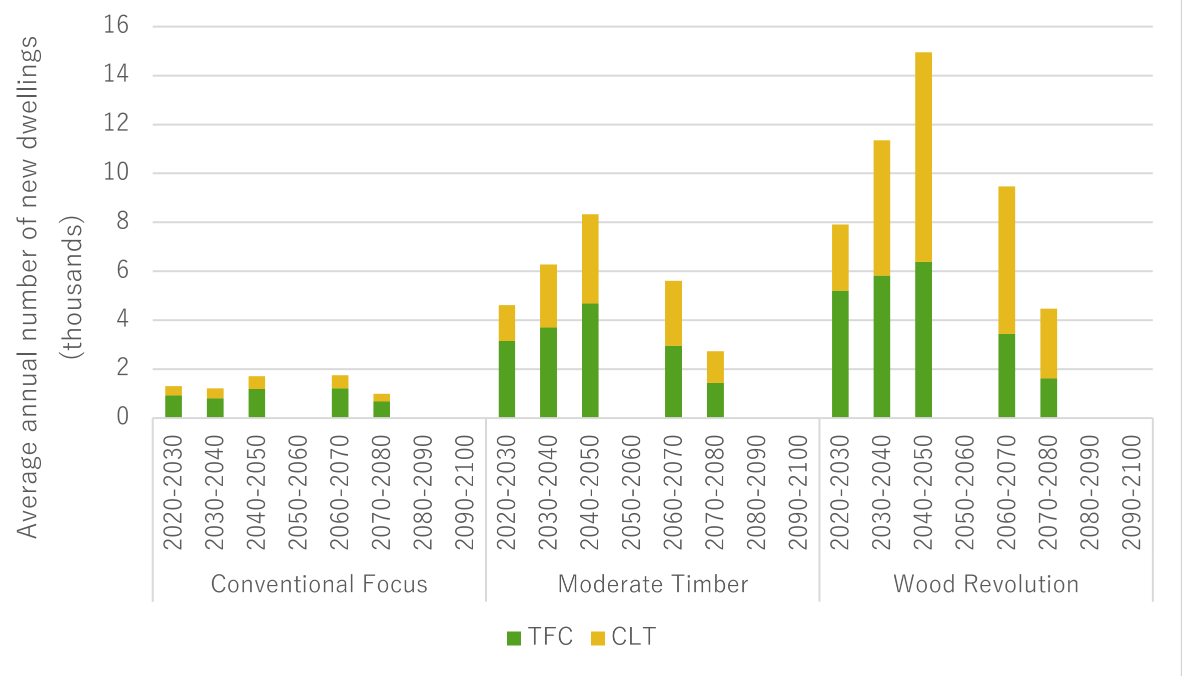

Figure 45. Average annual number of dwellings from TFC and CLT in the Netherlands from 2020-2100: wood use scenario Conventional Focus, scenario Low pop.

The results for the technical potential of the number of dwellings from timber in population scenario High pop. are presented in Figure 46.

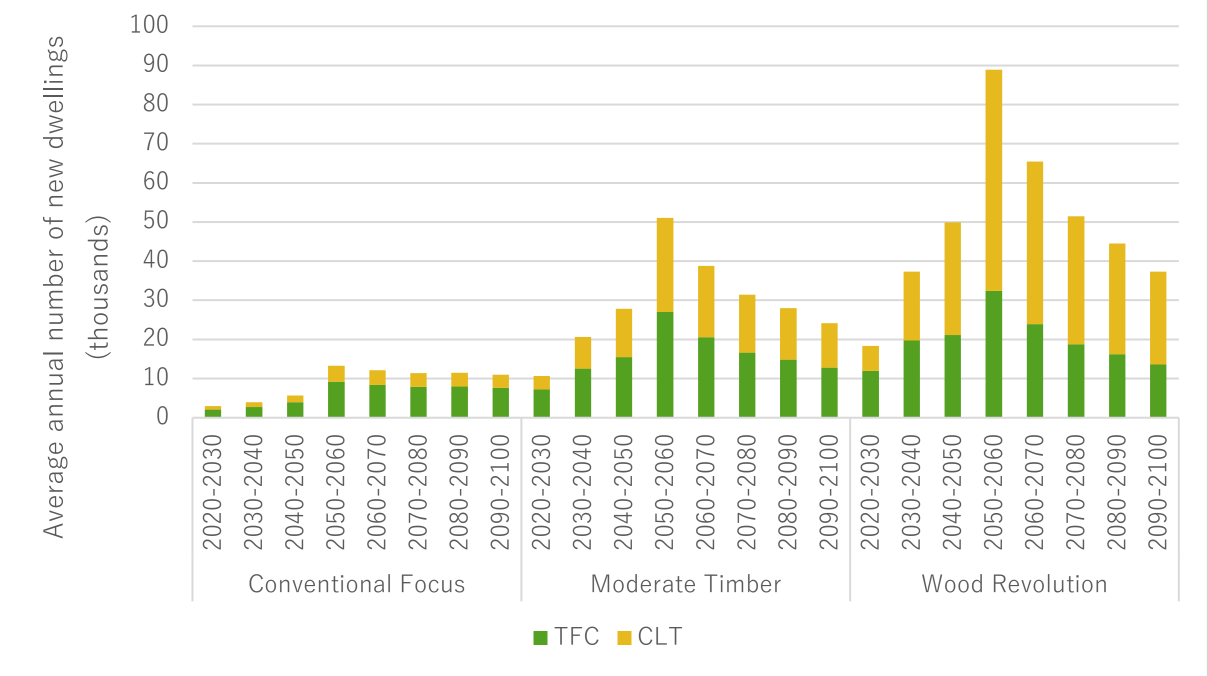

Figure 46. Average annual number of dwellings from TFC and CLT in the Netherlands from 2020-2100: wood use scenario Conventional Focus, scenario High pop.

Appendix VI. Potential timber quantities for storage

Currently, the model does not take into account storage potential, thus it is assumed that the available timber from existing dwellings that cannot be reused in new dwellings is either recycled into lower-value end products or incinerated with energy recovery. If storage was modelled, the potential timber quantities for storage are presented in Figure 47. The values are not intended to be representative for what will be stored, as this depends on the development of timber storage capacity in the future.

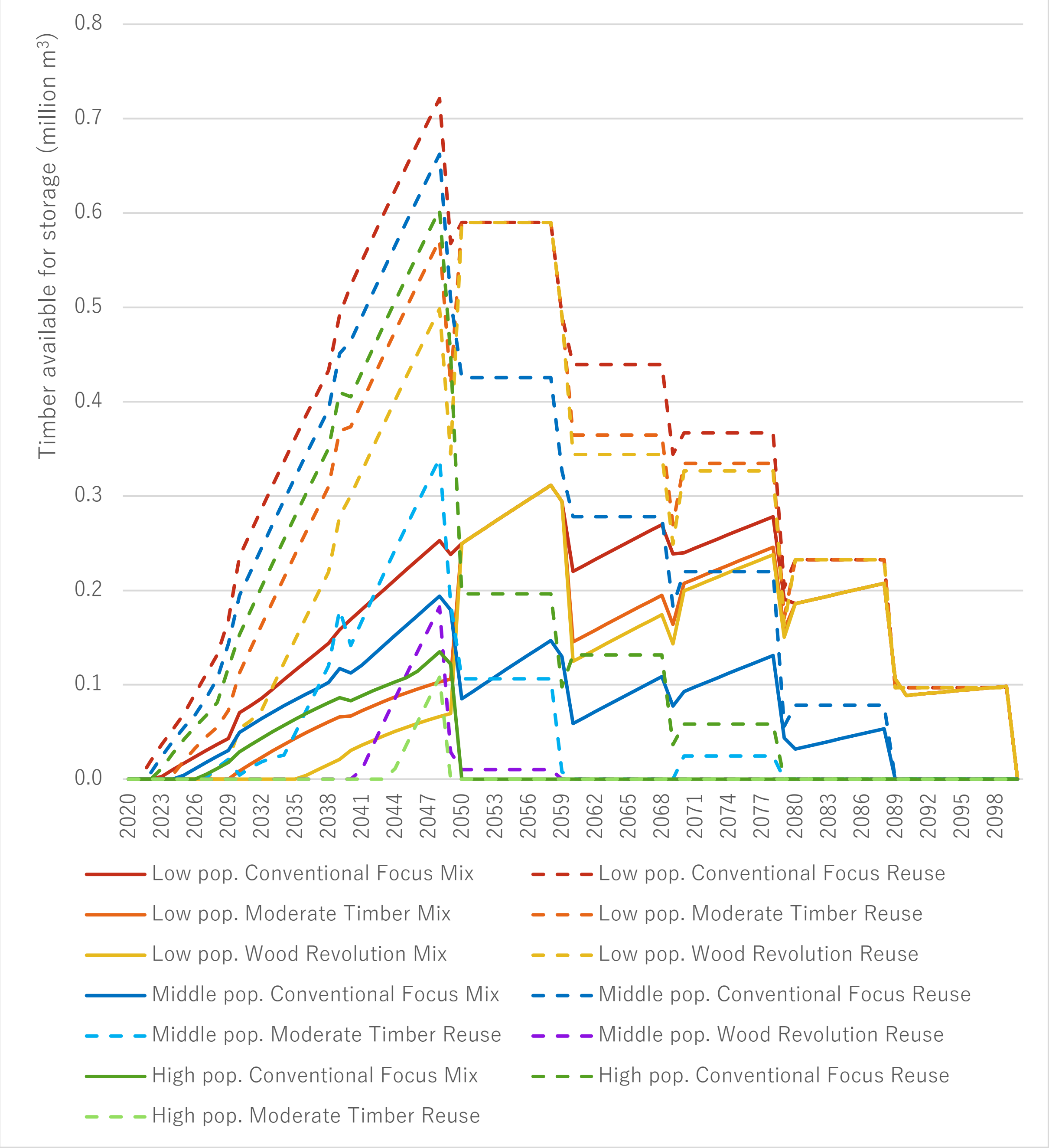

Figure 47. Potential timber available (million m^3) for storage. Only the scenarios in which there would be potential quantities for timber storage are presented.