REUSE OF SCRAP WOOD

IN A BUILDING PRODUCT

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MSC THESIS
ARCHITECTURE, URBANISM AND BUILDING SCIENCES (BUILDING TECHNOLOGY TRACK)
TU DELFT
P5 VERSION | 31-10-2023

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Master Thesis
Architecture, Urbanism and Building Sciences (Building technology track) | TU delft

P5 version 31 - 10 - 2023

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ABSTRACT

Climate is changing. The average temperature on earth is rising due to excessive emissions of greenhouse gasses such as CO2. In the meantime the economy is a linear economy where a produced from exhaustive materials are consumed and turned into waste. In order to fight climate change and exhaust the earth less the greenhouse gas emissions need to decrease and less waste needs to be produced. The goverment has set goals to have a circular economy by 2050. A circular economy means the elimination of waste, instead all materials are reused and recycled to its final potential and new materials come from renewable sources.

One commonly used renewable material in the built in environment is wood. Besides, wood sequesters CO2, has a low environmental impact and can be reused and recycled. When more wood is used and forests keep growing, more CO2 is sequestered, especially when it is substituted for product that emit a lot of CO2. Wood can so contribute to the overall decrease in CO2 emissions.

But at the moment there is also a huge waste production of wood, with a annually production of 1,8 Mton waste wood, of which 435 kton is scrap wood (waste wood from the construction and demolition industry) (Sloopcheck, 2021). Most is incinerated or otherwise recycled. Only a small portion is reused. In order to contribute to the circular economy goals scrap wood should therefore be reused and recycled. This thesis aims to research why the portion of reusing scrap wood is so small and tries to find a suitable building product to show that scrap wood can and should be reused. The suitable building product is CLT, due to the used lamellae consisting of varying dimensions, mechanical properties and possibly wood species. This research shows that scrap wood can be implemented into scrap wood, although the portion of scrap wood into a panel depends on the availability of certain required properties. The substitution of scrap wood in CLT panels always results in extra CO2 savings, and therefore the reuse of scrap wood into CLT panels can contribute to reducing CO2 emissions.

PREFACE

This report is the final result of the graduation thesis of the Building Technology track of tthe faculty Architecture and the Built Environment of the TU Delft. At the time of writing this thesis when the climate chance impacts not only the Netherlands but the whole world. The Netherlands is at the moment starting to try to transform to a circular economy, but this is in the beginning phase. Materials have to be more reused and the research on how more reuse can be achieved and why certain product are not commonly reused in done while writing this thesis. The information about scrap wood is scarce and multiple companies are doing research on this topic. On the other hand, the Netherlands is dealing with a housing shortage and needs a million new homes by 2030. This thesis tries to shed some light on the issues surrounding reusing scrap but also to show that scrap wood can be reused so the amount of scrap wood can be decreased and simultaneously decrease the CO2 emissions. The outcome of scrap wood in CLT incidentially can also contribute to construction more houses to fight the housing shortage.

I would like to thank my mentors Arie Bergsma and Leo Gommans for guiding me through this thesis, and giving me the confidence of the importance of this thesis, while also showing patience and support throughout this process.

I would also like to thank Hermen van de Minkelis, Renewi, Woodjoint, Herso, Vermeulen Sloopwerken, Stiho, Sanne Pelt and Hout met historie for taking the time to help me with this thesis through (videocalling) or sitevisits.

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INTRODUCTION

1.1 CONTEXT

Wood will play an important role in the challenge of creating a more sustainable world to combat climate change caused by greenhouse gas emissions resulting from the rapid growth of the world's population and its increasing consumption. Material and waste management must be rethought to create a closed loop to meet demand and avoid relying on exhaustible materials. This means that the reuse of materials, in this case wood, will be an important factor in this challenge.

This chapter will discuss the context of this thesis and how the issue of 'reusing waste wood' is relevant in today's society. Firstly, some sustainability goals to combat the problem of climate change will be discussed. Then the circular economy principle will be discussed and how this principle is implemented in the built environment. These principles are important for the relevance of reusing waste wood. Next, the sustainable benefits of wood as a material are discussed. Then the amount of waste wood and its potential is discussed. Finally, the use of virgin wood and waste wood will be compared in terms of sustainability.

1.1.1 CLIMATE CHANGE & SUSTAINABILITY GOALS

Climate change is a serious problem globally. The temperature on earth is rising, due to the enormous increase in greenhouse gas (GHG) emissions in the air, CO2 and nitrogen, since the industrialisation. Figure 1 shows the growing annual GHG emissions in the world, with a total of 53,6 billion ton GHG in 2021 and the steep rise in the emissions in a hundred years (Jones et al., 2023). The consequences, such as more extreme weather conditions could be catastrophic for the earth, nature, animals and humans. When the temperature rises more than 2 degrees the consequences would be irreversible (De Munck, 2021) So, measures need to be taken to reduce the GHG emissions to minimize the average temperature increase (Ministerie van Infrastructuur en Waterstaat, 2022b). The population keeps growing and along with material consumption, mostly from non-renewable resources, which

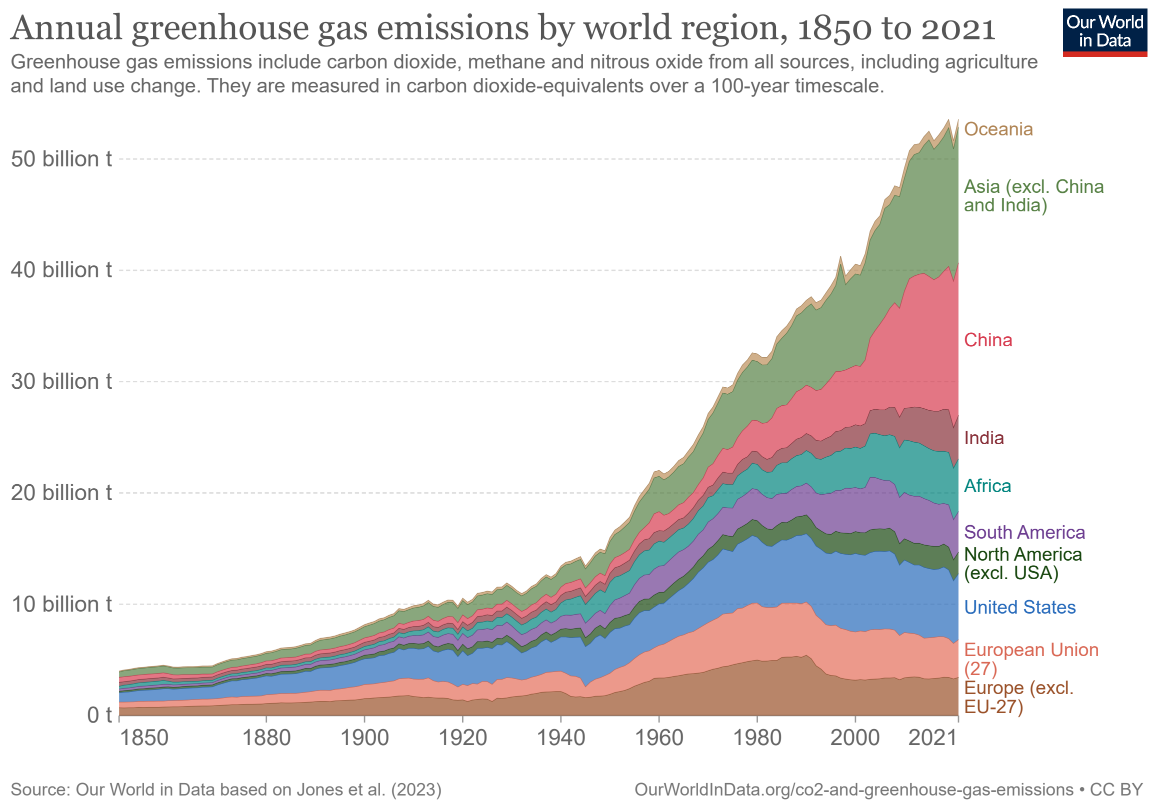


Figure 1_Annual greenhouse gas emissions by world region, 1850 to 2021 (Our World in Data, 2023)

creates massive amounts of waste each year. In fact, the world produced 2.02 billion tons of municipal waste worldwide in 2016 (Alves, 2023). The material usage needs to change to be able to provide humanity with necessary products and food without exhausting the earth.

Countries worldwide, such as the Netherlands, alone and together are taking measures to combat climate change, adapt to the consequences of climate change and change their material consumption. The global goal is to limit the rise on temperature at 1,5 degrees, by decreasing global CO2 emissions of 810 Gt (Van Der Lugt, 2021). In the Netherlands all those measures together form 'het Nederlandse Klimaatbeleid' (Dutch Climate policy) (Ministerie van Infrastructuur en Waterstaat, 2022b).

In 2015, the United Nations, which is an international organization made up of 193 member countries and works on common issues for humanity and the earth, developed the '2030 Agenda for Sustainable Development' goals. This agenda includes 17 sustainable development goals (SDGs) (United Nations, 2015) to:

"provide a blueprint for peace and prosperity for people and the planet, now and into the future."

Part of the 17 SDGs is focused on fighting climate change, improving the built environment to provide safe & healthy cities and communities, change the material consumption to responsible and sustainable consumption by implementing more of a circular economy than the current linear economy.

The government has set certain goals to transform the Netherlands into a sustainable and circular country, which are set out in "SDG Nederland" (translated and adapted from the SDGs of the UN), the adaptation plans: the Deltaprogramma, the 'Nationale Adaptatiestrategie' (National adaptation strategy) and for the minimalization of climate change: 'Klimaatakkoord' (Climate agreement).

In 2050 the government wants to operate as a fully circular economy. To reach that goal certain sub goals are set in 2030, where the government wants to reduce the CO2 emissions in relation to 1990 with 60% and use 50% less primary raw materials (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022b).

1.1.2 CIRCULAR ECONOMY

One of the keys to reduce CO2 emissions and to handle raw materials more sustainable is a circular economy (CE). The principle of a circular economy is a closed loop from production to user phase to recycling, so without waste production, see figure 2. Waste is instead reused or recycled, functioning as a "new" material. The (new) materials brought into the CE loop are mostly renewable, to decrease the use of exhaustive materials and exhaust the earth less. Wood is a natural raw material that is renewable and biodegradable (Centrum Hout, 2016; Rowell, 2013). Together with the non-renewable materials, such as concrete and steel, the materials are reused, repaired, recycled, etc. to their final potential. A circular economy results in a decrease of raw material and

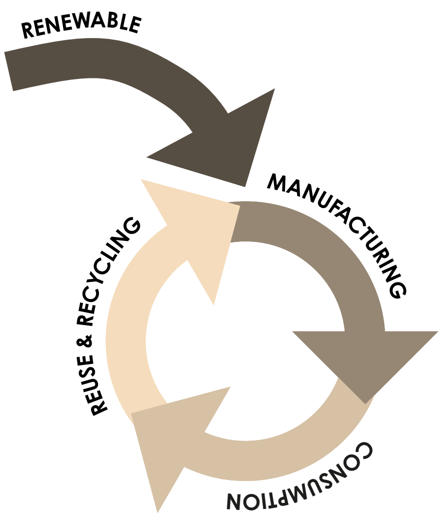


Figure 2_Diagram of a circular economy (own image)

products usage and eliminates waste (Rijksoverheid, n.d.). However, not all waste can be recycled or recovered, so a 100% is not possible (Vereniging Afvalbedrijven, n.d.). Raw materials, creating products and waste incineration all release large amounts of CO2 emissions. By adopting principles of the circular economy, CO2 emissions can be reduced.

Currently, the Netherlands follows a linear economy, where products from raw materials become waste at the end of their lifecycle. Although the Dutch linear economy does contain a recycling system. Around 80% of the total waste is recycled (Vereniging Afvalbedrijven, n.d.), although it mostly results in downcycling. Households already separate paper & cardboard waste, plastic waste, biodegradable waste and glass waste. Large items, such as furniture, renovation waste, electronics, etc. can be handed in or picked up by a recycling center. Textile bins and second hand stores are available in most cities, and otherwise people can sell secondhand products on websites such as Marktplaats.nl or Vinted.nl (predominantly clothes). As a result, many people are already reusing and recycling products, bringing the Netherlands a step closer to a circular economy.

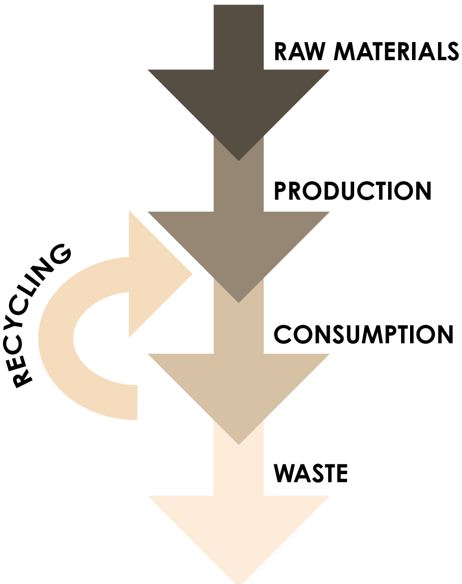


Figure 3_Diagram of a linear economy with recycling (own image)

Reusing isn't yet common in the service, office and stores sector, they only recycle 50% of their waste (5 Mton) (Vereniging Afvalbedrijven, 2023). There's still a lot of non-renewable materials being used and every person produces 490 kg of waste per year, but only 60% is separated (Milieu Centraal, n.d.). Therefore, significant effort is necessary for the Netherlands to achieve a circular economy.

The government has put the transition to a circular economy into three objectives (Ministerie van Infrastructuur en Waterstaat, 2022a):

1. More efficient use of raw materials within production processes to lower the need of raw materials.
2. When raw materials are necessary, those materials should be sustainable produced, renewable and commonly available. Fort example materials from plants or food. This is better for the environment and the dependence on fossil resources becomes less.
3. New products should be designed circular and new production methods should be developed.

The last goal also translated into designing products in such a way that they can easily be repaired or otherwise reused or recycled. This thesis focuses on decreasing the waste production by finding ways to reuse or recycle the waste wood production. Wood is a renewable and raw material and therefore fits into the objectives of a circular economy.

1.1.3 CIRCULAR BUILD ECONOMY

Transformation from a linear economy to a circular economy in the Netherlands should take place in all sectors. One of the industries with a large impact on the environment is the Construction & Demolition industry (C&D). In the transitie agenda Bouw Nelissen et al. (2018) discussses this impact and the needed transition to become more circular. The built environment in the Netherlands uses 50% of total raw materials used, and has the largest waste production, 40% of the total waste production. Besides waste, the built environment produces 35% of total CO2 emissions, uses 40% of the total energy usage and 30% of the total water usage. On the other side, the built environment also reuses and recycles approximately 97% of its construction & demolition waste, although most of it ends up in the infrastructure sector for low-grade applications.

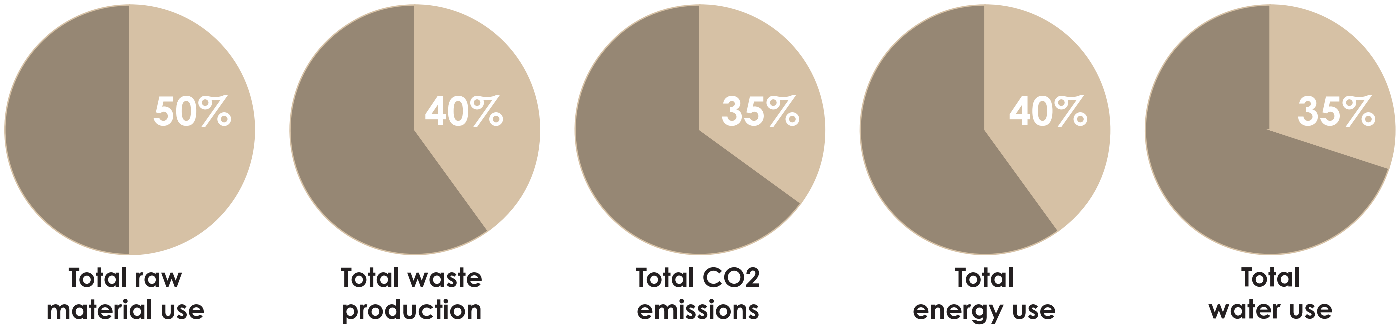


Figure 4_Environmental impact of the built environment

The built environment, Buildings & Utility buildings (B&U) and infrastructure (GWW), mostly uses non-renewable, very heavy materials, like concrete, steel and stone in massive amounts (Nelissen et al., 2018). Most of these materials have a limit on the amount of times it can be reused or recycled or have little potential for reuse. A circular economy with only these traditional materials is therefore not realistic. So, other, renewable materials need to be implemented (more), such as wood (Centrum Hout, 2016). Not only the usage, but also the extraction, manufacturing and transportation of those materials uses a lot of energy, releases a lot of CO2 emissions and has therefore a big impact for the earth (Nelissen et al., 2018).

Therefore, the built environment is a major contributor to climate change and must be transformed into a circular (build) economy in order to achieve the sustainability goals of the UN and the Netherlands, to fight climate change and to change the way we use materials on a massive scale. The government set certain goals for the built environment to become circular. These are set out in the Transitieagenda Bouw (Nelissen et al., 2018). The goal is to have a Circular Build Economy in 2050 and by 2030 the CO2 emissions are bisected. The Agenda states that buildings and infrastructure will be developed with a high quality, in a way that all (raw) materials are renewable to stop the use of fossil fuels.

Definition Circulair Construction
”Circular construction means developing, using and reusing buildings, areas and infrastructure, without unnecessarily depleting natural resources, polluting the living environment and affecting ecosystems. Building in a way that is economically responsible and contributes to the well-being of people and animals. Here and there, now and later.” (Nelissen et al., 2018)

Meanwhile, the built environment also needs to build 1 million houses in 10 years to address the massive housing shortage (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022a). This will require massive amounts of materials. In order to reach the sustainability and circular economy goals, the buildings need to be built in a more circular way. This means that not only more renewable materials should be used, but also recycled materials, and that the production (of materials) and construction should emit less CO2 than is currently the case.

The C&D industry is therefore a major contributor to climate change, waste production and material use. One of the most commonly used construction materials is wood, which is the only renewable material. Wood is therefore likely to play a major role in the transition to a circular build economy. Waste production, although mostly downcycled, should also decrease. Instead of downcycling, waste could be reused or recycled into new building products, so the use of new materials could also decrease.

1.1.4 WOOD

As mentioned above, wood is the only renewable construction material. Although concrete and steel are more commonly used today, wood will play a greater role in the transition to a circular build economy, and not just because of its renewability. Wood has the ability to store CO2 by removing it from the air through photosynthesis (Centrum Hout, 2016). Buildings and their products have a long lifespan, some for centuries. So the storage capacity results in long-term CO2 storage in buildings.

Other sustainable benefits of wood compared to concrete & steel include the lowest CO2 footprint for production, the lowest energy requirement and the lowest environmental impact (Centrum Hout, 2016). Wood can also be reused and recycled many times over its lifetime. Eventually it is recovered as bio-energy, releasing only the stored CO2 (Centrum Hout, 2016). The lifecycle of wood is shown in figure 5. So over its lifetime, wood emits very little CO2 and can even be carbon neutral. By using wood as a building material instead of products with high CO2 emissions, CO2 emissions can be massively reduced (Centrum Hout, 2016). These aspects characterise wood as a sustainable material that is highly suitable for use in a circular economy. For these reasons, wood has become

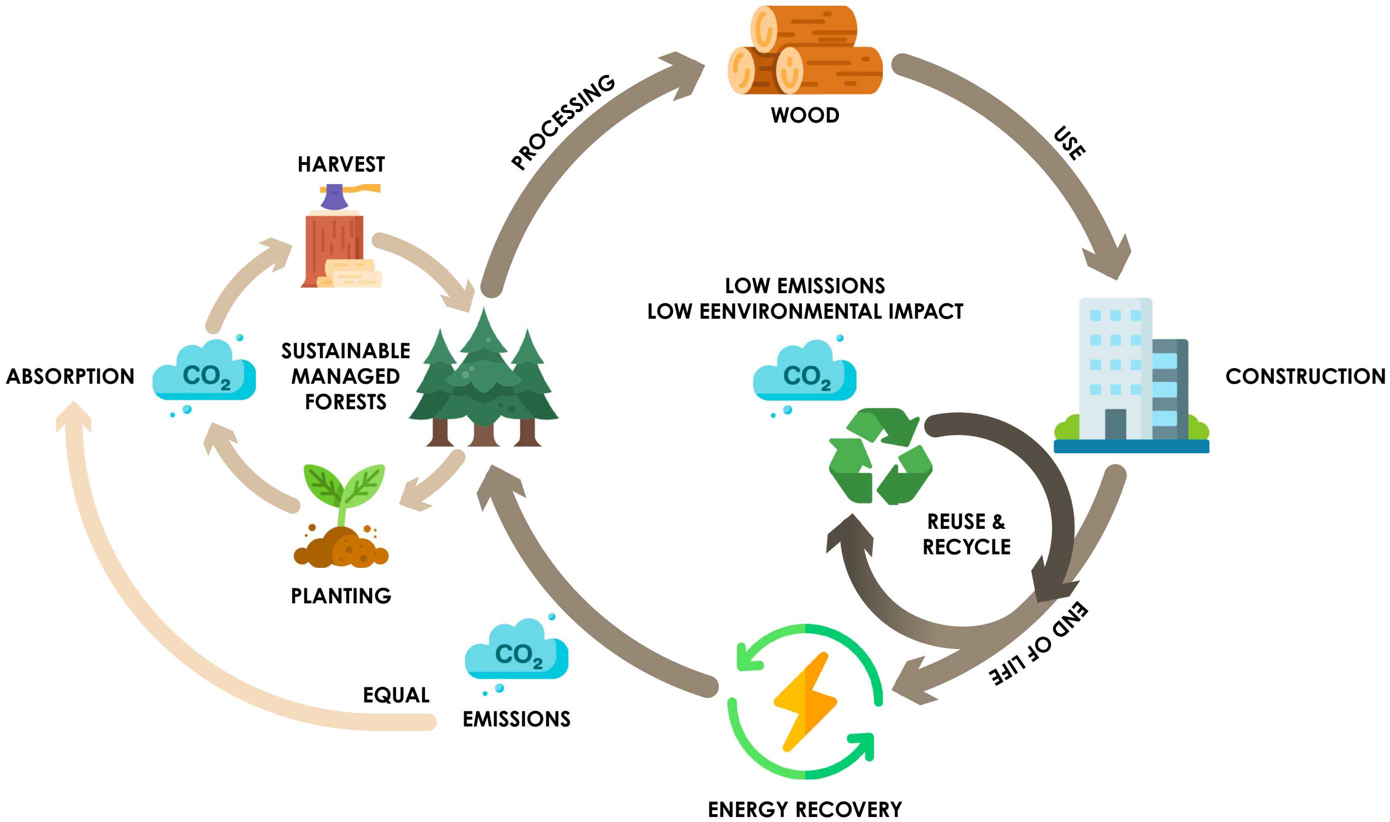


Figure 5_Lifecycle of wood (own image based on Sumitomo Forestry, n.d.; Centrum Hout, 2023)

an increasingly popular building material. The demand for wood is increasing, resulting in wood scarcity and increasing prices. In 2021, prices will rise by 50% for softwood, up to 60% for wood-based panels and 25% for tropical hardwood (Redactie Houtwereld, 2021).

1.1.5 SCRAP WOOD

Besides the sustainable benefits of wood, it also contributes to the waste production with an annual production of approximately 1.8 Mt of wood waste in the Netherlands. Wood waste from the C&D industry, known as scrap wood, amounts to approximately 435 kton yearly, which is 24% of the total wood waste production. Of the 1,8 kton waste wood, most is incinerated (73,3%), some is recycled (17,1%) and only 9,6% is reused (BlueCity, n.d.).

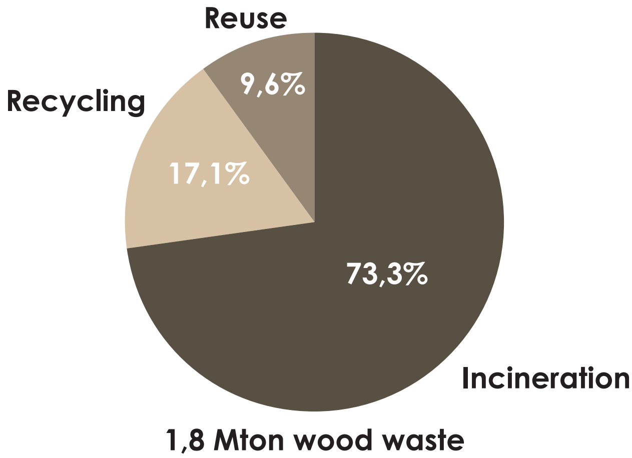


Figure 6_Wood waste divisions

The 435 kton scrap wood is enough to build 50.000 family houses from CLT (Van de Minkelis, 2021), that's half of what needs to be built annually to reach the goal of 1 million houses in 10 years. Although the incineration is a form of energy recovery as bio-energy, scrap wood should first be reused and recycled to its final potential in a circular (build) economy. Incineration should therefore not be the largest part of waste wood management. This principle is not in line with the transition to a circular economy. Increasing the reuse and recycling of scrap wood not only reduces the amount of waste, but also contributes to a reduction in CO2 emissions, as the CO2 stored in scrap wood is stored for a longer period of time instead of being emitted back into the atmosphere, resulting in an overall reduction in CO2 emissions over time.

Figure 7_Scrap wood (own image)

1.1.6 NEW VS. SCRAP WOOD

Wood will be a major contributor to the built environment in the transition from a linear to a circular built economy because of its ability to sequester CO2 and because it is a renewable material. So why should we look at reusing waste wood when wood is already a sustainable material?

Firstly, as mentioned above, scrap wood is waste and in order to become more circular, the production of waste should be eliminated. Secondly, prolonging the life of waste wood leads to longer and more CO2 storage, which reduces CO2 emissions. Thirdly, the demand for timber is likely to increase because of the sustainability label. At present, the Netherlands imports 4.6 million m3 of construction timber per year, of which 82% is imported from Europe, mainly from Scandinavia, Germany and the Baltic States, 4% from tropical forests and 8% from Dutch forests, see Figure 8. In sustainably managed forests, as explained in Chapter 2, a new tree is planted for every tree that is harvested, so that forests are always regrowing and only 65% of this regrowth is harvested again. This means that forests continue to grow. The harvesting of wood even has a positive effect on preservation of those forests (Circulaire Bouweconomie, 2023). So, the forests have a buffer to accommodate the rising demand. The issue with importing wood is therefore not deforestation, but transport, as most virgin wood has to be transported to the Netherlands.

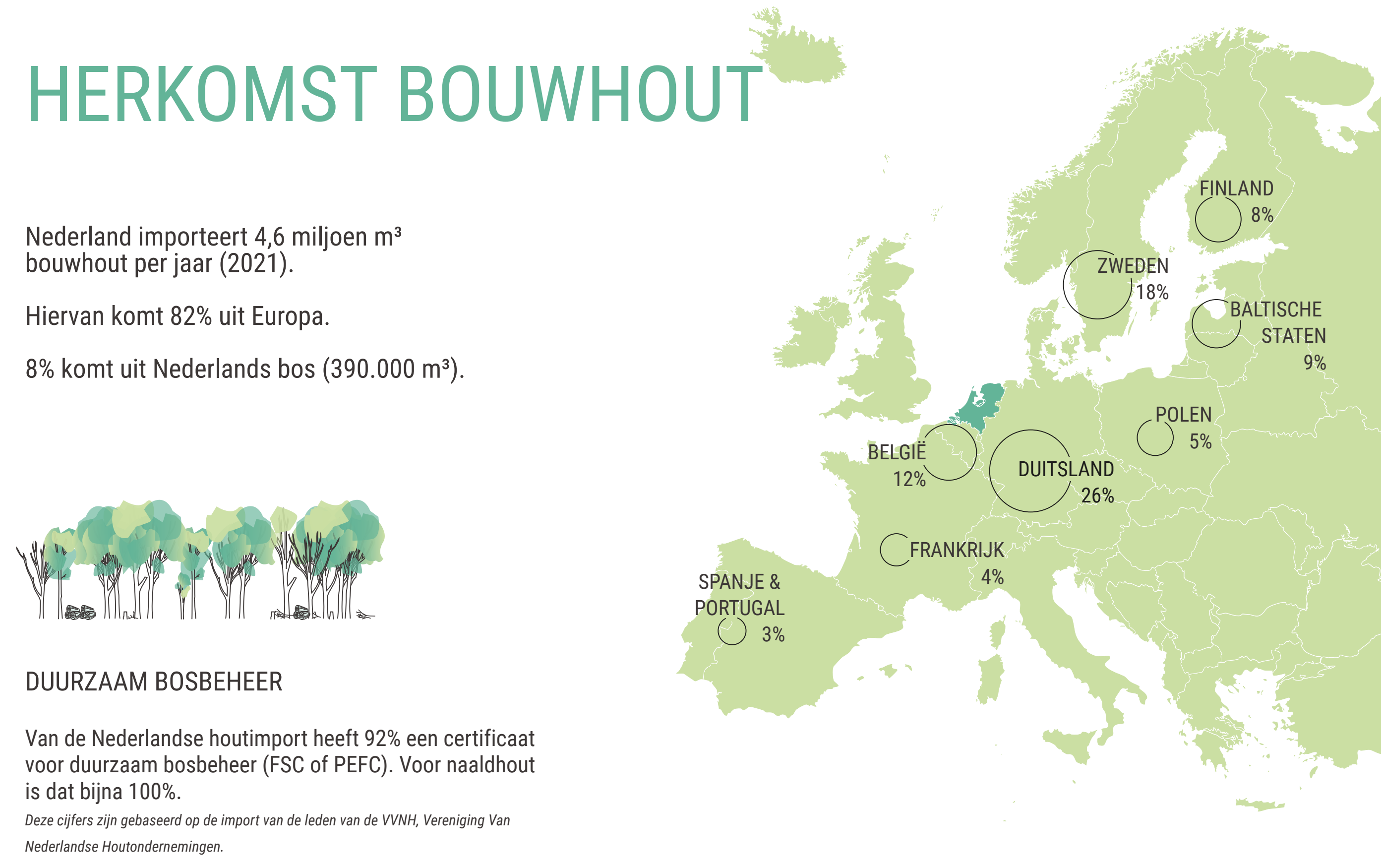


Figure 8_Construction timber in Europe (source: Probos & Centrum Hout, 2023)

Transport is also a large contributor to the CO2 emissions. In the Netherlands 35% of the total CO2 emissions of the C&D industry are caused by transport (Walther Ploos van Amstel, 2022), with 10,6 Mton CO2 emissions in 2019 (TNO, 2020). Specific information on carbon emissions from international timber transport could not be found. However, most international transport has higher carbon emissions than national transport due to the longer transport distance. Scrap wood is locally sourced from demolition sites and therefore requires less transport distance than virgin wood, resulting in lower carbon emissions from transport.

The rise in demand for wood can partly be accommodated by scrap wood, which either reduces the demand for virgin wood or makes it possible to build more wooden constructions. In the Netherlands there is enough scrap wood for 50.000 CLT houses and even more wood waste. Although not all of this waste wood can be reused, it can still contribute to the housing crisis. The use of waste wood in the built environment therefore contributes to reducing CO2 emissions and increasing the demand for wood.

1.1.7 CONCLUSION

In short, the world must become more sustainable in order to combat climate change and material scarcity before the consequences become irreversible. This means reducing CO2 and nitrogen emissions and changing the way we use materials. The UN and the Netherlands have set certain goals and strategies to combat climate change. One of the goals is to transition from a linear economy to a circular economy. At the moment, the Netherlands has a linear economy with recycling methods.

The built environment has a massive impact on the environment. So to fight climate change, the built environment also needs to become more sustainable. The goal is also to have a circular build economy. Meanwhile, 1 million houses need to be built in 10 years, which requires more material use. In order to achieve the sustainability goals and build these needed houses, new and smarter methods of material use and waste management need to be developed.

One such method is to increase the use of wood in the C&D industry. Wood is a sustainable material which is already widely used in construction. The ability to store CO2, together with the long lifespan of buildings, can contribute to the reduction of CO2 emissions. Wood also has the lowest energy requirements, the lowest carbon footprint (almost CO2 neutral) and the lowest environmental impact. Incineration at the end of its life provides energy recovery, but releases the stored CO2. Wood will therefore play a role in the transition to a circular economy, which will result in an increase in demand.

On the other hand, the built environment produces 435 ktons of scrap wood per year, enough for 50,000 CLT houses. The majority (73,3%) is incinerated, with the remaining quarter either recycled (17,1%) or reused (9,6%). In a circular economy, there is no waste and all materials are reused and recycled to their final potential. This isn't currently the case for waste wood. To minimise waste production, more waste wood should be reused and then recycled. The benefits of reusing waste wood are that the lifespan of the wood is prolonged and the CO2 is stored much longer, the (international) transport of virgin wood is reduced, which also leads to a reduction in CO2 emissions, and the increasing demand for wood can be partially accommodated. Reuse of scrap wood is therefore necessary in the transition to a circular economy and can contribute to a reduction in CO2 emissions, but reuse in the built environment is not yet widespread.

1.2 RESEARCH FRAMEWORK

1.2.1 PROBLEM STATEMENT

The context resulted in the following problem statement:
The Netherlands wants to have a circular (building) economy by 2050 in order to combat climate change. Currently, the built environment is one of the largest contributors to waste production and CO2 emissions. Even the renewable building material wood produces 435 ktons of waste wood per year, enough for 50,000 CLT houses. Most of this is incinerated and only some is recycled. Although there is potential for reuse, there is a lack of reuse principles in the C&D industry.

Sub problem statements:

1. There is a lack of information about the consistency of scrap wood
2. There is a lack of circular strategies for scrap wood as building products on a big scale
3. There is a lack in assessment & grading methods to reuse scrap wood as building products

1.2.2 OBJECTIVES

From the main problem statement the general objective is:
Explore what kind of scrap wood has potential for circular strategies in the built environment

The sub objectives are:

1. Collect information about the consistency of scrap wood
2. Explore and define circular strategies for scrap wood in the built environment
3. Explore the barriers for the lack of reuse of scrap wood

1.2.3 SCOPE

Objective boundaries
The scope is limited to (1) scrap wood from (2) Dutch construction & demolition waste

1. The built environment needs to transform from a linear to a circular economy. To achieve this goal, materials need to be reused or recycled instead of becoming waste. The focus of this thesis is on wood waste, in particular scrap wood. Wood will play an important role in the transition to a circular economy due to its sustainable aspects. Although the total amount of wood waste is larger, the focus will be on developing a reuse method for scrap wood. This is a personal preference and because researching all waste wood (consistency, quality and reuse methods) is too large for the timeframe of this thesis.

2. The focus is on the scrap wood produced in the Netherlands. To reduce carbon emissions, transportation distance should also be minimised. Therefore it is preferable to manufacture products with locally sourced materials. Moreover, a significant amount of scrap wood, approximately 435 kton, is generated annually in the Netherlands, which is already a massive amount.

1.2.4 RESEARCH QUESTIONS

Research question

How can scrap wood be reused in the built environment and what is a suitable building product?

Sub questions

1. What does scrap wood consist of?
2. What are existing circular methods for scrap wood?
3. What kind of scrap wood is not reused?
4. What are the barriers for reusing scrap wood?
5. What would the reuse process of scrap wood look like?
6. What kind of scrap wood has the most potential to be reused and for which product?
7. What is the sustainable footprint against virgin wood use?

Background questions

8. What kind of wood is there?
9. What kind of wooden products consists in buildings?
10. What are production techniques for the chosen wooden building product?
11. What are performance requirements for wooden building products?

1.2.5 DESIGN CRITERIA & GOALS & APPROACH + FINAL PRODUCTS

Design criteria

The design criteria consists of figuring out what kind of scrap wood has te potential for reuse or other circular strategies and for what kind of building products those scrap wood pieces are suitable.

1. The product should elongate the lifespan of the scrap wood
2. As much scrap wood as possible should be reused
3. The scrap wood products should be in line with its performance requirements and building degree

Design goals

The design goal for this thesis is developing a potential reuse method for scrap wood pieces that aren't reused but have potential with as example a building product.

Design approach & final products

The design approach consists of figuring out what kind of scrap wood is not yet reused and why. Then find a building product where those scrap wood pieces could be implemented. The final product is a case study of scrap wood pieces in a suitable building product.

1.2.6 APPROACH & METHODOLOGY

In appendix 1 is the methodology scheme that was applied in this thesis. The methodology is divided into a few categories: literature review, interviews, scrap wood research, and a case study.

Literature review

In order to answer the research questions, a literature review was needed to provide the necessary background knowledge to understand what scrap wood actually consists of and what the barriers are to reusing scrap wood. The subquestions and background questions could be divided into a few categories: wood (7), wooden building products (8-10) and scrap wood (1-6). The literature review was divided into the same categories. The literature review included academic resources, government publications and reports, books, websites and information from various companies in the construction, demolition and wood industries. Collecting information from multiple sources was essential to gaining a complete understanding of the wooden building products and construction and demolition industries. This data shows that there aren't enough recycling methods in the construction industry, but it also shows potential opportunities. The search for literature was conducted using Google Scholar, ScienceDirect, Worldcat, the TU library, and Google.

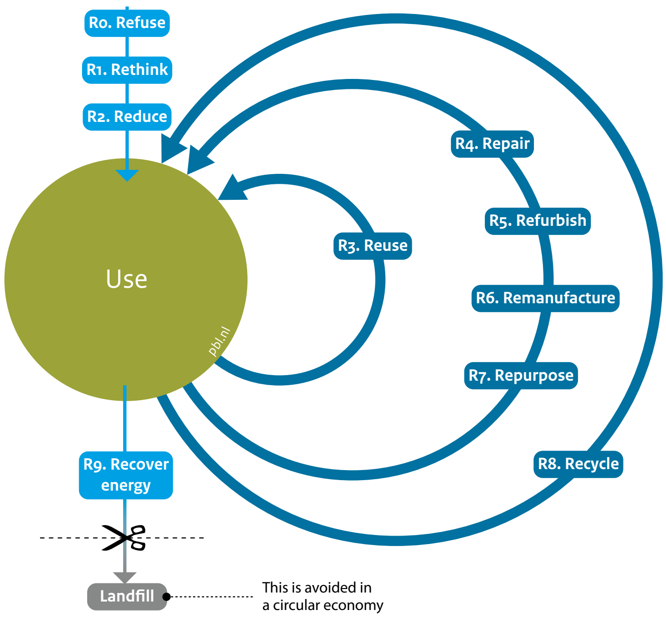


Figure 9_R-ladder for circular strategies (PBL, 2018)

Throughout the thesis the R-ladder for circular strategies is used to explain the hierarchy of how the different R-strategies should be applied to scrap wood. The R-ladder consists of 10 R-strategies that explain how the use of new materials can be reduced and how materials should be handled in a circular economy. The ladder is set up as a hierarchy with the best method at the top (R0) and worst at the bottom (R9) (Rood & Hanemaaijer, 2016), see figure X. An explanation of the strategies is in appendix 2.

As can be noted from the diagram and explanation of the R-strategies, the handling of scrap wood is about extending the lifespan of scrap wood, so the strategies R3-R7 apply. Although reuse is the most circular option, this actually contains the reuse of wooden products itself. In this thesis the focus will be on figuring out remanufacturing (R6) scrap wood pieces into products, because the reuse of scrap wood products is already partly happening but those products are whole. The focus will be on remanufacturing because that contains the broken scrap wood products and all scrap wood pieces. The remanufacturing of scrap wood is not yet a common practice in the built environment for highvalued products, and therefore interesting to figure out the reasons for the lack of such and process and research the potential of it. In this thesis the word "reuse" will be used, which will refer to the reuse of individual scrap wood pieces that aren't a product anymore.

Design by Research
The research process will lead to scrap pieces that have potential for reuse/remanufacture and a fitting design will show how scrap wood can be reused in a building product. This design functions as a case study for the whole thesis.

Interviews
The people that know the most about how scrap wood is handled within the construction & demolition (C&D) industry are the people that work in that industry. So, in order to gain more knowledge about scrap wood, interviews with different links from the C&D industry will be held, a summary of the interviews is in appendix 5.

Case study
The design will function as a case study on a possible method of how scrap wood can be reused or remanufactured into new building products.

1.2.7 SOCIAL AND SCIENTIFIC RELEVANCE

Social relevance
This thesis will contribute to changing the built environment from a linear to a circular economy. In order to meet the sustainability goals and fight climate change a circular economy is necessary. Within a circular economy materials and products will be reused or recycled, and renewable materials will be used. The material and product stream is circular, so there will be no waste. This thesis will contribute to that by reusing a waste material, scrap wood, for a new building product. Wood is also a renewable material. To fight climate change, less carbon emissions need to be released in the air. Wood stores CO2, so it has a positive effect on lowering carbon emissions, especially by reusing wood. Developing a circular strategy for scrap wood, contributes to changing the mindset of using waste materials for building products.

Scientific relevance
Sustainability is an important concept in the world. Every industry needs to transform into a more sustainable industry. The EU and the NL want to transform their economy from a linear to a circular one. Within the circular economy products and materials should be reused/recycled (or other R-strategy) instead of becoming waste. Waste is a big issue in the built environment (40% of total waste). So, to come up with a design made out of scrap wood (from waste within and outside the built environment), more (wooden) materials and products are being reused or recycled instead of becoming waste. It contributes to minimising the total amount of waste and to transforming from a linear economy to a circular economy, within and outside the built environment. There is a lot of research on why the built environment needs to transform to a circular economy, but research on how is lacking. Especially the 'how' in more detail, which happens in this thesis. Scrap wood is not yet fully reused and there is not a lot of information about scrap wood. This thesis contributes to chart scrap wood and its possibilities.

2

SUSTAINABILITY

In this chapter the sustainable effects of the use of wood in the built environment are further discussed and compared to concrete and steel. The environmental benefits are discussed through CO2 emissions, transport and MPG. The benefits of reuse of scrap wood are also discussed and show the relevance of reusing materials such as scrap wood.

2.1 WOOD VS. CONCRETE & STEEL

Wood has many advantages over the traditional building materials concrete and steel, which are discussed by Van der Lugt (2021) in "Houtbouwmythes ontkracht" The first advantage has already been mentioned: wood is the only renewable material. Concrete (80-90%) and steel are more widely used than wood (3%), but have a much greater environmental impact. The extraction and production of concrete and steel account for 11% of total CO2 emissions in the C&D industry. Concrete has a high recycling rate of 86%, but most of it is recycled as road fill, which means that new concrete has to be produced for buildings. Steel and other metals are mostly high-value reused and therefore better in terms of circularity. In fact, there is a shortage of secundair steel, which actually requires new steel.

Figure 10[1], Timber construction

Figure 11[2], Concrete construction

Figure 12[3], Steel construction

Timber construction can be very strong and its lighter weight makes it the most structurally efficient building material. Timber construction has great advantages not only in the construction but also in the disassembly of buildings, as the construction has dry, demountable connections and is easy to handle and dismantle due to its light weight. Timber is therefore more reusable than concrete. By using timber instead of concrete and steel, the demand for concrete and steel can be reduced, thereby reducing CO2 emissions and the use of exhaustible raw materials. This does not mean that all concrete and steel should be eliminated from the construction industry; concrete and steel also have advantages over wood in the construction industry, such as better stability cores in high-rise buildings or larger spans. The ideal is to use more wood in the built environment and in combination with steel and concrete, but the latter materials should be used where necessary and high quality reuse and recycling methods need to be developed for concrete.

2.2 CO2

To fight climate change, CO2 and other greenhouse gas emissions must be reduced. Of all traditional building materials, wood has the lowest carbon impact. The use of wood as a construction material instead of steel and concrete could therefore help reduce those emissions and benefit the sustainable goals of the built environment (Gustavsson & Sathre, 2006). For example, a reduction of 106 kton CO2 emissions is yearly possible by construction of 10.000 houses from HSB. This can even be 200 kton each year if facades and the roof are also made from wood. In fact, during the lifespan of a building, wood can have a negative carbon impact since the amount of CO2 stored is greater than the amount of wood produced (Centrum Hout, n.d.-a).

[1] *Source: (Hourigan, 2022)*
[2] *Source: (Ecohome, 2021)*
[3] *Source: (Buildings-UK, n.d.)*

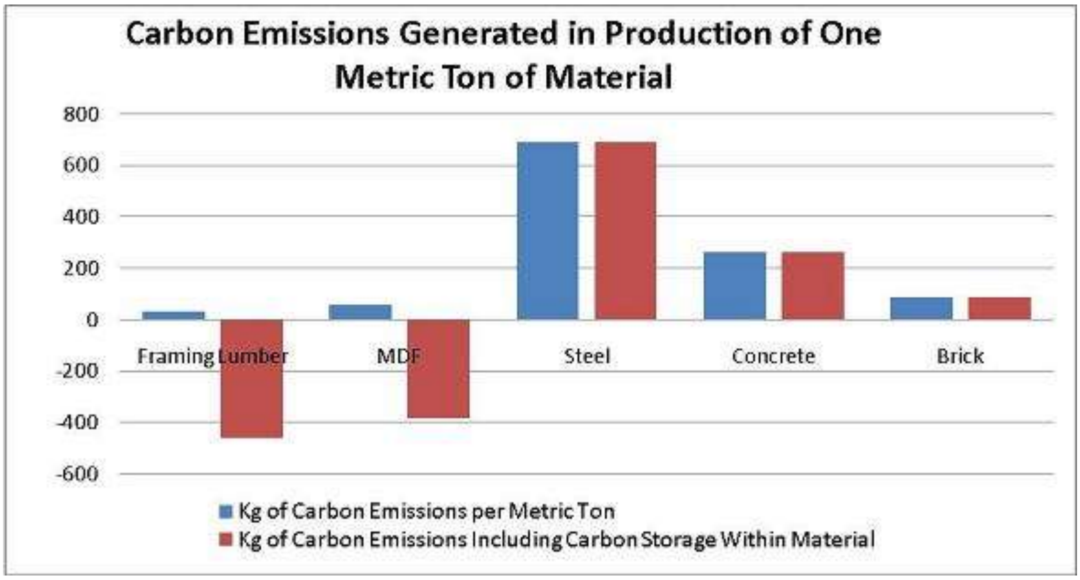


Figure 13_CO2 emissions caused by production of 1 ton product (Centrum Hout, 2016)

Wood stores approximately 0,9 ton CO2 /m3 wood, but the actual amount depends on species. Although the production and transport of wood emits CO2, those amounts are in total lower than the amount of CO2 that is stored in wood (Van Der Lugt, 2021). In 2015 the total amount of absorbed CO2 in wooden products, such as sawn wood, plate material and paper & cardboard, is around 335 Mt CO2eq and every year until 2030 another 440 Mt CO2eq will be added (De Munck, 2021).

When wood is used instead of concrete and steel, for example in construction, additional CO2 savings are made, as concrete and steel emit much more CO2 in their production phase without the ability to store CO2. According to Van der Lugt (2021) around 0,75 ton CO2 is saved per m3 used softwood, when it is substituted for concrete and steel. So, the total saved CO2 emissions by choosing wood is the amount of stored CO2 (0,9 ton CO2/m3 wood) AND the amount of CO2 which would have been emitted by the production of concrete and/or steel (0,75 ton CO2/m3 wood), minus the CO2 that is emitted for the production of timber, see figure 14. The energy used to produce wood is mostly derived from biofuels through incineration, so only stored CO2 is emitted, not additional CO2 as is the case with fossil fuels (Centrum Hout, 2016). This formula also applies to the use of waste wood. In fact, substituting virgin wood for scrap wood saves even more CO2 emissions. Scrap wood also contains stored CO2 and when it is substituted, the stored CO2 in the virgin wood is also evaded.

Figure 14_Total saved CO2 emissions for substituting concrete and/or steel with virgin wood (own image)

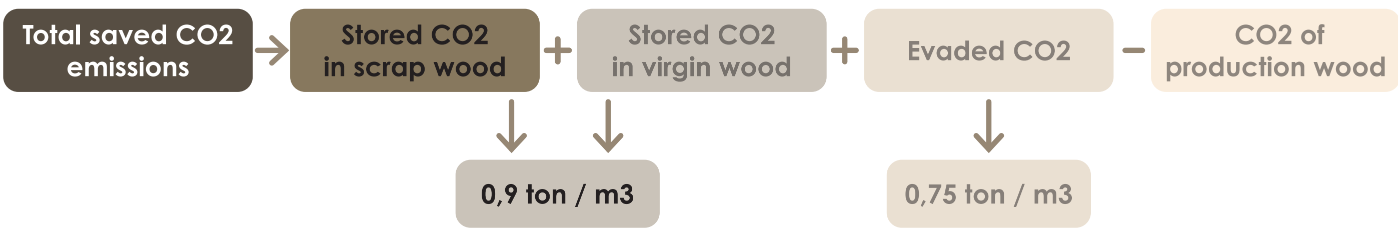


Figure 15_Total saved CO2 emissions for substituting virgin wood with scrap wood (own image)

The virgin wood and its stored CO2 is either still in the forest or used for other projects, so in total more CO2 is stored, see Figure 15. It can also be seen that when scrap wood is reused instead of incinerated, the CO2 remains stored instead of being released.

The effect of substitution can be a reduction in environmental impact of 10-44% (De Munck, 2021). Without taking into account the amount of CO2 stored in European forests, the use of wood in buildings worldwide can result in a global CO2 saving of 110 Gt by 2050, due to CO2 storage in wood and the CO2 saved by choosing wood over concrete and steel (Van Der Lugt, 2021).

The amount of CO2 stored in wood depends on the type of wood. On www.opslagco2inhout.nl the CO2 storage can be calculated for the 50 most commonly used species of wood. For example, 50 m3 of spruce wood, the most commonly used species for construction, stores 31.130 kg of CO2 (net of -31.130 kg). This amount of CO2 is regrown in 3 seconds in European forests and stores as much CO2 as is emitted by a middle-class car over 263.810 km or as much as is consumed by 35 households for energy in a year (Centrum Hout, n.d.-b). The website even shows comparisons with other commonly used building materials such as concrete, PVC, steel and aluminium. For example, concrete has a net CO2 emission of +15,565 kg/50 m3 concrete.

Buildings have an estimated lifespan of 50-150 years, and some even centuries, depending on their function, construction period and structure, materials used, etc. (Andersen & Negendahl, 2023). Wooden building products and structures can also be reused several times. The wood can then be further recycled, for example into chipboard or OSB. So when wood is used in buildings and reused and recycled several times, the CO2 stored in the wood can potentially be stored for centuries. In the meantime, the amount of wood used has already grown back in the forests several times, where the new trees have stored new CO2. At the end of its life, the stored CO2 is released through incineration, but the incineration results in heat and biofuel, which then reduces the amount of fossil fuels needed (Centrum Hout, n.d.-a).

So, taking all these aspects into account, the use of wood has a reducing effect on the amount of CO2 emissions, especially now and in the following decades. Wood can therefore contribute to achieving the 2030 and 2050 sustainability goals in terms of reducing CO2 emissions. When the CO2 emissions are released during incineration at the end of its life, i.e. after 2050, there may be new methods to capture these emissions or to manage the emissions in a sustainable way.

CO2 in Forests

Forests are also essential in the fight against climate change. Globally, forests already hold 662 Gton of CO2 and are responsible for absorbing 25% of anthropogenic CO2 emissions each year. Through sustainable forest management: tackling deforestation, forest degradation and reforestation, this percentage could be even higher. Deforestation is not caused by the timber industry, but by agriculture, fires and other circumstances (De Munck, 2021).

Sustainably managed forests are forests where fewer trees are cut down than are planted, so these forests are actually growing. Trees are planted and harvested in a way that does not degrade forests and biodiversity. For example, only 65% of the regrowth in forests in Europe is harvested, so every year about 600,000 ha of forest is added (Centrum Hout, 2016).

Wood from these sustainably managed forests receives a certification, FSC or PEFC. The wood has a chain of custody, a documentation of where the wood comes from, where it has been and what its properties are. Worldwide, 400 million hectares of forest are certified (Gadero, 2019). In the Netherlands, 86% (in 2013) of all imported wood comes from sustainably managed forests. A wood product can be FSC or PEFC certified if 70% of the material comes from a sustainably managed forest or from recycled material. In addition, for every tree harvested, at least one new tree must be planted. There is another certification for the construction industry: KOMO, an international quality standard that guarantees a high quality and safe product (KOMO, 2018).

Figure 16_PEFC and FSC certification logo (Tradis Design, 2020)

Figure 17_KOMO certification logo (KOMO, n.d.)

As mentioned above, European forests are growing every year. Substituting wood with scrap results in a lower demand for new wood and can therefore contribute more to forest growth. As a result, more CO2 is stored in these forests each year, estimated at 2.7 to 17.9 Gt CO2eq per year by 2030 and 0.5 to 3.6 Gt CO2eq per year by 2050. The combination of expanding forests and keeping wood and waste wood in circulation as long as possible has the greatest impact on reducing CO2 emissions (De Munck, 2021). If (scrap) wood is kept in the cycle longer than it took to grow that amount of wood, the CO2 emissions that will eventually be emitted by incineration have already been absorbed by the new trees.

Although forests will continue to grow, the demand for wood will increase due to circular economy goals. There is enough forest to meet the growing demand, but part of the demand could be met by scrap wood. Especially because the growing demand for wood cannot be met by Dutch forests. There aren't enough forests suitable for the construction industry, and it takes 40-50 years to plant and grow these trees. At the moment only 100,000 m3 are suitable for the construction industry, which is only enough for 1900 CLT houses (Van Der Lugt, 2021). However, there is enough scrap wood for 50,000 CLT houses. Although the Netherlands will continue to depend on wood imports, part of the demand can be met with scrap wood.

2.3 MPG

The MPG (milieu prestatie van gebouwen: environmental performance of buildings) is a calculation obligated for new buildings that shows the environmental impact of a building, and is determined by the European Norm EN 15804. The outcome is the shadow cost of a building per m2 per year, which depends on the estimated lifespan of the building. The shadow cost is an indicator of the environmental impact of a material or product, converted into euros in order to compare materials. The calculation is based on the Life Cycle Analysis (LCA) calculation, where the environmental impact of a product is determined throughout its life cycle (Sobota et al., 2022; Stichting Nationale

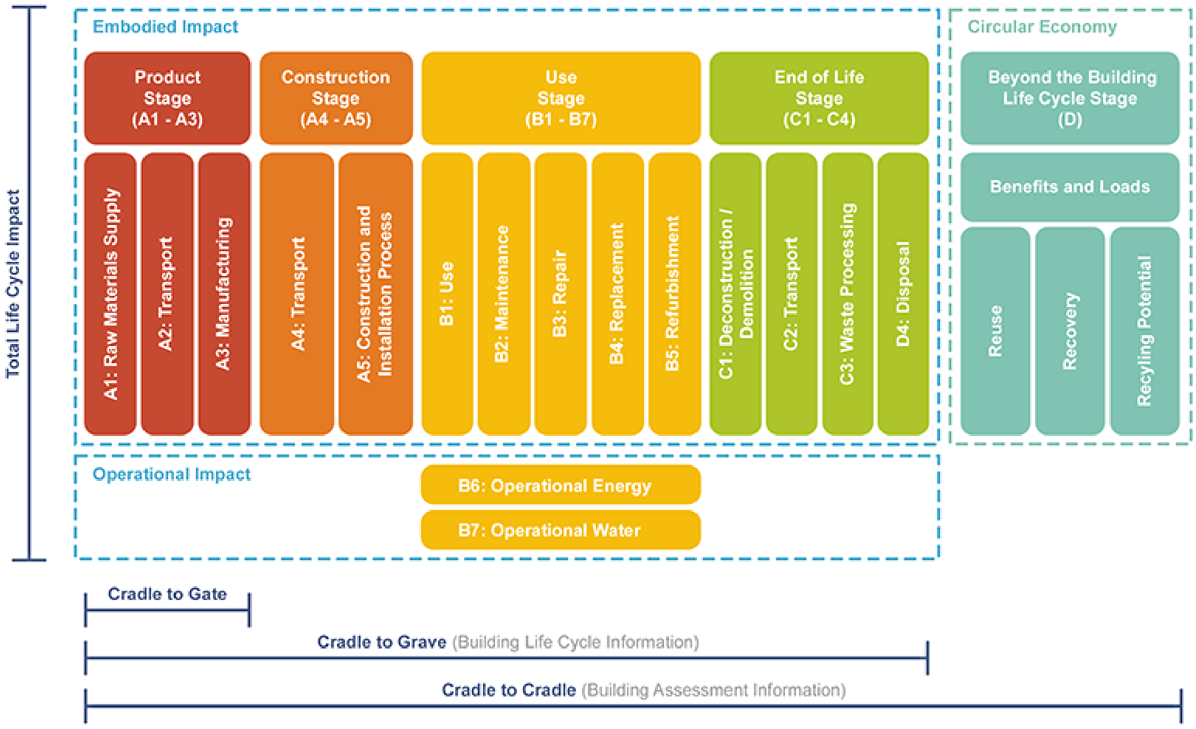


Figure 18_Building lifecycle used in LCA (Overbey, 2021)

Milieudatabase, n.d.), from the product stage (A1-A3), construction stage (A4-A5), use stage (B), end of life stage (C) and beyond the building life cycle stage (D), which includes principles such as reuse, recycling, recovery, etc., see Figure 18.
The outcome of the LCA are EPDs (Environmental Product Declaration) as shadow costs [€]. The MPG is a combination of the LCA values of all materials used in a building, divided by the amount of m2 and the lifespan in years. The Dutch government has determined that the MPG for new buildings should be below 0,8 (euro/m2/year). The materials used for the MPG are included in the National Milieudatabase (NMD), which consists of general materials, but companies can also add their specific products through an official LCA calculation (Sobota et al., 2022; Stichting Nationale Milieudatabase, n.d.).

Wood products have a good overall score in the MPG, but not all the benefits are taken into account. The low score is mainly due to the low energy required for production, its light weight and its harvesting from sustainably managed forests. What is not yet taken into account is the reusability of wood and its ability to store CO2. At the end of its life cycle, it is decided that wood will be incinerated, releasing the stored CO2, instead of being reused or recycled. Incineration is seen in the Netherlands as a way of saving biomass rather than as a substitute for the Dutch energy mix. The latter, which is common in Europe, has a more positive effect on the MPG than the former. In the case of timber constructions, it can even have a negative environmental impact (Van Der Lugt, 2021).

The ability to store CO2 contributes to the reduction of overall carbon emissions. If this is not taken into account in the MPG, concrete and steel can perform as well or better than wood. For example, in Figure 19, Van der Lugt (2021) shows the amount of CO2-eq emitted for an HSB, CLT and concrete dwelling for the current method and when temporary CO2 storage is included. With the current method, CLT has a higher environmental impact than concrete, but with the other method, CLT actually has a negative impact due to the amount of wood used. So, in the new method, wood has a

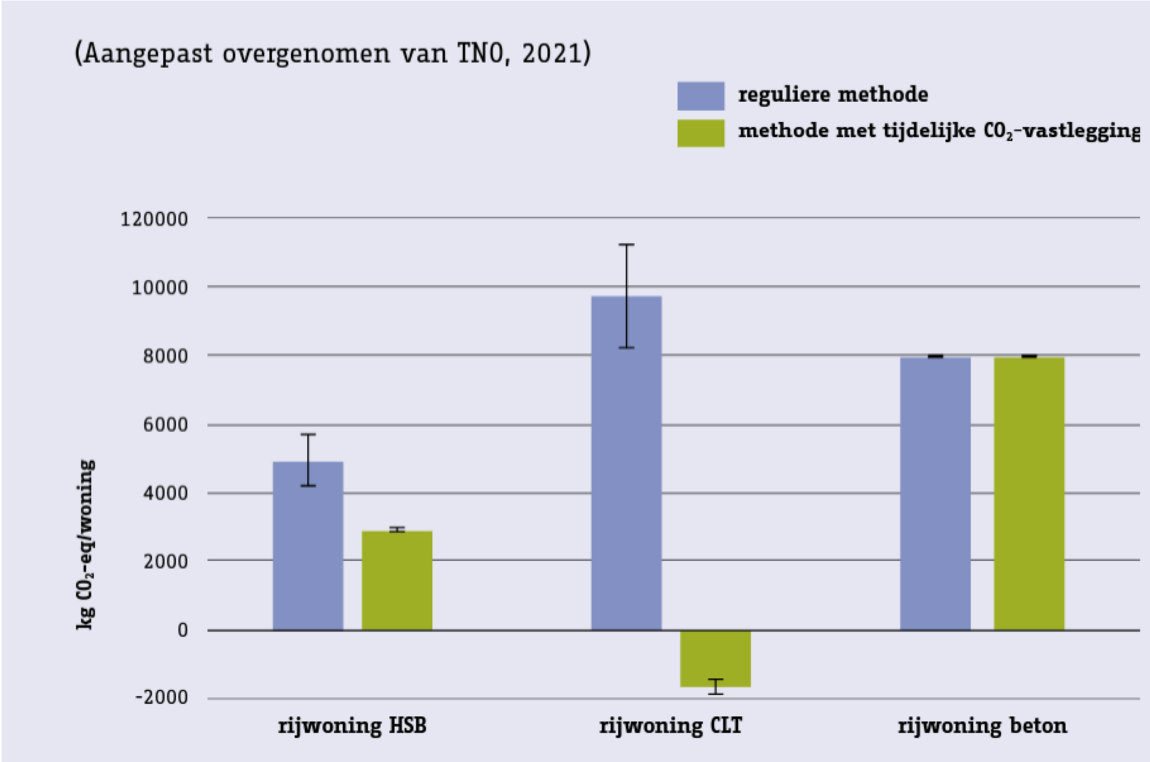


Figure 19_Comparison of CO2 emissions in HSB, CLT and concrete for the regular MPG method and the method with temporary CO2-fixation (Van Der Lugt, 2021b)

lower environmental impact than concrete. The temporary sequestration capacity is not taken into account at the moment because the sequestered CO2 is emitted at the end of its life. However, this method motivates people to choose wood instead of concrete and therefore helps to increase the use of wood in construction, which means more CO2 is sequestered. So including CO2 sequestration in a way that improves the MPG score for wood, but without forgetting that the CO2 will eventually be emitted, can help achieve sustainability goals. At the moment, organisations are trying to change the MPG to include temporary CO2 sequestration (Van Der Lugt, 2021; De Munck, 2021).

Most materials in the database are new materials, not reused or recycled materials. Reused and recycled materials have a lower environmental impact than new materials because certain aspects, such as the CO2-eq emissions caused by the extraction and production of the materials, have already been taken into account and the lifespan of these products is extended. This is not yet included in the MPG calculation, but they are trying to add reused and recycled materials to the database. If a reused material is not in the database, a reuse factor can be added to the calculations, which is a factor of 0.2 that needs to be multiplied with the numbers from A1-A3, C3, C4 and D. The actual environmental impact of a reused product has a lower value than the result of the reuse factor (Stichting Nationale Milieudatabase, 2023). It is therefore important to include reused wood products in the NMD. Including reused scrap wood in the MPG can ensure that more scrap wood products are chosen because of their lower environmental impact. An increase in the demand for scrap wood can motivate to reuse more waste wood instead of incinerating it.

2.4 TRANSPORT

A major contributor to the CO2 emissions of wood is transport, especially when wood is transported from far away, and especially when compared to the CO2 emissions of other processes, see Figure 20 (Holz von Hier gGmbH, 2023). The vehicles, such as trucks, trains and ships, emit a lot of CO2

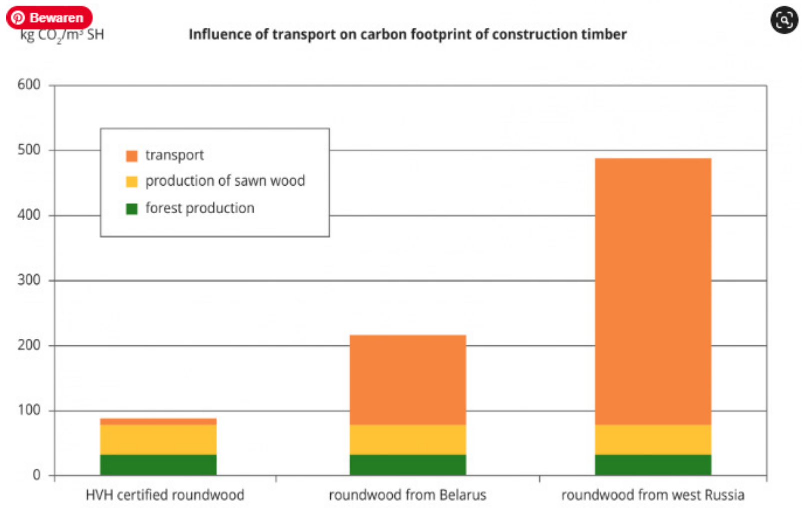


Figure 20_Influence of transport of carbon footprint of construction timber over different transport distances (Holz von Hier gGmbh, 2023)

from fossil fuels, the amount depends on the vehicle and the distance. On co2emissifactoren.nl there is a list of estimated CO2 emissions per tonne-kilometre in average circumstances, where a tonne-kilometre is the transport of 1 tonne of goods over 1 km.

Figure 21 (Richter et al., 2023) shows the relation between the amount of sequestered CO2 and the emitted CO2-eq, divided into different production steps of 1 m3 of spruce wood. The amount of CO2-eq emitted during transport is also shown for a distance of 50 km and 500 km. Although the amount of CO2-eq emitted is still much lower than the amount of CO2 sequestered, transport still accounts for a large proportion of the CO2-eq emissions. For 50 km, transport contributes between 23% and 29% of the total CO2-eq emissions, and for 500 km, between 75% and 80%, depending on the type of handling.

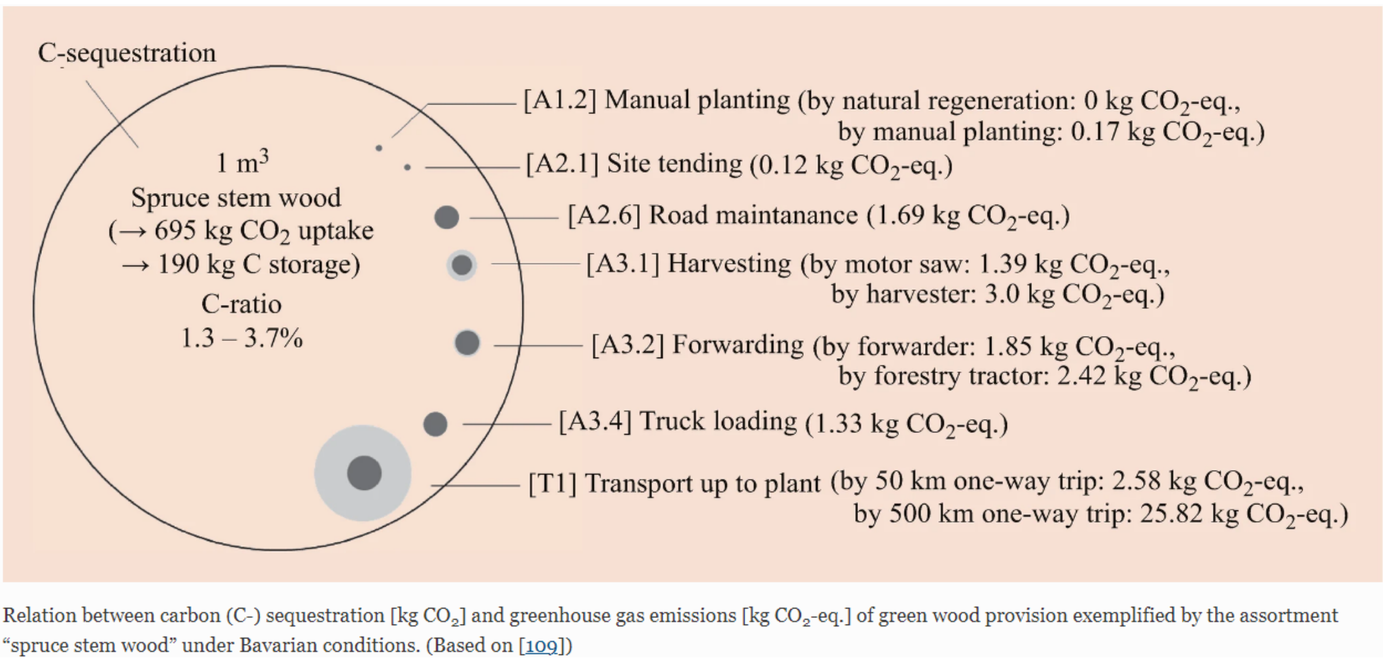


Figure 21_Carbon storage and production of one 1 m3 of spruce wood, Source: (Richter et al., 2023)

Most of the wood is transported from Germany and Sweden. In Sweden, the largest sawmill, which also supplies the Netherlands with wood, is Södra in Värö (Redactie Houtwereld, 2016), which is about 1000 km by road from Delft. Looking again at Figure X, the light grey transport circle representing the 500 km distance is doubled for the 1000 km distance: 51,64 kg CO2-eq/m3 of spruce wood.

This is 7.4% of the total CO2 uptake and 86%-89% of the total CO2-eq emissions. Germany is much closer and therefore has lower transport emissions. Transport is thus a large part of the total CO2-eq emissions, and the shorter the distance, the lower the impact of transport.
Scrap wood is sourced locally. If the entire process, from demolition to reuse in new building products, takes place locally, the transport distance of the recovered wood will be shorter than that of virgin wood, resulting in lower CO2 emissions from transport. This is especially true for tropical hardwoods, which are transported from tropical regions such as South America, Africa and South Asia. In terms of production, scrap wood is now recycled and turned into chipboard, but this chipboard is not produced in the Netherlands, but in Belgium (Renewi, personal communication, 20 April 2023), which means that scrap wood is transported from the Netherlands to Belgium and back, increasing the transport distance. So, local scrap wood can contribute to the reduction of CO2(-eq) emissions caused by transport, but only when the reuse and recycling processes also happen locally.

2.5 CIRCULARITY STRATEGIES

There are various strategies for prolonging the lifespan of scrap wood, such as the R-ladder for circular strategies, see chapter 1.2.6. There is a certain hierarchy between these strategies. The higher a strategy is on the ladder, the better the option is. In terms of circularity and keeping the material in the user loop as long as possible, the strategy is to go for the highest ranking strategy, repeat until it is no longer possible and then go for the next possible strategy. This is the cascading principle, see Figure 22 for an example of cascading timber (Van Der Lugt, 2021). For the use of wood in the built environment, this means reusing wood (construction) a few times, then remanufacturing wood into new products, then recycling it into OSB or particle board, and finally wood can be incinerated for energy recovery, releasing the sequestered CO2. As mentioned in “2.2 CO2”, this cascading principle can result in CO2 sequestration of wood over one or more centuries. Cascading also

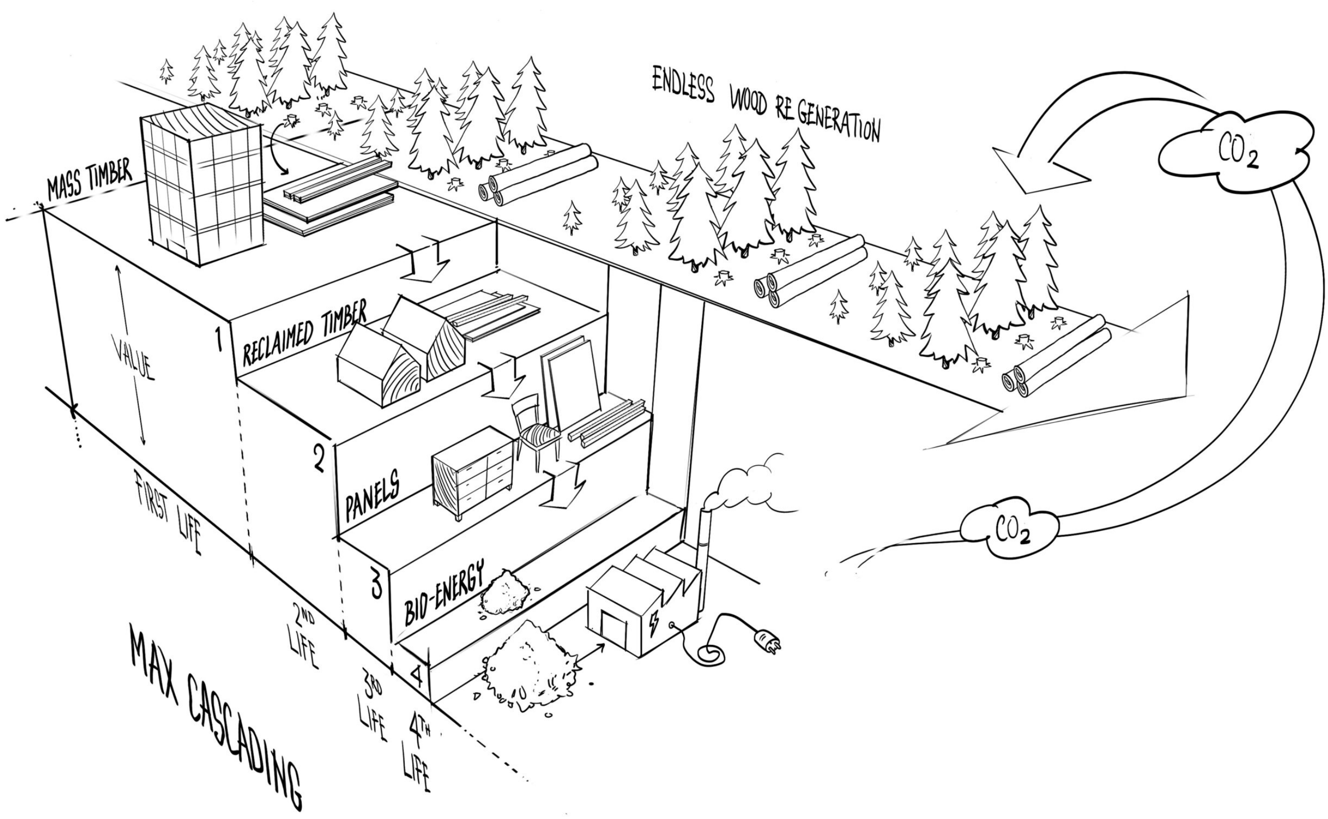


Figure 22_Cascading diagram of timber (Van Der Lugt, 2021a)

contributes to a more sustainable use of materials. Materials are used to their final potential instead of being used once or twice, resulting in less need for virgin materials and less waste.
Figure 23 shows a simplified cascading diagram of scrap wood. Reuse is the highest priority, but it means using a waste product again without changing anything. This is not always possible, but scrap wood can then be remanufactured into new building products. The best way to prolong CO2 sequestration is to use scrap wood in structural elements such as HSB (timber frame construction)

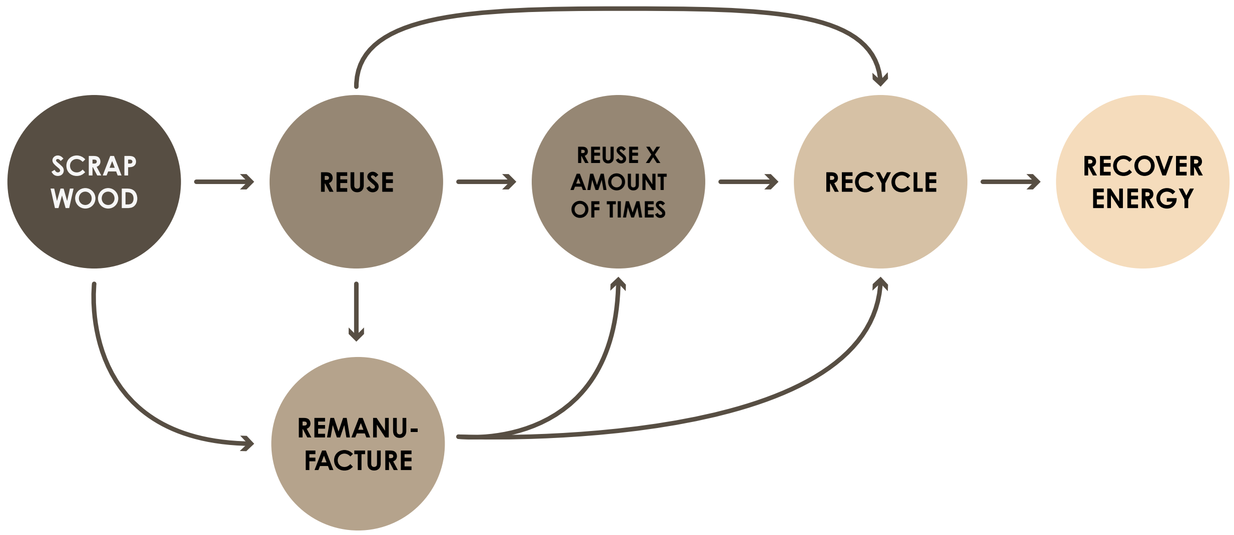


Figure 23_Simplified cascading diagram of scrap wood (own image)

or CLT (cross-laminated timber), as these elements have the longest lifespan. It can then be recycled and ultimately recovered.
Currently, most scrap wood that is not incinerated is recycled. Recycling wood primarily involves shredding the wood and converting it into products such as chipboard, MDF, OSB board, and others. These shredded woodchips cannot be turned into larger solid wood pieces again, so high-value reuse is likely not possible after recycling (Van Der Lugt, 2021). The current approach does not adhere to the cascading principle. Recycling and incineration are not wrong options, chipboard, MDF and OSB are widely used products, but scrap wood should first be reused and remanufactured to its final potential. Afterwards, the scrap wood can still be recycled.

Although the most efficient method for scrap wood or any waste material is direct reuse, no processing is required. Small-scale reuse is already happening via marktplaats.nl or demolition contractors themselves. This sector should be expanded and the barriers to reuse will be examined, but the main focus will be on scrap wood that is no longer a whole product, i.e. the smaller, broken and/or damaged pieces of scrap wood. The focus will be on the remanufacturing of these pieces, while identifying the barriers and possible solutions.

2.6 CONCLUSION

Overall, wood is an sustainable material that can contribute to the necessary reduction of carbon emissions in the built environment. Unlike concrete and steel, wood emits fewer carbon emissions during its extraction, production and construction. Wood also absorbs lots of CO2, can replace concrete or steel for construction, is lightweight and can be easily prefabricated. Transport is the biggest cause of CO2-eq emissions in the timber industry since it’s internationally sourced, resulting in long transport distances. All this is not to say that wood should replace all concrete and steel, these materials also have their advantages, but the share of wood can be massively increased.

The increase in wood use does not cause deforestation, especially when forests are managed sustainably. When wood is used repeatedly in buildings, there is ample time for forests to regrow their trees. Also, CO2 is stored in scrap wood for a longer period, allowing growing forests to absorb even more CO2. As a result, it is better to reuse or remanufacture more scrap wood rather than incinerate it.

In summary, using wood in construction over other conventional building materials reduces CO2 emissions by:

- CO2 sequestration in buildings
- In the meantime new trees grow back, absorbing CO2
- Substituting for the higher CO2 emissions of traditional building materials

When wood is used in buildings and reused, remanufactured, and recycled several times, the CO2 can remain sequestered for over one or more centuries. These factors can aid in achieving the sustainability goals of reducing CO2 emissions.

Despite wood's sustainable label increasing the demand for wood in the built environment, concrete and steel are still more common. Wood performs well in the MPG ranking, yet it faces competition from concrete and steel. However, considering the temporary CO2 sequestration and viewing energy recovery as a replacement for fossil fuels renders wood a more sustainable option in the MPG.

Using wood instead of concrete and steel reduces CO2 emissions. Reusing scrap wood can contribute even more to this reduction. It can meet some of the demand for virgin wood and allow more wood to be used in the C&D industry. Reusing scrap wood also prevents the release of sequestered CO2 from incineration and helps decrease CO2 emissions. Scrap wood is sourced locally, so it emits less carbon during transportation. Currently, only a small part of the NMD consists of reused and recycled materials, but these materials have a lower environmental impact as their emissions and other impacts have already been accounted for during their initial use. Therefore, it is crucial to include scrap wood products in the NMD to encourage architects to use more reused materials.

Most scrap wood is either incinerated or recycled today, and according to the cascading principle these options aren't necessarily wrong, but should be a later possible option after it has been reused and remanufactured to its final potential. Unfortunately, this is not currently the case. Therefore, this thesis will concentrate on remanufacturing scrap wood pieces.

3

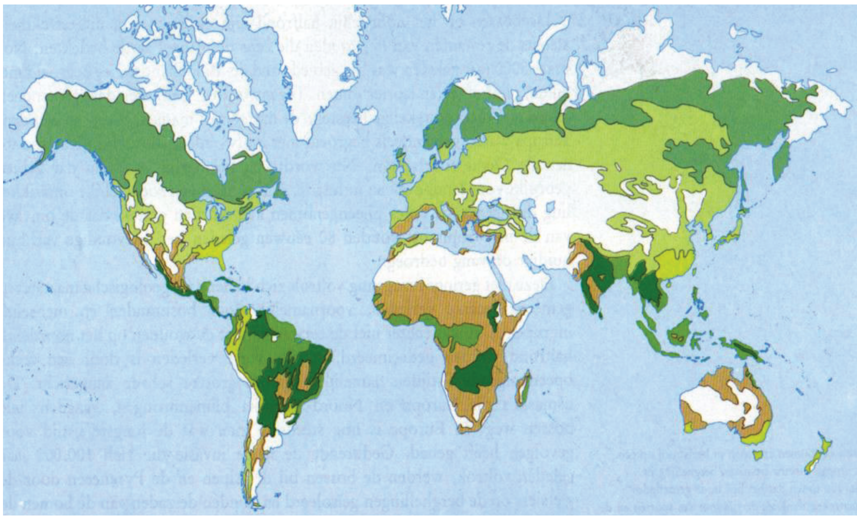
WOOD

Wood is the oldest building material, and wooden structures can last for hundreds of years. The oldest wooden structure is a temple in Asia from the 7th century (Rowell, 2013). The oldest wooden building in the Netherlands is a barn dating from 1261. Wood was used for building and construction from the 17th century onwards, but its use declined after an official ban on building wooden houses in 1669 to reduce the risk of fire. Later, load-bearing timber construction was replaced by alternatives such as stone, steel and concrete (Icibaci, 2019). In addition to construction, it is a versatile material used for paper, packaging, furniture, tools, decoration, quays, flooring, biofuel, etc.

This chapter answers the background question: What kind of wood is there? Before looking at the composition of scrap wood, it is important to know what wood is and what the main differences are between different types of wood. This will provide the background information to understand some of the barriers to the recovery of scrap wood. Firstly, the sustainability of wood is discussed. This is followed by a closer look at the different types of wood. The differences between hardwood and softwood are discussed and an overview of important properties is given. Finally, the identification of different types of wood is discussed.

3.1 FORESTS

Worldwide (at least in 2011), 4 billion ha, or one third of the world, is covered by forest, see figure 24. About 1.34 billion ha of forest is used as (potential) production or multifunctional forest. Due to ecological (micro) conditions such as climate, soil, altitude, exposure, there is a wide variety of forest types and tree species, resulting in many types of wood. Trees can grow in mountainous regions up to an altitude of about 2200 m. The height of the tree itself can vary from a few centimetres to 115 metres, depending on the growing conditions (Centrum Hout, 2013). There are three types of forest: coniferous, deciduous and a combination of both. Coniferous forests are found in colder regions,



Six foresttypes around the world
On global scale, the bostypes can be roughly divided into:

- *Coniferous forest from the northern regions*
- *Summer green forest from the temperate regions*
- *Always green rainforest from the humid tropical regions*
- *Monsoon-savannah forest*
- *Always green rainforest from the humid subtropical regions*
- *Deciduous forest from the dry subtropical regions*

Figure 24_Six foresttypes around the world adapted from (Centrum Hout, 2013) such as the northern coniferous forests, and can withstand more extreme conditions. They are mostly made up of trees with coniferous leaves, which prevent excessive dehydration. Deciduous forests are made up of broadleaf or deciduous trees. These trees are found in the warmer regions of the world, such as the Amazon and other rainforests. The shape of the leaves allows good evaporation. The transition from coniferous forest to deciduous forest is slow. Within each forest, the consistency of tree types varies according to region, area and climate (Centrum Hout, 2013) See figure 25 for examples of deciduous and coiferous trees.

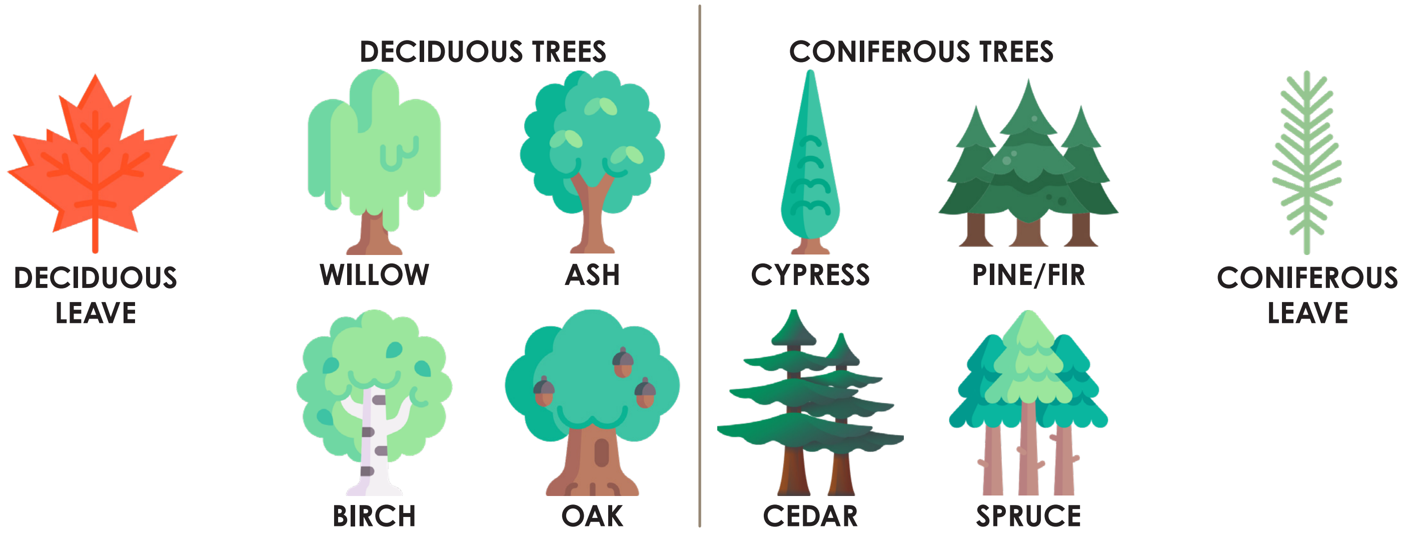


Figure 25_Deciduous and coniferous trees and leaves (own image)

3.2 GENERAL INFORMATION WOOD

Around the world there are approximately 60.000 different tree species. (Kraaijvanger, 2017). Each tree species has their own properties. The densities vary remarkably, from 150 kg/m3 (balsa) to 1150 kg/m3 (coromandel). Each tree consists of carbon, hydrogen and oxygen in the form of cellulose, hemicellulose and lignin. The type and amount of consistency differs for each tree. (Centrum Hout, 2016; Risbrudt, 2013)

A tree consists of two parts: the part above ground (shoot) and the subterranean parts (roots). The shoot consists of a trunk, branches and leaves. The wood comes from the trunk. From the outside to the inside layer there are 6 parts, see figure 26:

1. The outer bark: helps in limiting water loss evaporation and to mechanically protect the softer inner bark.
2. Inner bark: tissue that translocate photosynthate (sugars produced due to photosynthesis) within the tree
3. Vascular cambium: produces tissue for inner bark and wood each year
4. Sap wood: living wood (active) that conducts sap (water) through the tree
5. Heartwood: death wood that is not conductive, most of the time darker-coloured due to chemicals
6. Pith: remnant in the middle of the trunk from the first growth of the tree before there was wood.

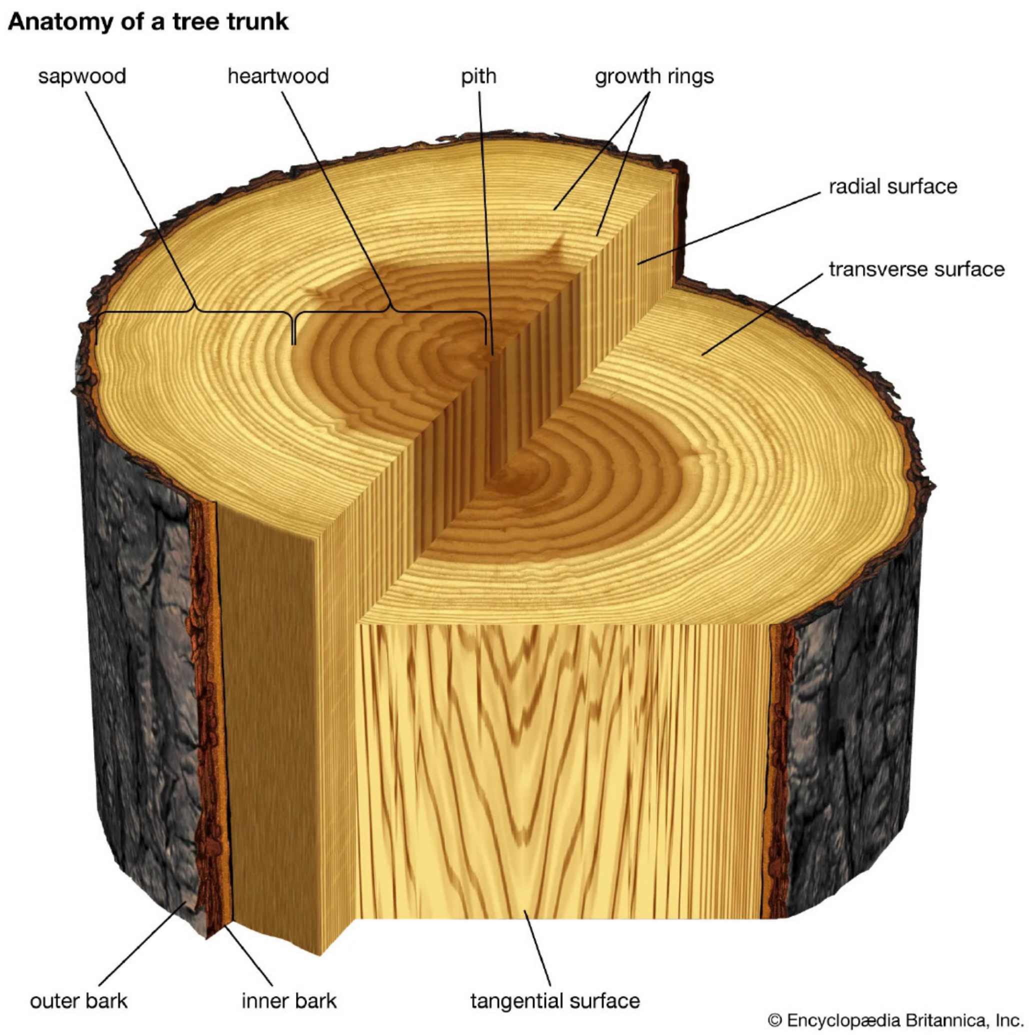


Figure 26_Transverse slice of a trunk (Ecyclopaedia Britannica Inc., n.d.)

3.3 HARDWOOD VS. SOFTWOOD

The first division of tree species is between hardwood and softwood. The term hardwood and softwood is somewhat misleading, as not every softwood is soft and vice versa. For example, there are hardwoods that are softer than softwoods (Thomas, 1977; Wiedenhoeft, 2013). Hardwoods come from angiosperm trees, which are flowering trees, such as oak, maple, teak, meranti, birch and ash. Most of these trees change the colour of their broad leaves each year and lose them in the autumn. Coniferous trees are gymnosperms, trees that produce seeds, such as conifers, pines, spruces, firs and cedars. Most, but not all, of these trees have needle-shaped leaves and retain them throughout the year. The difference between hardwood and softwood is the cell structure (Hassani, 2018).

Hardwood has a more complex structure than softwood. Softwood consists of two cell types with little variation in structure: longitudinal tracheids and transverse parenchyma. Hardwood has 4 cell types and the variability within these cell types is greater: vessel segments, fibres, transverse and axial parenchyma. Hardwood has a cell that functions as a pore, a vessel element that transports water through the tree. Softwood lacks these cells. The cells of the longitudinal tracheids have a dual function: support and conduct water (Thomas, 1977; Wiedenhoeft, 2013). The cell structure of hardwood and softwood is shown in Figure 27. An important difference between hardwood and softwood for the built environment is the durability to the external environment. Hardwood is more resistant to decay and rotting than softwood, making hardwood more suitable for outdoor use than softwood.

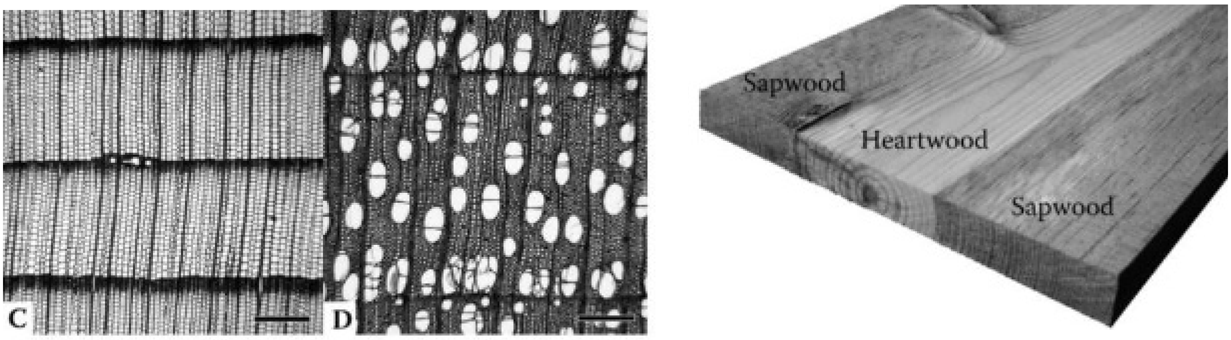


Figure 27_Cell structure of softwood (C) and Cell structure of hardwood (D), Heartwood and Sapwood (Rowell, 2013a)

One similarity between softwood and hardwood is the presence of sapwood (outer wood) and heartwood in the middle, see Figure 27. Most of the mature cells in the wood are dead, even in the sapwood. The living cells are called the parenchyma. The sapwood not only transports water or sap through the tree, but also acts as a reservoir for the synthesis of biochemicals such as photosynthate in the form of starch and lipids, and carbon in the living parenchyma cells. Starch can cause complications in the wood industry. Bacteria with an overflow of starch can cause foul-smelling compounds or cause aesthetic reasons that reduce the value of the wood. Heartwood is old, dead sapwood, but much stronger. It is darker in many species. This is because heartwood stores long-term biochemicals that vary from species to species. These chemicals are called extractives and can be extracted with solvents. Extractives protect the wood and impart characteristics to wood from different species, such as natural durability, resistance to decay, stability and/or water resistance. For the latter, extractives consist of waxes and oils. Teak is an example of a popular species with high water resistance. Other characteristics include colour, such as mahogany or Brazilian rosewood, and scent, such as sandalwood (Thomas, 1977; Wiedenhoeft, 2013). Most plantation-grown trees lack heartwood because they are harvested before the heartwood can form, resulting in wood that is not as strong as wood harvested in the past when the trees were much older.

Figure 28_Growth RIngs of Pine (Wagrati, 2016)

The vascular cambium produces tissues or cell layers that result in growth rings (growth increments) consisting of earlywood cells formed at the beginning of the time interval and latewood cells formed later in the growth increment (Thomas, 1977; Wiedenhoeft, 2013). In regions where there are noticeable seasonal changes or trees with annual cycles, the growth rings are visible and are often referred to as annual rings, see figure X. In other regions without seasonal changes, such as the tropics, these annual rings are less visible. Within conifers and deciduous trees there are three patterns of transition within the annual rings: no transition, gradual transition and abrupt transition, see Figure 29. The width of the annual rings depends on the size of the earlywood cells in conifers. The width of the latewood zones is relatively constant (Centrum Hout, 2016).

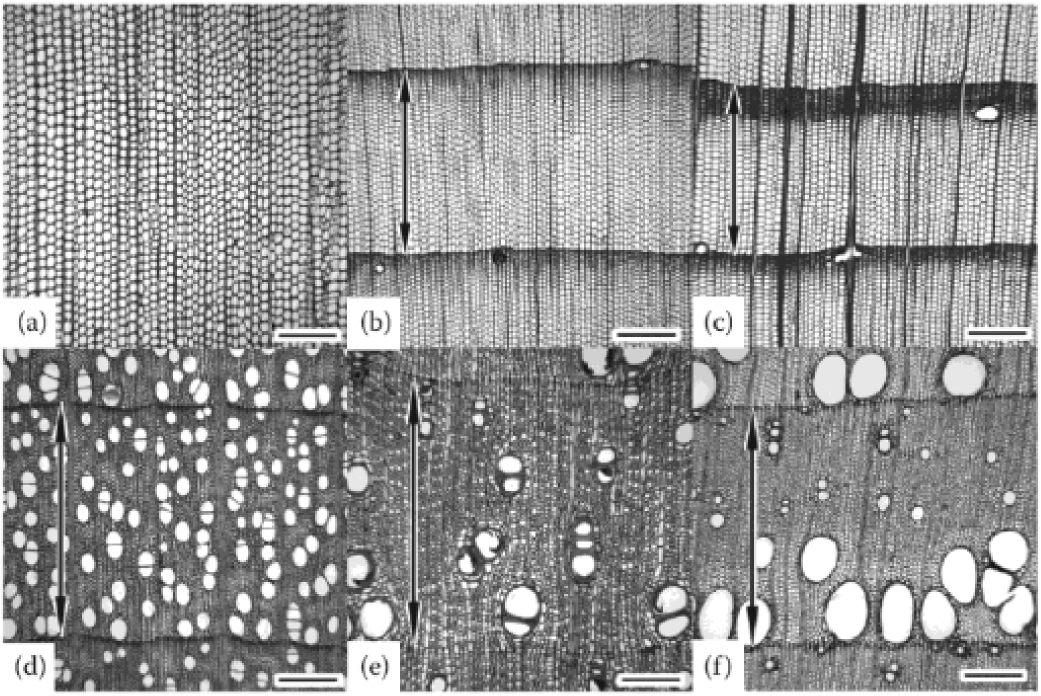


FIGURE 2.5 Transverse sections of woods showing types of growth rings. Arrows delimit growth rings, when present. (a)–(c) Softwoods. (a) No transition within the growth ring (growth ring absent) in *Podocarpus imbricata*. (b) Gradual transition from earlywood to latewood in *Picea glauca*. (c) Abrupt transition from earlywood to latewood in *Pseudotsuga menziesii menziesii*. (d)–(f) Hardwoods. (d) Diffuse–porous wood (no transition) in *Acer saccharum*. (e) Semi-ring-porous wood (gradual transition) in *Diospyros virginiana*. (f) Ring–porous wood (abrupt transition) in *Fraxinus americana*. Scale bars = 300 μm.

Figure 29_Transverse sections of hardwood & softwood showing growth rings. (Rowell, 2013b)

3.4 PROPERTIES OF WOOD

3.4.1 PHYSICAL PROPERTIES

One of the most characteristic properties of wood is its density [kg/m3]. Density is the mass of wood in kg divided by the volume of wood in m3. Density depends on moisture content, expressed in %. An increase in moisture increases the mass and volume of the wood. Although the coefficient of linear expansion is negligible with an increase in temperature, moisture is lost, which causes the wood to shrink when the moisture level falls below the fibre saturation point (Centrum Hout, 2016). Shrinkage is not gradual, so stresses can occur in the wood that can lead to cracking. The amount of shrinkage depends on the type of wood; for example, beech shrinks a lot, but teak doesn't. When a tree is freshly cut it can be 100%. Density is usually given at the same moisture content, for example 12%, or when there is a certain equilibrium of moisture content after the wood has been climatised at a certain temperature to compare species.

Density varies between 150 kg/m3 and 1150 kg/m3, depending on the type and species of wood (Centrum Hout, 2016). Denser wood is better because it influences the strength, elasticity and durability of the wood. Wood that grows more slowly has a higher density. Plantation-grown wood therefore has a lower density than older wood due to its rapid growth process (Huuhka, 2018). Hardwood tends to have a higher density than softwood due to a slower growth process. The density of wood also depends on the annual rings. For softwoods, the density decreases when the growth rings are wider (Centrum Hout, 2016). Density also affects thermal insulation, a lower density results in lower thermal conductivity.

The different properties and densities result in different uses for hardwood and softwood species and even between different softwood or hardwood species. It is therefore important to know what these properties or species are.

3.4.2 MECHANICAL PROPERTIES

The mechanical properties of wood are its abilities to resist different types of external forces, which are called stresses (force/unit area). The shape of wood can be deformed or distorted under sufficient stress. This is the strain of the wood. The properties vary not only between species but also within a species due to the complex structure of wood. The values given are therefore an average with a possible range of variation. Mechanical properties are therefore important for (construction) building products that are exposed to these external forces , such as load-bearing structural elements (Record, 2004). The most important mechanical properties are (Centrum Hout, 2013b; Record, 2004):

- Bending strength
- Elasticity/stiffness
- Compressive strength
- Tensile strength
- Shear strength
- Cleavability (splitting)
- (Janka) hardness

Bending strength is the stress required to break a piece of wood. Bending stress is the stress that occurs when a beam is loaded in bending. This property is therefore important for load-bearing structures. The modulus of elasticity is a constant (a ratio) between this bending stress and the (relative) internal deformation caused by this stress. Compressive strength is the compressive force (per unit area) required to break a piece. The opposite is tensile strength, which is the force required to break a piece under tension. Another mechanical property is shear strength, which is the force per unit area required to cause surfaces to slide apart. This is usually tested in the tangential and radial planes. Wood can also split. The strength, force/mm perpendicular to the grain, required to split a piece of wood is called cleavability. Finally, there is the hardness of the wood. The Janka hardness is a commonly used method of measurement. This is a test in which a steel ball with a compression area of 100 mm2 is pressed halfway into the wood (Centrum Hout, 2013b). These mechanical properties make certain types of wood more suitable for load-bearing structures than others. It is therefore important to know the mechanical properties of wood.

3.4.3 DETERIORATION

When wood is exposed to the weather, its physical properties begin to deteriorate. The deterioration results in a change in colour or texture. Exterior wood is exposed to changing weather conditions such as sunlight, rain, snow, humidity, dew, temperature changes and gases in the air. The most damaging effects are caused by UV light and water. UV light depolymerises the lignin in the cell walls of the wood and causes surface erosion. In order to maintain the physical properties of the wood, outdoor wood needs to be protected from weathering degradation (Sudiyani et al, 1999). Some types of wood are more resistant to outdoor conditions than others. In general, hardwoods are more resistant than softwoods. Each type of wood has different physical and mechanical properties. Because of these properties and the cellular and chemical composition, each wood reacts differently to external conditions.

3.5 WOOD INDENTIFICATION

Wood identification consists of recognising the characteristic cell patterns and features of wood (Wiedenhoeft, 2013). For example, there are two types of trees: coniferous trees with needle-shaped leaves, and deciduous trees with broad leaves. These differences between trees are easy to spot, but identifying wood is more complicated. The first difference is between hardwood and softwood, which can be seen in the cell structure. A microscope is needed to see the difference. Then, within each trunk, the wood is made up of heartwood and sapwood, the difference for most species is easily recognised because the heartwood is darker in colour. Annual growth rings can also give an indication of the region of origin or the species of wood. For example, visible annual rings indicate regions of seasonal variation. The transition between earlywood and latewood can also indicate the region or climate. The thickness of the earlywood or latewood can indicate whether it is softwood or hardwood. Identification is different for each species and can be affected differently under varying conditions, but there is also overlap between species. So although these aspects can help to identify the species, it is still difficult to determine the exact species.

Figure 30_Commonly used wood species (Federal Brace, 2021)

For the wood industry, wood identification is critical to prevent serious problems. Woodworkers within the industry, such as furniture makers, wood graders, hobbyists, etc., identify wood by its colour, smell, density, grain pattern and hardness. This method is applicable, but the experience of the person and the quality of the wood determine the accuracy, with possible misidentification. Wood can usually be accurately identified through a microscope with a 10x - 20x hand lens. There is also an accepted method using a light microscope with a 10x objective, but this requires a good reference collection. There is scientific research into identifying wood using molecular biological techniques, which will hopefully become more accessible and cheaper as technology improves (Wiedenhoeft, 2013). See figure 30 for some commonly used wood species.

For sustainably harvested primary wood, the wood species is indicated. Primary wood that is not sustainably harvested may not have this identification. Secondary wood is even more difficult to identify. The wood species may depend on location, origin, availability at a certain time, year of construction, manufacturer/builder, building product, etc. Wood that is now (becoming) secondary wood may not give information about the species and properties. For these products, an easier, quicker and cheaper identification method needs to be developed to make reuse or recycling of secondary wood more accessible. Products made from primary wood today that will later become secondary wood can have this information on the product or for example in a material passport. This will make it easier to reuse the product in the future.

3.6 CONCLUSION

In short, wood consists of many species, each with their own physical and mechanical properties, and therefore each species reacts differently depending on exterior circumstances. Wood can be classified as either hardwood or softwood. Hardwood is usually harder, denser and more resistant to external conditions. Softwood is usually softer and easier to work with, but is not suitable for outdoor use. The difference can be seen in the cell structure. Other differences between species that apply to both hardwood and softwood are annual rings, heartwood and sapwood, density and mechanical properties.

On the one hand, wood is a versatile material used for many different kinds of products and functions, such as construction, furniture, decoration, paper & cardboard, etc. On the other hand, wood identification is challenging. Identification is done visually but is prone to error depending on the knowledge of the expert. Accurate identification can be done with a microscope, but this is a time consuming and expensive process. The differences between wood species have an impact on scrap wood, because for certain products the wood species or certain properties are important, especially for products that are subjected to stress, such as structural elements. It is therefore necessary to identify the species and properties of scrap wood.

4 WOODEN PRODUCTS IN BUILDINGS

Scrap wood includes wood waste from the construction and demolition industry, i.e. it consists of wood products from all types of buildings. In order to better understand the nature of scrap wood, this chapter will discuss aspects of different building products. Firstly, some of the different wood materials are listed, then where and what species of wood are used. Next, an overview of what these wood products are is given and the diversity of dimensions and wood species between and within the different building products is discussed. Finally, some of the performance requirements that wood building products must meet are discussed.

4.1 ASPECTS OF WOODEN PRODUCTS

4.1.1 WOOD BASED MATERIALS

Wooden building products consist of either solid wood materials or varying wood-based materials. These wood-based materials can be divided into 5 categories, see figure 31 for examples:

- Solid-wood materials
- Veneers (plates or blocks of thin slices of glued wood)
- Particle-based materials
- Fibre-based materials
- Composite materials

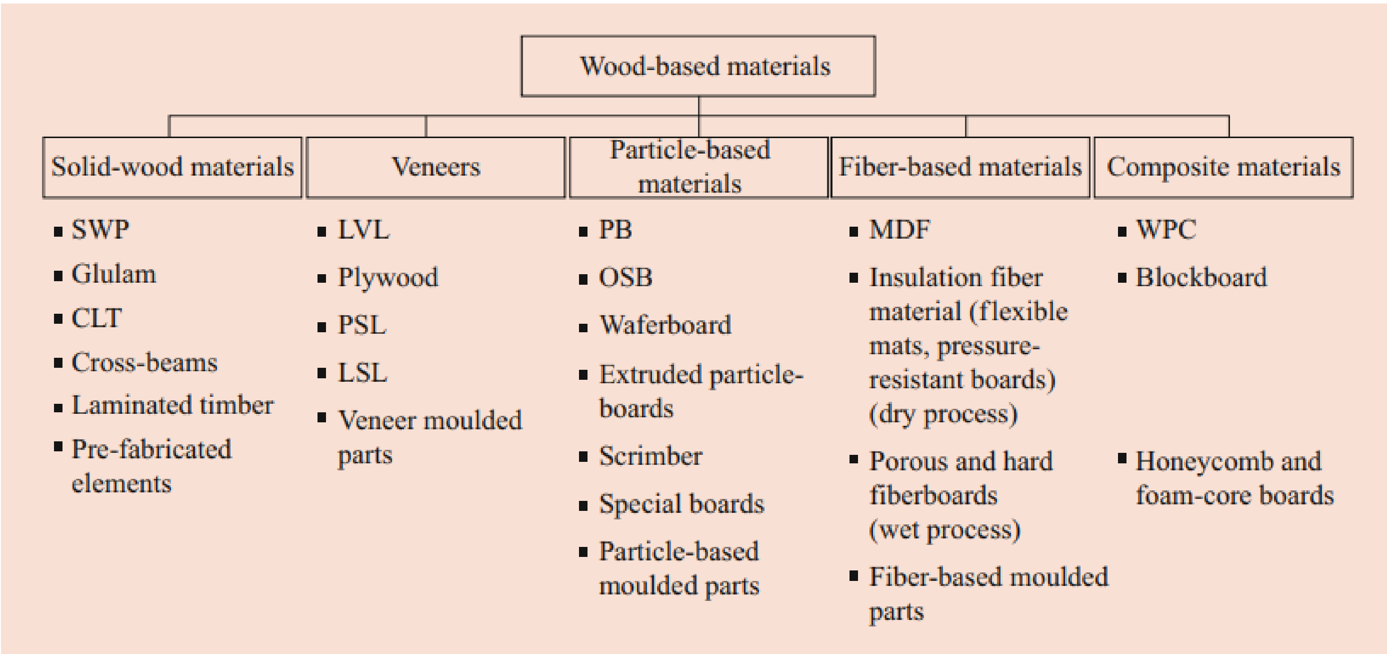


Fig. 24.4 Classification of wood-based materials according to their structure [4]

Figure 31 Wood based materials (Tobisch et al., 2023)

The solid-wood category is the only category that consists of solid-wood pieces, either as single pieces or glued together. The other categories consist of thin layers or particle-, strand-, rod- and fibre-shaped elements that are hold together with (in)organic binders (Tobisch et al., 2023). These categories are made from solid wood, but it does not work the other way around. Smaller pieces can never become bigger. Scrap wood is recycled into products of the particle-based materials. These products come in the shape of plates, blocks, ribs or slats and can be used for a wide variety of products, such as finish layers, construction, columns or beams, furniture, doors. For this thesis the focus will be on solid wood scrap wood.

4.1.2 INTERIOR VS. EXTERIOR USE

Wooden building products are used both inside and outside a building. The latter are exposed to the elements such as rain, moisture and insects. Not all wood species are resistant to these conditions and are therefore not suitable for exterior use (Probos, 2009). The durability class, discussed in 4.3.2, indicates how resistant the species are.

The previous chapter discussed the characteristics and differences between hardwoods and softwoods. For the construction industry, this results in differences in function and placement in a building. Hardwood has a higher level of strength and durability. This makes hardwood particularly suitable for exterior use, where it is most commonly used for windows, doors and cladding. Indoors, hardwood is mainly used for floors, furniture and stairs, and in places exposed to moisture. with the European hardwood species: oak, beech, ash, walnut, maple, elm, poplar, cherry and chestnut, and robinia being the most commonly used (Kozijnen van hout, n.d.). The most common tropical hardwood species are teak, padauk, mahogany, meranti, iroko, merbau or afzelia. These species are the most durable and resistant to moisture, but it is not necessary to use them indoors. The use of tropical hardwood should be limited due to deforestation and long transport distances, both of which have a high environmental impact.

Softwoods grow more quickly, making them cheaper than hardwoods, but they are less strong and durable. As a result, most softwood species are less suitable for outdoor use unless thermally or chemically modified. Interior softwoods are used for (load-bearing) structures, interior walls, doors, ceilings, the inside of window frames and interior panelling, and exterior softwoods are used as cladding. The most commonly used species are spruce (vuren) and pine (grenen), but other common species are: fir, pitch pine and larch, cedar and douglas (Constructiv, 2014; Milieu Centraal, n.d.-b).

Hardwood species

- Oak
- Beech
- Ash
- Walnut
- Maple
- Elm
- Poplar
- Cherry
- Chestnut
- Robinia

Tropical hardwood species

- Teak
- Mahogany
- Meranti
- Merbau
- Afzelia
- Padauk
- Iroko

Softwood species

- Spruce
- Pine
- Fir
- Larch
- Douglas
- (Red) Cedar

4.1.3 PRESERVATION OF WOOD

The lifespan of wood species can be extended through preservation. This can be done through either modification or impregnation. The former is more sustainable because modified wood does not contain toxic chemicals and can therefore be reused. Modification is either thermal, where wood is heated with steam or boiling water, or acetylation, where wood is treated with vinegar. Impregnated wood is treated with pesticides, which is dangerous for the environment because the toxic chemicals can leach into the soil. Impregnated wood is not allowed to be reused or recycled (Milieu Centraal, n.d.-b). Preserved wood is a suitable option to use softwood instead of (tropical) hardwood for exterior use.

WOODEN BUILDING PRODUCTS

32. (Geldersche Houtbouw, n.d.)
33. (Gadero, 2020)
34. (Renovatie-gids, n.d.)
35. (Woodstoxx, n.d.)
36. (Floorsite, n.d.)
37. (Willem design vloeren, n.d.)
38. (Newstairs, n.d.)
39. (Marlou, 2021)
40. (Oosterlinck-Hout, n.d.)
41. (Windows 4 u, n.d.)
42. (Rockwool, n.d.)
43. (De Vree, n.d.)
44. (Houtvakman, n.d.)
45. (Bruggink & Degen, n.d.)

4.2 WOODEN PRODUCTS

Before most buildings were constructed of concrete and steel, most buildings were constructed of wood. Industrialisation brought fossil fuels at the end of the 19th century and in the 20th century wood was replaced by concrete, steel and glass. The role of wood changed from a construction element to various types of building products, such as doors and window frames, roofs and rafters and floors (Het Houtblad, 2016). Today, wood is again used for (load-bearing) structures and in products for facades, windows and doors, stairs, floors, ceilings, interior walls and furniture because of its sustainable label. Scrap wood consists of waste, i.e. all those wooden building products. The consistency of scrap wood is therefore highly variable and depends on the choice of building materials and the year of construction. For example, the structure contributes significantly to the volume of wood: a timber-framed house contains 15-20 m3 of wood, while a non-timber-framed house contains 3-4 m3 of wood (Icibaci, 2019).

The most common wood species and shapes and possible dimensions for common building products are listed below. The focus is on solid wood products, as the focus of this work is on remanufacturing solid wood waste pieces. Appendix 3 contains a table of wood products with their different dimensions and the most commonly used wood species. On Houtdatase.nl there is a database of all the different species of wood and board materials used in construction and civil engineering, with information on their properties and possible building products.

4.2.1 CONSTRUCTION

Timber can be used in both non-load bearing and load bearing structures, the latter requiring the timber to be of a certain strength class, discussed in 4.3.2. The structure is made of either HSB, CLT, a combination of the two or in combination with concrete and/or steel. HSB (Dutch: houtskeletbouw) stands for timber frame construction and consists of timber columns, beams and rafters as well as ribs and slats for internal walls, see Figure 46, 47 and 48. CLT stands for cross laminated timber and consists of timber panels glued together perpendicularly and can be used for walls, floors and roofs (Centrum Hout, n.d.-d.), see Figure X.

Figure 46 HSB (De Vree, n.d.)

In most cases, the entire structure is covered with external and internal finishes such as plasterboard, although there may be exposed elements. As a result, the structure is usually not exposed to the environment and does not deteriorate much. Timber can therefore be reused several times. Finishing layers are usually attached to the wood with metal fasteners such as screws, nails or staples. Spruce (Vuren) is the most commonly used species, but pine, fir and oak can also be used (Centrum Hout, n.d.-d).

Figure 47 Ribs & slats (Rockwool,

HSB products consist of rectangular or square columns and beams with varying dimensions in cross section and length, depending on the function, required strength, spans and dimensions of the building. These aspects also explain the different dimensions of CLT panels. However, the panels are much larger. Chapter 7 takes a closer look at the dimensions. CLT is a relatively new building product, only 30 years old, so it is unlikely that today's scrap wood will contain CLT products.

Figure 48 CLT (Bruggink & Degen, n.d.)

4.2.2 WINDOW FRAMES

Window frames can be used for either interior or exterior purposes, although the latter is more common. Most are therefore made from tropical hardwoods or European hardwoods. Interior windows can also be made of softwood. The most commonly used species are: meranti and mahonie, but they can also be made of merbau, iroko, oak, chestnut, larch, douglas, western red cedar, and for internal frames: spruce, pine (Geveltimmerwerk, n.d.; nbd-online, n.d.). Window frames consist of profiles of different lengths, depending on the size of the window. Figure 49 shows the different profiles within a window. In a building, the dimensions and shapes of the window frames are likely to vary, resulting in pieces of wood of different lengths and profile shapes.

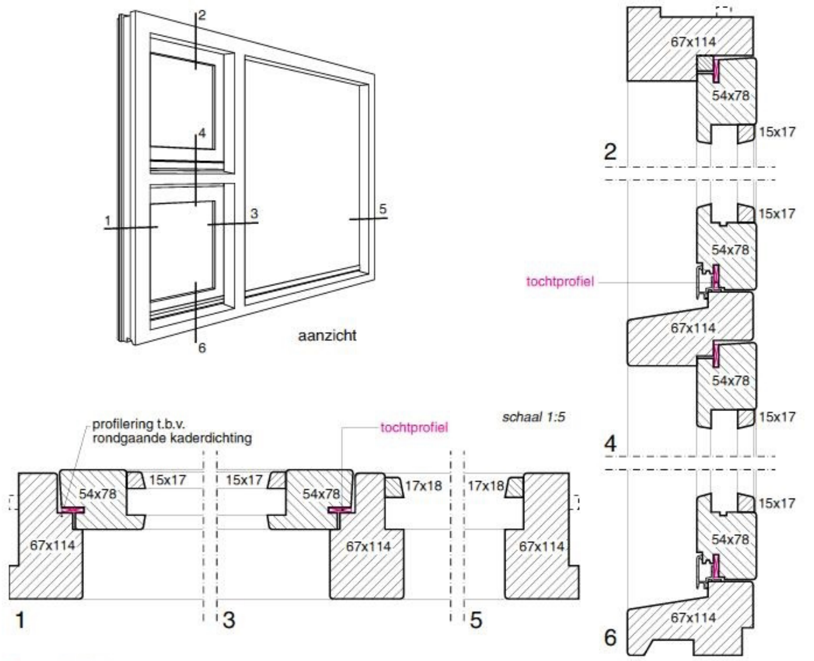


Figure 49 WIndow frame profiles (Geveltimmerwerk, n.d.)

4.2.3. DOORS AND DOOR FRAMES

Doors consist of two components: the door panel and the door frame, and are used both indoors and outdoors. Doors can be made of either solid wood or a solid wood frame with an MDF panel and insulation in between. The latter is most commonly used for exterior applications as the thermal insulation of solid wood is too low. Door panels can consist of a plain panel or various boards and mullions, see figure 50. Door panels are over 2.1 m high, wider than 70 cm and between 38 and 67 cm thick, due to the old regulations of the Bouwbesluit. The new requirements for doors are at least 2.30 m high and 85 cm wide (Bouwbesluit, 2012, § 4, art. 4.22.1). The door frame consists of slats with a square or rectangular cross-section or with a profile. The length of the slats is slightly longer than the height and width of a door.

The same types of wood are used for solid wood doors and frames as for window frames: meranti and mahonie, merbau, iroko, oak, chestnut, larch, douglas, western red cedar. Spruce and pine are the most commonly used softwoods for interior doors, except in areas exposed to moisture.

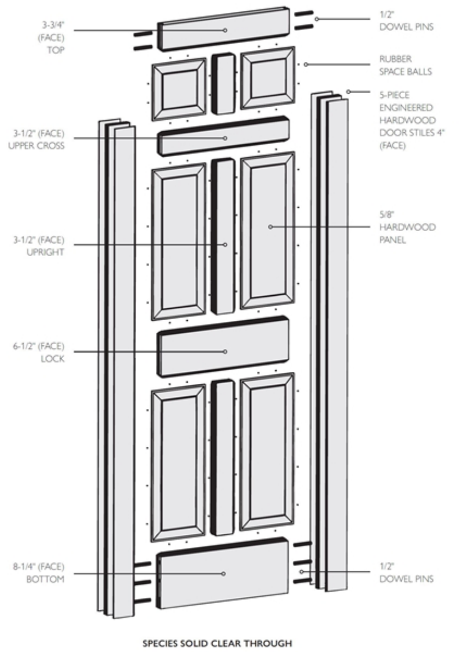


Figure 50 Door components (Baird Brothers, n.d.)

4.2.4 PLANKS

Planks can be used on floors, ceilings, walls and facades. The floorboards can either be part of the construction and have a layer on top, such as carpet, or they can be the top layer of the floor. Planks consist of a rectangular cross section with a width of 70 - 400 mm and a smaller thickness of 10 - 80 m) and varying lengths, depending on placement, function and aesthetics. The cross section can either be a normal rectangle or have some tongue and groove at the edges to allow the planks to click together. Some examples are shown in Figure 51, 52 and 53

For exterior use on facades, hardwoods such as Oak, Western Red Cedar, Larch or Douglas fir or modified or impregnated softwoods such as Accoya, Spruce or Pine are most commonly used. For interiors, all kinds of species are used, depending on aesthetics and taste, although the top floor panels are usually hardwood, such as oak, ash, poplar, beech, chestnut or walnut, because the floor is exposed to moisture from cleaning and mopping. Common softwoods include larch, finti, pine and fir.

Figure 51 Douglas planks (VanDouglasHout, n.d.-b)

Figure 52 Douglas plank with double lip profile (VanDoglasHout, n.d.-a)

Figure 53 Plank with tongue and groove profile (Bouwmaterialen Zeel-and, n.d.)

4.3 PERFORMANCE REQUIREMENTS

The government imposes certain requirements on building products in order to guarantee a safe product or construction and to reduce the impact on the environment. These requirements are laid down in European or Dutch standards: the NEN standards (Ministerie van Algemene Zaken, 2022). At present, these standards apply specifically to virgin wood. Scrap wood is more likely to be rejected when tested according to the standards, whereas scrap wood may still be usable. At the moment there is a lack of grading rules to specifically determine the performance requirements of scrap wood. (Icibaci, 2019; Sloopcheck, 2022) Certain products must meet certain performance requirements. For load-bearing structures, the wood must be of a certain strength class. For resistance to weathering and decay, wood species are classified into durability classes.

4.3.1 STRENGTH CLASS

The strength class applies to timber used as a structural member. It is determined by Eurocode 5 according to the European strength classes in NEN-EN 338. The strength class consists of the letter C for coniferous wood (softwood) or the letter D for deciduous wood (hardwood) and a number indicating a value for the strength properties corresponding to the bending strength. There is a distinction between solid wood and laminated wood (EN 14080) in 12 classes for softwood and 8 classes for hardwood (Houtinfo, 2014). The most commonly used strength classes are C18 and C24, especially the latter (Sleiderink, n.d.).

4.3.2 DURABILITY CLASS

In the Netherlands and Europe, wood has a certain durability class, ranging from 1 to 5, with 1 being the most durable and 5 being the least durable. This classification system, shown in Figure 54, shows the lifespan of wood according to its durability class, using common wood species as examples. The lifespan is tested under the worst conditions, so the lifespan of most species is likely to be longer depending on the conditions to which the wood is exposed. For outdoor use, the rule of thumb is to use class 3 and below. Indoors, wood is rarely exposed to external conditions and can therefore have a higher durability class. There is also a difference between the use of heartwood and sapwood. The classification system is based on the heartwood. Heartwood is much stronger and more resistant to insect attack due to the chemicals released as the cells die. Sapwood is less strong and is therefore always classified as class 5 timber, for both hardwood and softwood (Logic Manufactured Bespoke, 2022).

Durability class	Designation	Timber life (worst case) [years]	Examples
1	Very durable	25+	Tropical hardwood, Teak, Opepe
2	Durable	15 - 25	UK grown Oak, Ekki, Iroko, Other tropical hardwoods
3	Moderately durable	10 - 15	Douglas Fir, Walnut
4	Slightly durable	5 - 10	European Elm, Scandinavian Pine, Larch
5	Not durable	0 - 5	Beech, Ash, Balsa

Figure 54 Durability class (adapted from Logic Manufactured Bespoke, 2022)

4.4 CONCLUSION

Thus, building products can consist of all kinds of different wood-based materials and products, such as construction components: beams, columns, rafters, ribs & slats, and building products: window and door frames, planks, stairs, cladding panels, etc. All these products have varying dimensions and shapes, although they are usually rectangular or square and can be made from different types of wood. An overview of wood products with their varying dimensions and the most commonly used wood species is given in Appendix 3. The range of dimensions is estimated by research, but may vary outside the ranges given. (Tropical) hardwoods are most commonly used outdoors and in damp locations, although preserved timber is also an option, and softwoods are more commonly used indoors.

The different dimensions and species of construction products automatically apply to the consistency of scrap wood. In other words, there is a lot of variation between all 435 ktons of scrap wood. For certain building products, the wood type (hardwood or softwood), wood species, strength class and/or durability class must be determined. It is therefore necessary to identify the scrap wood pieces or to use the scrap wood pieces in building products where these aspects don't play a role. This also applies to European standards and performance requirements. These are not available for the reuse of scrap wood, resulting in unnecessary scrap wood being rejected. All these different aspects and variables contribute to the challenges of reusing scrap wood.

5

SCRAP WOOD

This chapter provides information about scrap wood. Firstly, the quantity and consistency of scrap wood will be discussed to give an overview of what scrap wood contains. This will provide a basis for further research into how it can be reused and remanufactured. Next, the potential reuse process will be discussed to show what this process would look like and where the problems are that contribute to the lack of reuse of scrap wood. This section will first discuss the history of reuse of materials and existing reuse and recycling methods. Then the whole chain. The last section discusses other problems in the reuse of scrap wood.

5.1_CONSISTENCY OF SCRAP WOOD

5.1.1 QUANTITY OF WASTE & SCRAP WOOD

According to Sloopcheck and Van de Minkelis (2022), approximately 3,5 Mt of wood will be produced annually in the Netherlands (in 2019), of which 29% is roundwood and 71% is waste wood (2,485 Mton). On the other hand, 16,6 Mton of wood is used every year. Of the 71% waste wood, 83% is incinerated for energy production and only 17% is recycled, mostly downcycled. Unfortunately, information on the amount of reused waste wood is not available and the most detailed information is from 2017. This data is therefore used in this paper. According to Sloopcheck, the total amount of waste wood in 2017 was about 1,7 Mton, which is lower than in 2019.

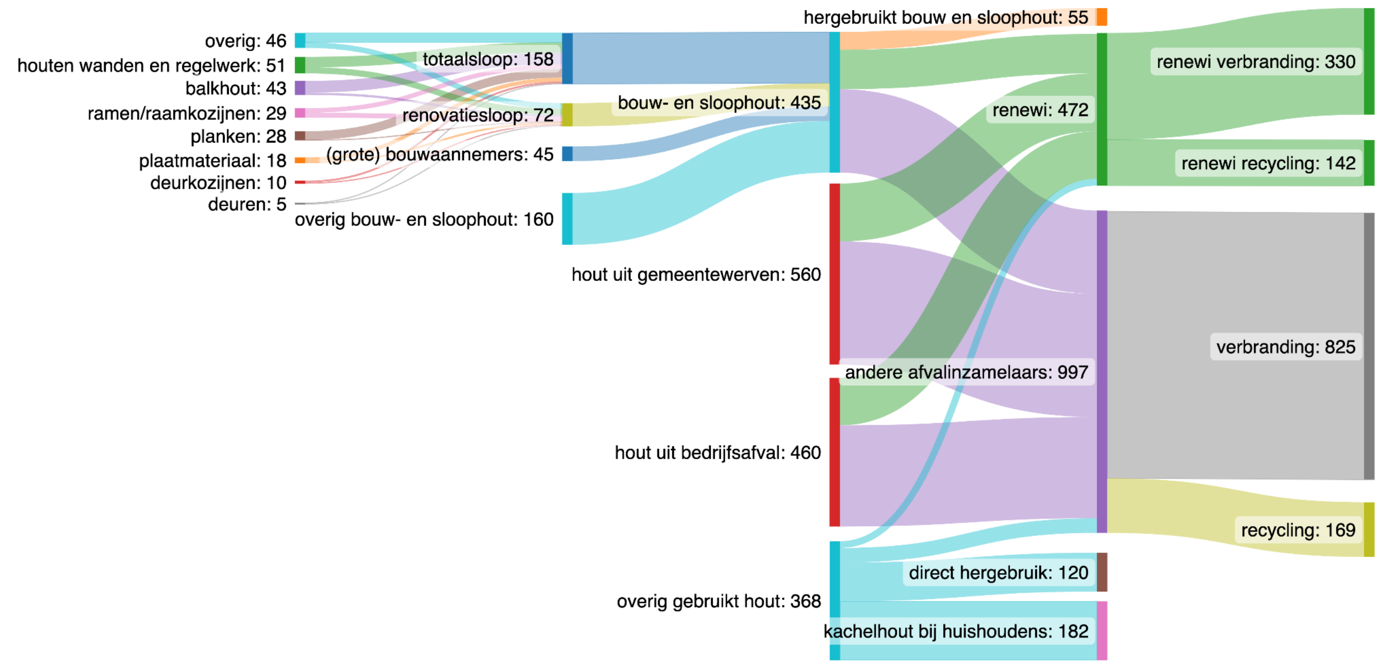


Figure 55_Amount of waste wood (Pelt, n.d.)

Sanne Pelt (n.d.) made a detailed flow diagram of the waste wood stream, see Figure 55. In this diagram the total amount of waste wood is 1823 kton. The waste wood is divided into 4 categories: 435 kton (24%) construction & demolition wood, 560 kton (31%) from municipal yards, 460 kton (25%) from company waste and lastly 368 kton (20%) from other sources. This work focuses on waste wood from construction and demolition

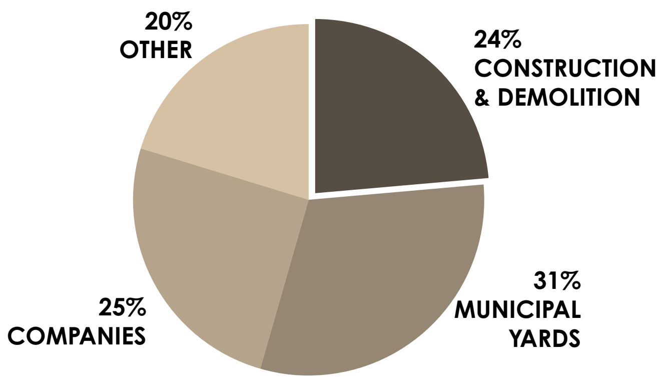


Figure 56_Waste wood division (own image)

(435 kton), also known as scrap wood, as the study of all waste wood is too broad for the scope of this work. Scrap wood also consists of products from the built environment, so the scrap wood already has certain properties or aspects that are required for building products.

The majority of waste wood, 1.337 kton or 73,3%, is incinerated. 311 kton or 17,1% of the waste wood is recycled, of which 142 kton is recycled by Renewi, where it is shredded and turned into OSB and chipboard (Renewi, personal communication, 20 April 2023). Finally, only 175 kton of waste wood, or 9,6%, see figure 57, is reused. 120 kton is directly reused and 55 kton contains reused scrap wood. This is only 12.6% of the 435 kton of scrap wood. Most of the scrap wood is also incinerated. According to Sloopcheck (2021), 435 kton is enough wood for 50.000 family homes from CLT if all scrap wood could be reused. According to Van de Minkelis (2023) more scrap wood has potential for reuse than is reused now.

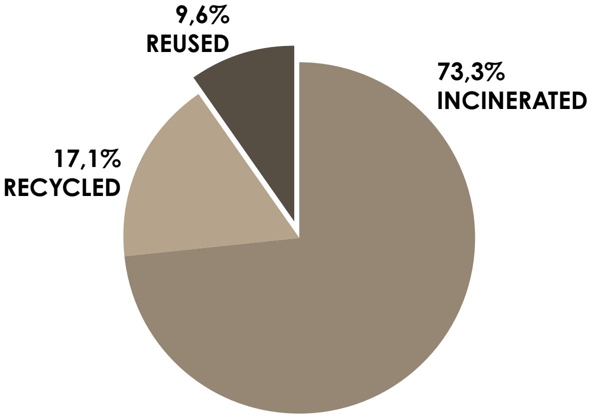


Figure 57_Waste wood strategies (own image)

5.1.2 CONSISTENCY OF SCRAP WOOD

Scrap wood is divided into four categories: 158 kton from total demolition, 72 kton from renovation demolition, 45 kton from construction companies and lastly 160 kton from small renovations and other unknown demolition projects. From the first two categories, total demolition and renovation demolition, with a total of 230 kton, the breakdown of construction products is as follows:

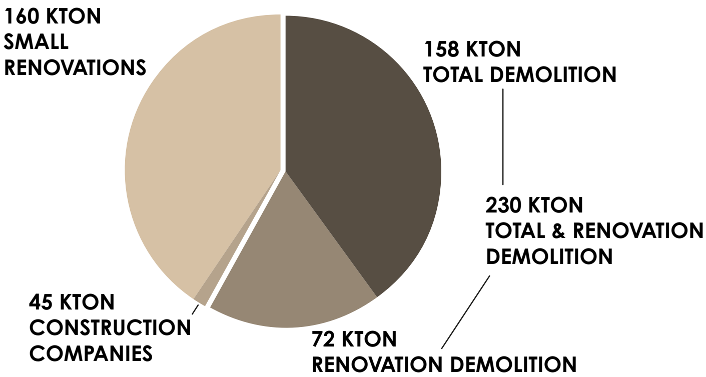


Figure 58_Division of scrap wood (own image)

- 43 kton beams (19%)
- 28 kton planks (12%)
- 29 kton window frames (13%)
- 5 kton doors (2%)
- 10 kton door frames (4%),
- 51 kton walls & framework (22%)
- 18 kton board material (8%)
- 46 kton other (20%)

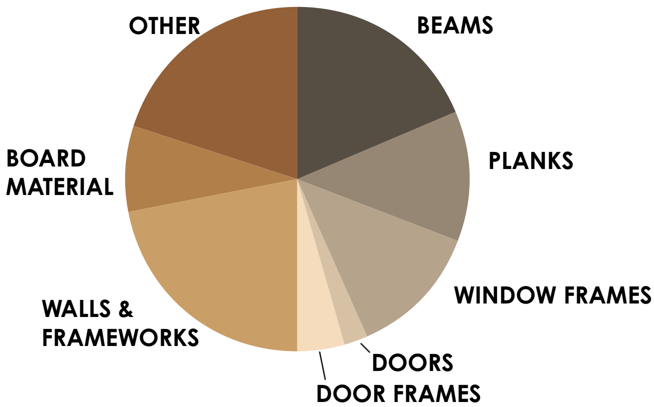


Figure 59_Division building products in scrap wood (own image)

The other 205 kton (construction & scrap wood from other sources) products consist of doors and window frames, wood from small renovations, leftovers and wood from unknown projects. Information on the reuse (potential) of the 205 kton is unknown (Van de Minkelis, 2023).

Thus, for about half of the total amount of scrap wood, the quantity per building product is known, but the actual consistency of the scrap wood in terms of dimensions, wood species, quality, mechanical properties and possible finishes is unknown. As discussed in Chapter 4, these aspects vary between similar and different wooden building products. But even between the same building products from one building, there may be (small) differences due to adjustments during construction, repairs over time, damage or decay. Within the same building, quality differences are possible due to different exposure conditions (Huuhka, 2018). Therefore, the consistency of scrap wood is highly variable. Another aspect contributing to the variability is related to the construction date of the product and/or building. Aspects may have changed over time due to changes in availability, calculations, building physics requirements, building regulations and trends, resulting in similar building products with different properties and aspects. For example, the maximum U-value of a window has been reduced to 1.65 W/m2K (Bouwbesluit, 2012, §5, art. 5.1, section 9), which means that windows with a higher U-value cannot be reused.

5.1.3 PROPERTIES

The properties of scrap wood components also vary greatly depending on the species used. Salvaged solid wood can be considered the same as virgin wood for each wood species, only due to surface treatments and external conditions, the mechanical properties may be slightly different (Huuhka, 2018). In general, studies have found some evidence that mechanical properties such as load-bearing capacity, compression and tensile strength and bending strength don't deteriorate with age. The only mechanical property known to degrade with age is impact bending strength.

Wood degradation is mostly the result of biological (insects or decay) or physical damage. Physical damage can occur during use or dismantling due to (over)loading, fasteners (nails and screws) or poor handling. Fastener holes have the same degrading effect on tensile strength as knots. Therefore, scrap wood with many fastener holes may not be suitable for strength-requiring functions.

So, although the mechanical properties don't usually deteriorate, these properties are mostly unknown for scrap wood pieces and these need to be tested. There are visual and mechanical grades. Some degrading aspects of wood are clearly visible, such as decay, permanent warping or fixing holes. These can be easily identified and removed, but there are no official grading rules for the other less visible degradations. The development of such rules could have a positive impact on the reuse of scrap wood (Huuhka, 2018; Sloopcheck & Van de Minkelis, 2022). Mechanical properties are most accurately tested using a machine, such as the three-point bending test for strength (Department of Materials Science and Metallurgy, 2008), longitudinal resonance machines (Ridley-Ellis et al., 2022) or X-ray machines (Ingenieursbureau Evan Buytendijk, n.d.). However, this method now requires each piece of scrap wood to be individually tested, either manually or mechanically, which is a time-consuming process. The mechanical option is faster, but these machines are designed for virgin wood. Although the machines can grade different dimensions, similar dimensions are tested at the same time. The machines are not specifically designed for the varying pieces of scrap wood. Scrap wood is therefore more suitable for products where the properties are less important, or a scrap wood specific automated testing machine should be developed.

5.1.4 WASTE CLASSES OF SCRAP WOOD

Waste management has divided waste and scrap wood into three classes: A-, B- and C-wood. A-wood is untreated, unpainted and clean solid wood, see figure 62. A-wood is allowed to be reused and recycled. At the moment, A-wood is mostly recycled, or actually downcycled, into chipboard or biofuel. B-wood consists of wood that has been glued, painted or varnished, see figure 61. Common products include solid wood, laminated wood, plywood, fibreboard, particleboard, furniture, doors and window frames. At present, this type of wood is either recycled or burned for energy as biofuel. C-wood includes preserved and impregnated wood, the latter containing toxic chemicals, see figure 62. As a result, C-wood cannot be reused or recycled and can only be incinerated for energy recovery.

Figure 60_A- wood (Wastenet, n.d.)

Figure 61_B-wood (Cure-afvalbeheer, n.d.)

Figure 62_C-wood (Sneek Recycling, n.d.)

A-wood has the greatest potential for reuse. As it is clean wood, the need for adaptation is limited. The reuse process is the simplest and quickest. But B-wood is the largest category. In practice, B-wood is actually divided into solid B-wood and glued B-wood (such as laminated or plywood). These two categories of wood have different properties, consistencies, woodworking possibilities and possible functions. This results in different possibilities for reuse. For painted or lacquered (solid) wood, the wood can be sanded to remove the layer so that it can be reused (Bruggen & Zwaag, 2017; ContainerOnline, 2019).

5.1.5 DETERMINATION OF SCRAP WOOD

Scrap wood varies greatly in shape, dimensions, species and quality due to the different aspects of the wooden building products that make up the scrap wood, the deterioration caused by external circumstances and the handling during the demolition process. All these different aspects make it difficult to know exactly what the scrap wood consists of. As a result, some building products can be reused directly, while other pieces of scrap wood require some processing. For certain construction products, it is necessary to identify the wood species and properties and/or to construct a product using the same wood species and/or dimensions, which may not be widely available. According to some demolition companies, such as Vermeulen & Zn Sloopwerken (personal communication, 25 April 2023) and the waste management company Renewi (2023), sorting and determining the consistency of scrap wood is too time-consuming and less profitable than the time and money it costs. This is one of the reasons why the reuse of scrap wood is not a common practice in the built environment.

5.1.6 CONCLUSION

In short, about 1.8 Mt of waste wood is produced annually, of which 435 kton is scrap wood. The majority is incinerated, then recycled and a small portion is reused, for scrap wood only 55 kton (12.6%), while there is more potential for reuse. Reuse is hindered by the varying consistency of scrap wood in terms of dimensions, quality and quantity, and determining these aspects is too time-consuming and unprofitable.

5.2 REUSE PROCESS

In order to understand the 'reuse' process of scrap wood, the whole chain from demolition to end product was examined. The research identified a number of barriers throughout the chain to the current lack of reuse. Firstly, the history and existing methods of wood reuse are discussed. It then discusses the reuse chain, which is divided into three phases: the (post) demolition phase, the remanufacturing phase and the product phase. This research is partly done through interviews with companies from each stage of the chain, working with either virgin wood, waste wood or both. A summary of the interviews with each company is given in Appendix 5.

Important note: what is meant with "reuse"

As mentioned in the context, this thesis will focus on the reuse of scrap wood. A distinction is made between scrap wood **products** and scrap wood **pieces**. Scrap wood **products** include whole wooden building products such as window frames, doors, beams or any other building product that can be **reused immediately** or with some repairs. Although there are barriers to product reuse and more building products should be reused in terms of circularity, this reuse process is already more common on a small scale. For example, some demolition companies sell the products that are dismounted from a building during the demolition process, or used materials are sold on marktplaats.nl. On opalis.eu there is a map of companies that sell used building products. In addition, immediate reuse does not require any processing and does not need to be remanufactured.

The **focus** of this thesis is on the **reuse** of scrap wood **pieces**. These pieces are individual pieces of solid wood that can be either whole, damaged or broken. A scrap piece will most likely not be reused directly, but will need to be remanufactured into semi-finished products (halffabricaten), which can then be manufactured into various wood building products. The process of reusing scrap wood is not yet common practice on a large scale and is therefore interesting to research. Therefore, the focus is on how to **reuse scrap wood pieces**. Throughout this thesis, however, the reuse of products will sometimes be mentioned.

5.2.1 HISTORY REUSING PRODUCTS

Before the Second World War, it was common practice to dismantle old buildings and reuse their components. At that time, most buildings were made of brick and timber. Bricks were chipped and wood was stripped of nails and then reused. Demolition companies had storage space for demolition products, which were then resold (Sloopcheck, 2021). There was a massive housing shortage due to the Second World War and materials were scarce and expensive, so buildings had to be built quickly and cheaply afterwards. Concrete became a popular building material. The quality of these buildings is low and most of them now need to be demolished or renovated (Icibaci, 2019; Rijksdienst voor het Cultureel Erfgoed, n.d.). The disadvantage of concrete is its low reusability. It is mostly down-cycled into road material. Demolition companies have now stopped dismantling buildings and storing demolition products. Overall reuse of building products has declined. Today, only a few companies still operate in this way (Sloopcheck, 2021).

5.2.2 EXISTING RECYCLE & REUSE METHODS

In order to transform from a linear to a circular economy, it is necessary to reuse and recycle more construction products. Currently, most waste wood is incinerated (73.3%), some is already recycled (17.1%) and only reused (9.6%). There is more information available on recycling methods than on reuse methods for waste wood.

Wood recycling is already a common practice in the C&D industry. A common recycling route is the production of chipboard from A-wood and clean B-wood. Wood is shredded into small chips and manufactured into chipboard. Chipboard is a multifunctional product used for walls and furniture, but it is difficult to recycle afterwards (Bruggen & Zwaag, 2017). It can replace non-load-bearing products, depending on its former state. However, the chips can never be re-grown. Chipboard should therefore be a last resort for recycling when solid wood cannot be reused.

The reuse of scrap wood **products** is still a niche industry, with only 12.6% of scrap wood being reused. According to van de Minkelis (2021;2023), more scrap wood products have the potential to be reused than is currently being reused, if scrap wood is properly handled and processed. Scrap wood **pieces** are not reused in the C&D industry, but is reused in different markets in other industries where there are no performance requirements and no legislation to avoid certification and grading (Icibaci, 2019). For example, the company Herso (personal communication, March 16, 2023) collects scrap wood and remanufactures the pieces into flooring or wall panelling.

5.3 PROCESS CHAIN FOR REUSING SCRAP WOOD

5.3.1 WHOLE CHAIN

The reuse of scrap wood in the built environment for building products can be seen as a production chain with several links. This chain starts with the demolition of a building and ends with building products. The chain is shown in a diagram in Figure X, a bigger image is in appendix 4. It is divided into three phases, each with a few links. Within these links many smaller processes take place, but this paper will discuss the larger steps in the whole reuse process. The diagram shows the whole process as a sequential chain, but this is not necessarily the case. Some links occur simultaneously or several times throughout the chain. This is discussed below.

The three phases are the (post-)demolition phase, the remanufacturing phase and the product phase. The (post-)demolition phase consists of the links: demolition, collection and sorting. The

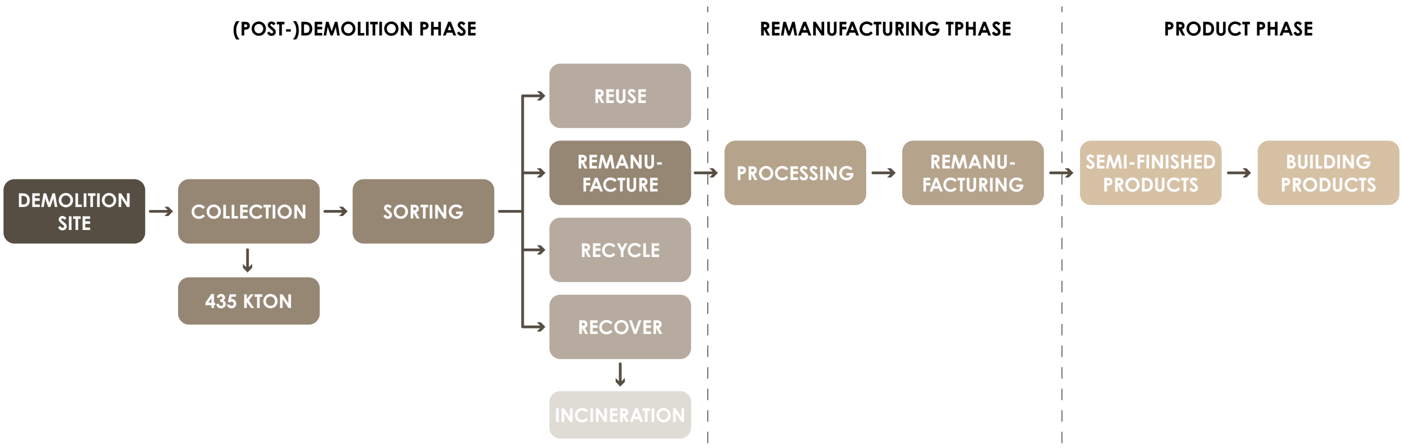


Figure 63 Reuse chain of reusing scrap wood (own image)

remanufacturing phase processes the scrap wood into pieces ready for the final phase and consists of the links: processing and remanufacturing. The last phase is the product phase and consists of the links: semi-finished products and building products.

5.3.2 (POST-)DEMOLITION PHASE

The first phase is the (post-)demolition phase. The post- is between (...) because the links occur both during the demolition of a building at the demolition site and after demolition at other sites. This phase consists of: demolition, collection and sorting. The method of gathering materials from a demolition site is decided before the demolition process.

5.3.2.1 Demolition

There are two methods of demolition: traditional demolition, see figure 64, and circular demolition, see figure 65. The method to be applied is decided in advance by the client. Both methods remove loose elements and materials from the buildings, which is called the pre-demolition phase. The difference is in how the material is handled after demolition. Traditional demolition is a faster process. After the loose materials have been removed, a Bobcat goes through the building and demolishes the internal structures and other associated materials. The shell of the building is demolished into rubble. The demolition waste consists of mixed materials. The waste materials are either downcycled or incinerated. The mixed materials prevent possible reuse or high value recycling.

Figure 64 Traditional demolition (A Jansen BV, n.d.)

Figure 65 Circular demolition (PBL, 2021)

Circular demolition sees a building as a temporary material storage bank and tries to disassemble all materials and products and reuse, remanufacture or upcycle these elements as much as possible (PBL, 2021). This reduces waste and provides materials that can partially replace the use of new raw materials, which are becoming scarcer and more expensive. However, the circular demolition process takes longer and demolition contractors do not always get enough time from the client to thoroughly demolish the circular. Selling demolition products and materials is difficult and time consuming. The development of hubs where these materials can be held is beneficial to sales, as long as the hubs are local to reduce transport distances. There is also a lack of guidelines to promote high-value reuse and recycling, while the built environment would benefit from such guidelines (Bijlsma, 2021; Van de Minkelis, 2021).

In order to move towards a circular economy, circular demolition must become the standard instead of traditional demolition (PBL, 2021). In 2021, about 40% of the 426 demolition companies use circular demolition (Bijlsma, 2021), such as Vermeulen & Zn Sloopwerken (personal communication, April 25, 2023) and New Horizon. The collected materials are sold by the demolition companies themselves or by resellers, for example: gebruiktesloopmaterialen.nl, opalis.eu, marktplaats.nl.

5.3.2.1 Collection

The removal of materials during the (circular) demolition process is part of the collection stage. Materials are removed either manually or mechanically and some are easier to remove than others. For example, doors are easy to remove as they only need to be lifted off their hinges. In terms of circularity, it is best to remove **products** as carefully as possible to avoid damage so that they can be **reused** immediately, but this is not always possible and it is a time consuming process. A time consuming process results in higher labour costs, especially for manual labour (van de Minkelis, 2021; van de Minkelis, 2022) For example, door and window frames, solid wood floors, wall panelling and ribs & slats are difficult to remove. These elements are fixed to the walls with metal fasteners and are usually covered with a finishing layer such as plasterboard and backed with insulation. During demolition, these elements tend to break and mix with other materials, especially during traditional demolition.

In order to be able to **reuse scrap wood pieces** and remanufacture them into new building products, the most important factor is to avoid mixing them with other materials (Van de Minkelis, 2021). Broken or damaged pieces of scrap wood can still be remanufactured once the damage has been removed. However larger pieces are more suitable for remanufacturing different types of products, so some careful handling is desirable. Therefore, scrap wood is more suitable to be **reused as pieces** and remanufactured into new products.

Collection can also take place after demolition. Mixed products or elements can then be separated and the wood collected. Materials are first collected at the demolition site and later at hubs where these pieces can be sold or processed.

At present, the careful collection of products for immediate reuse is too time-consuming. The demolition company either doesn’t have the time or isn’t paid enough to carefully remove the materials. The proceeds are not worth the time and effort (Van de Minkelis, 2021). The bobcat is thus the preferred method. The reuse of scrap wood is therefore more suitable because it requires less attention.

5.3.2.2 Sorting

Sorting occurs both at the demolition site simultaneously with collection and afterwards. Sorting also occurs in certain gradations, and scrap wood can be sorted into several categories, see figure 66. The first step is to sort demolition waste by material, such as concrete, steel/metal and wood, etc. The next step is to sort scrap wood according to the R-strategies of the hierarchy: reuse (+repair), remanufacture, recycle and recover. All waste wood products that can be reused should be reused. Recovery only applies to scrap wood that either cannot be recycled, such as C-wood, or is too degraded. What’s left over should be remanufactured or otherwise recycled.

At present, scrap wood is sorted into A-, B- and C-wood and transported to waste management facilities. A- and B-wood are disposed of together on a huge pile. Here, C-wood is incinerated and A- and B-wood are shredded and recycled into OSB, chipboard, hardboard, softboard or MDF/HDF.

Hardly anything is reused or remanufactured, while A- and B-wood actually contains wood that is in good enough condition (Renewi, personal communication, April 20, 2023).
This thesis focuses on the remanufacturing of scrap wood. Therefore, the next sorting step is to sort the scrap wood according to one or more aspects such as wood species, dimensions, quality and/or mechanical properties. The sorting aspect(s) depends on the requirements of the product into which it will be remanufactured. Some building products require the use of the same species of wood or have specific dimensions. For example, exterior window frames require the use of the same hardwood species, while the floors of Herso (personal communication, March 16, 2023) consist of wood pieces of different dimensions and wood species.

As mentioned above, scrap wood consists of many different dimensions, species and qualities, and identifying the species can be difficult. Sorting according to all these aspects is a time-consuming process as each piece has to be sorted separately by hand. Sorting by species at the demolition site has the advantage over sorting at another location because the same wooden building products are likely to be of the same species, so only one building product needs to be identified. The manual labour and the long duration result in high labour costs (van de Minkelis 2021; 2023). For example, according to Vermeulen en Zn. sloopwerken (personal communication, April 25, 2023), it is not profitable to identify the species and dimensions of scrap wood products oneself. They let customers come and figure it out for themselves. This is one of the barriers to the lack of remanufacturing of scrap wood. This chain would therefore benefit from mechanical and automated systems that can sort and identify scrap wood.

Transport has a major impact on the environment, especially in terms of the total CO2 emissions of wood. It is therefore necessary to minimise the transport distance, which can be achieved in part by minimising the number of journeys. Scrap wood should therefore be thoroughly sorted at the demolition site as part of the circular economy strategies. Another option is to have a processing hub where all scrap wood to be remanufactured is collected and further sorted and processed into pieces that can be remanufactured. If these processing hubs are distributed throughout the Netherlands and close to demolition sites or companies, the transport distance is short. From these hubs, the scrap wood can either be remanufactured there or transported to companies that remanufacture it into building products.

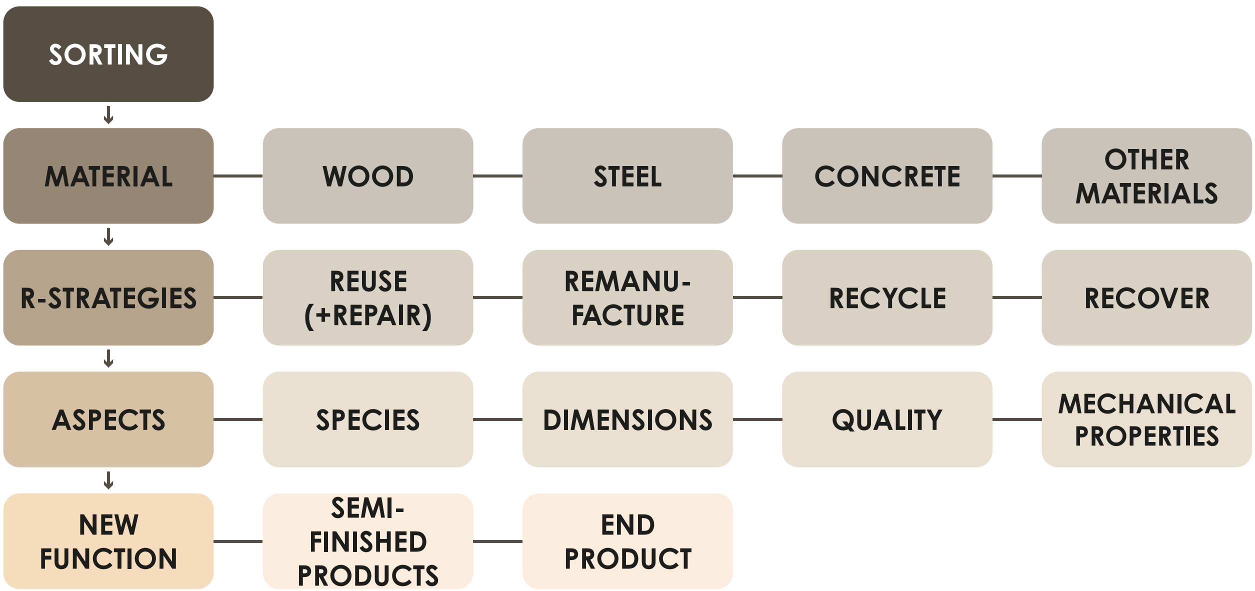


Figure 66 Sorting diagram (own image)

5.3.3 REMANUFACTURING PHASE

The remanufacturing phase is divided into two stages: processing and remanufacturing. The processing phase contains the methods to turn scrap wood into pieces suitable for the remanufacturing phase.

5.3.3.1 Processing

Scrap wood can contain metal, be dirty, damaged, have a finish such as paint or varnish, or have irregular shapes such as tongue and groove or window frame profiles. Before the scrap wood pieces can be processed into (semi) finished building products, the wood pieces must be shaped into reworkable pieces, such as rectangular or square slats, see Figure 67. The processing stage involves a number of operations, which do not necessarily apply to every piece of scrap wood due to its varying consistency.

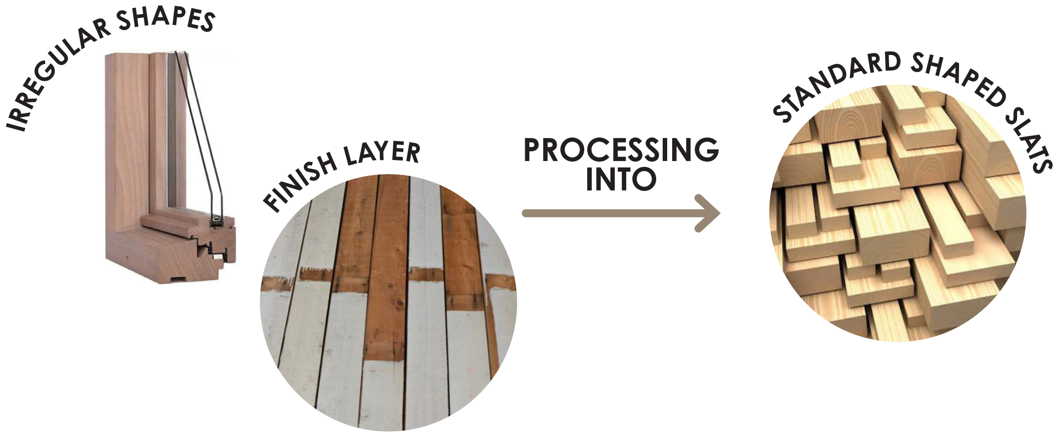


Figure 67 Processing diagram (left to right: Windows 4 u, n.d., Destijdsch, n.d., Limtrade, n.d.)

The first process is the removal of metal and other materials. Metal consists of connectors and fasteners such as nails, screws, bolts, staples or hinges. Metal fasteners can be found, for example, in ribs and slats where plasterboard has been nailed to them. Removing metal is essential because it can cause breakage of (expensive) processing machines, such as window frame profiling machines. The metal is usually removed manually, which is a time-consuming process. Some companies, such as Cirqwood, have machines that check whether scrap wood is free of metal. This time-consuming process is expensive due to labour costs. In order to make it profitable, the metal is removed by workers with at a disadvantage in the labour market, because their wages are lower than those of regular workers. Therefore, virgin wood can be cheaper than scrap wood (Woodjoint, personal communication, April 5, 2023). This process is one of the barriers to reuse scrap wood.

The next process is to clean the scrap. Some products have accumulated dirt from years of use, dust from storage or stains from the demolition process. Cleaning is done with a brush.

Another process is to shave off the top layer. Some scrap wood contains a top layer such as paint or varnish, either to protect the wood from environmental conditions or for aesthetic reasons, mostly scrap wood that is visible, both for interior and exterior use, such as window frames, doors, stairs, panelling and in some cases structural products. This type of wood is known as B-wood. This layer must be removed before the wood can be remanufactured. This process is an extra step that adds time and cost to the overall reuse process. However, exterior products such as doors and windows (frames) are made from tropical hardwoods which are very valuable. These B-wood pieces are therefore more profitable to salvage. The next process is to cut the wood into pieces suitable for remanufacturing, see figure 68. Some scrap can be sold even after this step, as some building products are only made of solid wood of a certain dimension, such as ribs & slats.

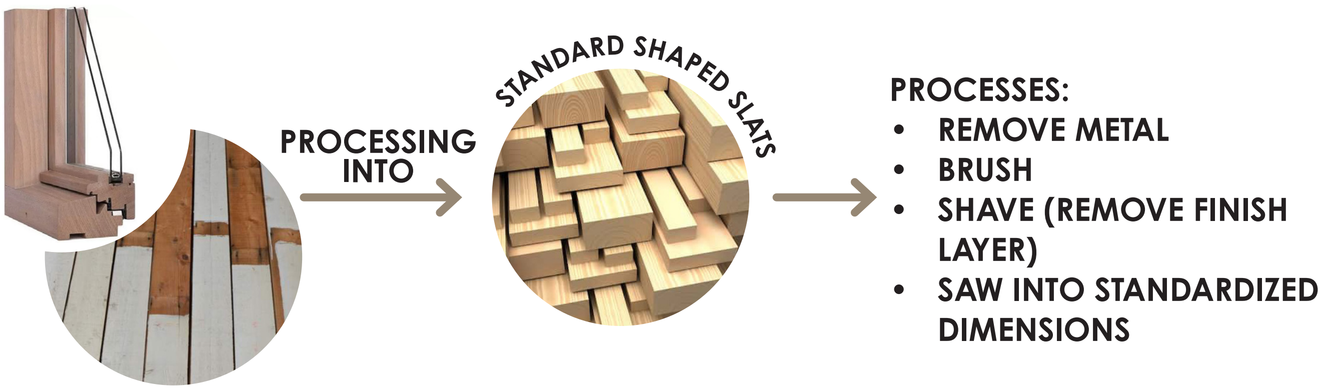


Figure 68 Diagram of processing steps (own image)

Scrap wood is sawn into dimensions, particularly the cross section, that are suitable for remanufacturing scrap wood into building products. These dimensions depend on the dimensions used for the building products and can therefore vary considerably. There are two options. Either the scrap wood is sawn into all kinds of standardised dimensions and then used for building products, or the scrap wood is first sorted according to the future building product and then sawn into the required dimensions. Each of these options has its own advantages and it is likely that both will be used. The cross-section is more important than the length because the length can be extended by finger-jointing, which will be discussed in the next stage. Due to the varying dimensions, this step results in varying standardised dimensions. Manual sawing is too time consuming and should be done mechanically. The machine should then be able to adapt to the varying dimensions.

All waste from the shaving and sawing process can be incinerated. The energy recovered can be used to power the processing hub, so that the hub can run on its own biofuel. Woodjoint already operates on this principle (personal communication, April 5, 2023).

5.3.3.2 Remanufacturing

From the processing stage, scrap wood ends up as wooden blocks and slats with standardised dimensions. In the remanufacturing stage, these elements are remanufactured into either semi-finished or end building products. The type of remanufacturing process depends on the building product. Scrap wood pieces vary in size and may be too short, too small, or both. However, scrap can be elongated by finger-jointing and made thicker and/or wider by lamination. Both options require the use of glue, but the result can be products that are stronger than solid wood.

Finger joint

Finger-jointing is a process in which both ends of wooden elements are sawn into finger-shaped cuts, approximately 10-15 mm deep joints, glued and pushed together, see Figure 69. This connection is stronger than wood itself. Different carpentry factories can produce up to 10 or 12 m long slats/planks (Woodjoint, 2019). Fingerjointing allows different dimensions to be extended as long as the dimensions of the elements that need to be fingerjointed are similar, otherwise too much of the leftover wood needs to be shaved off, resulting in more waste. According to Woodjoint (personal communication, April 5, 2023), the minimum length of a piece of wood is 20 cm. This technique also allows different types of wood to be joined together, such as hardwood and softwood. The resulting components can then be used for timber construction products. For example, longer jointed slats can be used for window frame profiles or as ribs and slats.klasse) C18 - C24. The pieces can also be joined over the width with glue: the lamination process.

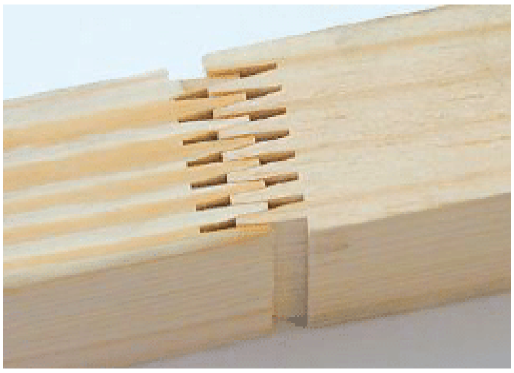


Figure 69 Finger joint (Ding et al., 2020)

Lamination

The lamination process involves gluing layers of wood together in width or height to form panels or beams. These can be used for a wide range of building products such as doors, planks, beams, but also for prefabricated structural elements such as HSB and CLT. Laminated timber is stronger than solid wood, especially when the wood is laminated horizontally, and lighter than similar elements made of concrete and steel. For example, laminated beams are lighter than steel structures. Using the same species of wood in a laminated product is important because each species has different properties and therefore reacts differently to environmental changes, such as the coefficient of thermal expansion. A change in humidity will result in different expansion rates, but if the glue holds everything together, the laminated product will tear. Although lamination limits the natural effects and warping. Finally, laminated wood is more resistant to fire because, in the event of a fire, carbon layers are formed which slow down the ingress of oxygen. This construction therefore retains its rigidity and strength for longer (Woodjoint, 2019). The components produced are used as semi-finished products (e.g. panels) or finished products (e.g. beams).

Figure 70 Laminated wood products (Kallesoe, n.d.)

Finger-jointing and laminating are suitable production techniques that produce larger pieces of wood from all kinds of smaller pieces of wood and gain a lot of strength. These techniques are therefore suitable for converting the various pieces of scrap wood into wood products. The holes in the scrap wood caused by the metal connectors have little effect on the strength of the wood, so this aspect does not affect the reusability (Woodjoint, personal communication, April 5, 2023).

5.3.4 END PRODUCT PHASE

The product phase consists of the production of wood building products and is divided into the semi-finished and end product phases. From the remanufacturing phase, wooden elements are produced that are either already end products or semi-finished products that still need to be manufactured into end products. Production from the remanufacturing stage to the semi-finished and finished product stages takes place either in the same factory or in separate factories producing their own wood building products.

5.3.4.1 Semi finished products

The semi-finished products are either rectangular or square profile lamellas or laminated panels. For the production of building products, these elements require further steps that include processing specific to the final building product. These processes include sawing wood to specific dimensions, profiles and cut-outs. For example, wooden slats for window frames need to be sawn into different types of profiles. Beams, planks and ribs & slats may be finished products after the reconditioning phase, but they may also require some re-sizing and reshaping. For example, some products aren't perfectly rectangular, but are slanted, or have a tongue and groove or other wood joint, see Figure X. Some products require a finishing layer, such as a coat of paint or varnish, for protection or aesthetic reasons. After this stage, the semi-finished products become finished products. The production of finished products can occur at the processing hub, but is most likely done by the companies themselves, as most companies use specific dimensions and/or shapes and therefore have their own woodworking factories.

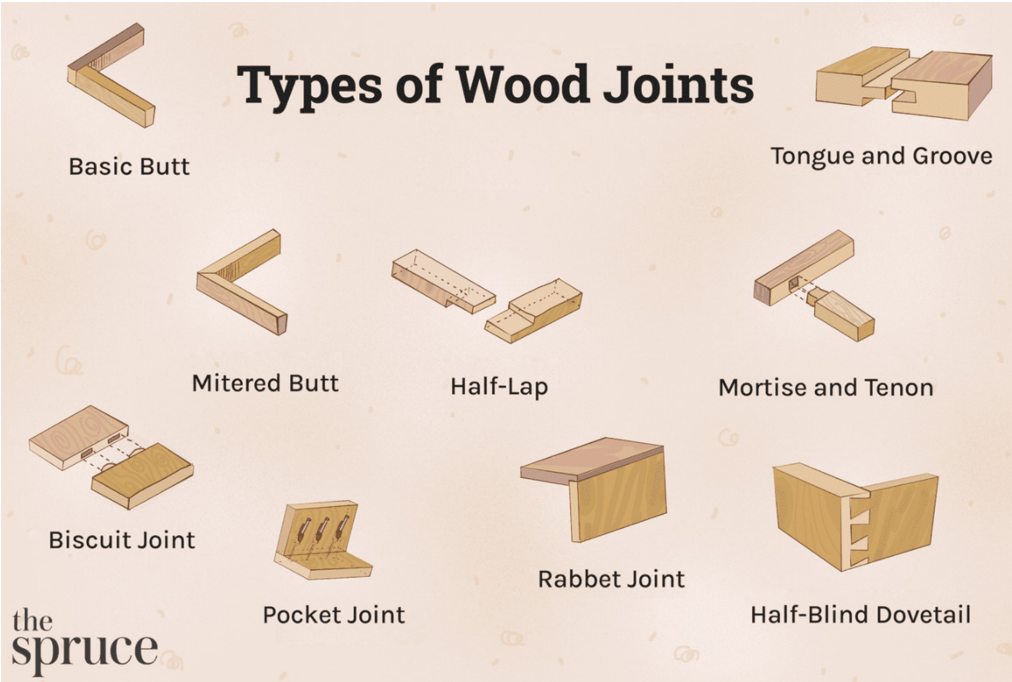


Figure 71 Types of wood joints (Sanders, 2022)

The problems that arise at this stage for scrap wood are mostly due to the varying consistency of scrap wood. For certain building products, the required dimensions and/or quantity of scrap may not be available. However, this problem can be solved by mixing scrap and virgin wood in a building product.

5.3.4.2 End product

The final stage is the end product process. At this stage, scrap wood pieces are remanufactured into building products such as planks, window (frames), door (frames), ribs & slats, HSB, CLT or other structural elements, or any other product used in the built environment. The end products can be sold and used in the built environment. The issue at this stage is price competition with virgin wood products. The process of remanufacturing scrap wood should result in a price similar to that of virgin wood in order to make a profit. Although customers may be more willing to pay a higher price because of the sustainable stamp of reused materials in a product, the products should still be affordable in order to be able to reuse scrap on a large scale. The price of wood rose sharply during the pandemic, but prices are now falling, see appendix 6. Virgin wood in the C&D industry is now around 450-490 euro/m3, but this varies between species. If the cost of reprocessing waste wood remains below the price of virgin wood, customers are more likely to choose scrap wood over virgin wood. The cost of remanufacturing waste wood does not include harvesting and transport to the Netherlands, but consists of high labour costs due to the time consuming process. The cost of remanufacturing scrap wood does not include harvesting and transport to the Netherlands, but consists of high labour costs due to the time consuming process. A diagram of possible routes for scrap wood during the chain is shown in fiugre 72. In appendix 7 this diagram is expanded with examples.

Note: This whole chain focuses on the reprocessing of scrap wood into building products, but this process is not necessarily linked to the built environment. This process can also be applied to other industries, such as the furniture industry.

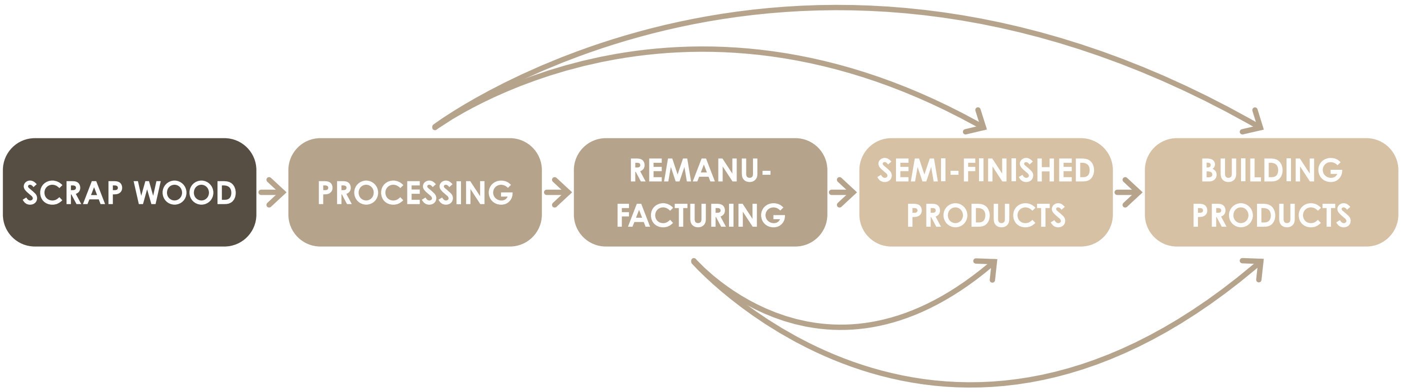


Figure 72 Diagram of processing scrap wood into building products (own image)

5.3.5 PROBLEMS IN THE CHAIN

5.3.5.1 Barriers

In conclusion, most barriers for reusing scrap wood occur at the beginning of the chain in the (post-) demolition phase and in the processing stage.

The barriers are:

- Time consuming process
- Varying consistency
- Money
    - High labour costs
    - Competing with virgin wood in price
- Lack of specific grading rules for scrap wood
- Uncertainty of supply (further explained in 5.4)

The biggest obstacle is the time consuming process, which results in high labour costs, as the consistency of scrap wood varies widely and most processes are manually performed. The time-consuming process occurs at the demolition, collection, sorting and processing stages. This is because all materials must be carefully removed from a building to minimise damage and mixing of materials. Sorting is time consuming because of the different consistencies and the lack of rapid sorting and identification machines, while identification of species (and mechanical properties) is important for use in (certain) building products. Other time-consuming processes are those used to transform scrap wood into remanufacturable parts, such as the removal of metal, cleaning and the removal of a surface layer.

Although re-use is the most circular option, remanufacturing is also an option, especially for loose, broken and/or damaged pieces. The remanufacturing processes of finger-jointing and laminating can produce larger pieces of wood with stronger joints than the wood itself. These pieces can then be used in various building products such as window frames, structural elements, ribs & slats, doors, planks, panelling, flooring, etc. After processing, scrap wood is standardised blocks or slats that can be easily converted into semi-finished and finished products, as most mechanical properties do not degrade over time. So the only barriers after the processing stage are the uncertainty of having enough of the same scrap wood due to varying consistency and the need to make a profit.

5.3.5.2 Solutions

The actions required in the reuse chain require certain methods and techniques to accelerate the whole process. A possible solution to the problems at the beginning of the reuse chain is a processing hub where scrap wood is collected, sorted, processed and possibly remanufactured into semi-finished products, see figure 73 (and a bigger image in appendix 8). These products can then be sold to building product companies to be manufactured into building products. Although the scrap wood will be sorted at the processing hub, it should also be thoroughly sorted at the demolition site in accordance with the r-strategies to minimise unnecessary transport from the processing hub to waste management facilities or resellers of scrap wood products. Transport is a major contributor to carbon emissions, so the distance and number of journeys must be minimised.

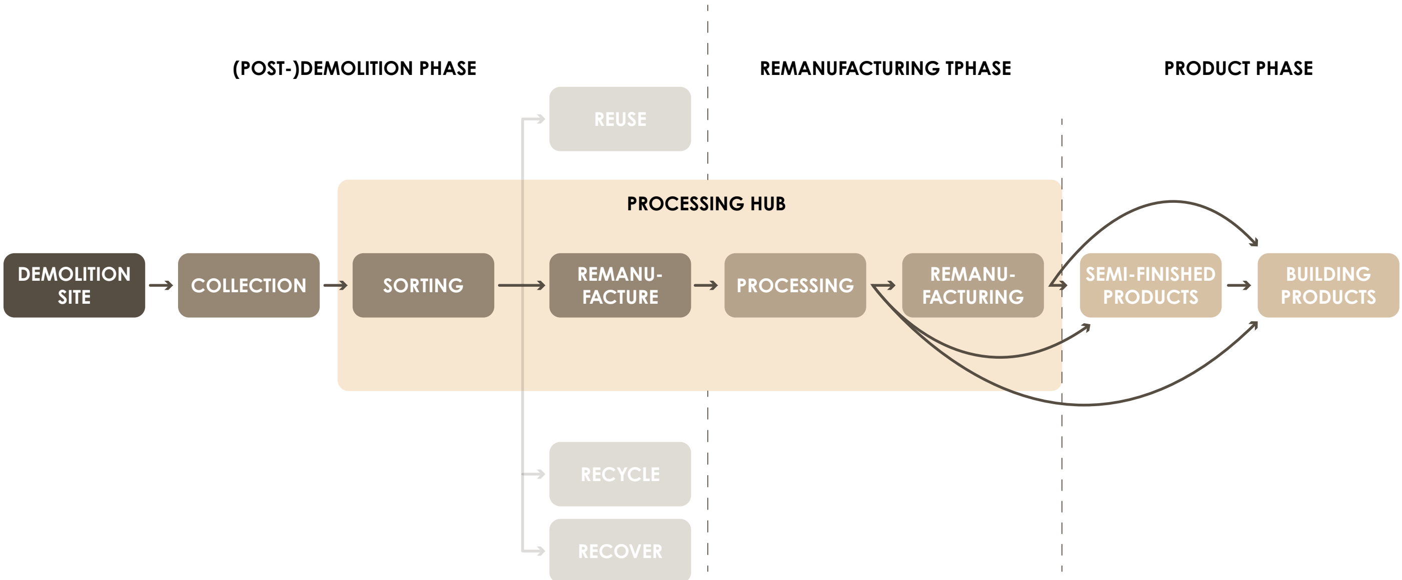


Figure 73 Diagram of processing hub (own image)

6

BARRIERS & IDEAS

This chapter discusses the barriers to the reuse of scrap wood. Some of the barriers are already mentioned in section 5.3.5 above, relating to the reuse chain. But there are also other barriers, which are added below. Then some possible ideas for overcoming these barriers are discussed.

6.1 BARRIERS

The literature review shows that there are several barriers to the reuse of scrap wood in building products. Some barriers are related to the different aspects of wood, some are related to the aspects of scrap wood and some are related to the reuse process. Each barrier requires a solution to encourage/promote the reuse of scrap wood, but some barriers have a greater impact or are more important than others. Therefore, the barriers are discussed below in order from the most influential barrier to the least influential barrier.

6.1.1 PROFIT & COST

Profit & cost, in other words money, is the biggest barrier to the lack of reuse of scrap wood. This barrier has already been partially mentioned in the reuse chain, but is further explained here. Profitability is an important factor in ensuring the start-up of processing hubs. Without the possibility of making a profit, such processing hubs will not be developed. This means that the processes of sorting, identification, testing and processing must be accelerated by mechanical processes so that labour costs can be reduced.
The price of scrap wood from a demolition site must be low so that the processing hubs can collect scrap wood at a low price. This is feasible because it costs demolition companies money to dispose of scrap wood in landfills. Disposal costs vary from province to province in the Netherlands. For example, individuals in Delft are charged €185 per ton of C&D waste by Avalex (Avalex, n.d.), but demolition companies probably have a cheaper price per ton, but this information could not be found. Demolition companies are therefore more likely to sell scrap wood to processing hubs than to pay for disposal.

Certain types of scrap wood have a higher demand than others because of their properties. Higher demand makes it more likely that these products and pieces will be sold (Sloopcheck, 2021). For example, there is a bias between types of wood. Older wood, which contains more heartwood than younger wood, is more likely to be reused because of its strength, resistance to decay and durability. In today's forest production, there is little heartwood and most of the wood is sapwood, which is not as strong. Hardwood is more popular than sapwood because of its strength and durability, especially for outdoor purposes (Huuhka, 2018; Icibaci, 2019).

Lastly, the reuse of wood has to compete with incineration for energy recovery and recycling. These products are currently more profitable due to a higher market value and a less time-consuming process. In order to build a well-functioning reuse industry, the reused products should be at least as profitable as the competition (Bruggen & Zwaag, 2017; Icibaci, 2019). The costs can also be partly covered by government subsidies, so that the price of scrap wood products can be similar to that of virgin wood products.

This barrier is not only a barrier in itself, but is also closely related to the other barriers. These are discussed below. In short, in order to sustain a reuse industry, each link must be profitable.

Therefore, the cost of the process must be lower than the price at which the products can be sold. And that price competes with the price of incineration, recycling and products made from virgin wood or other materials.

6.1.2 TIME CONSUMING PROCESS

Another barrier is the time-consuming process already discussed in 5.3.5. The problem is mainly at the beginning of the whole reuse process: collecting, sorting and processing the scrap wood before it can be reused in (building) products. There is a lack of mechanical machines for sorting and grading that can reduce the time required for this process. The time consuming processes result in higher costs, especially labour costs, as most of the work is done by hand. The high costs result either in products with a much higher price than competing products and/or in products without a possible profit margin.

6.1.3 LACK OF MECHANICAL PROCESSES

There is a lack of rapid mechanical methods for identifying wood species, sorting scrap wood and grading according to characteristics. Existing methods are labour intensive as each piece must be identified and tested separately, either visually by an expert or mechanically in a laboratory, resulting in high costs and more scrap wood being rejected.

6.1.4 IDENTIFICATION OF WOOD SPECIES

The identification of wood species can be hard. There are many species, although the portion that is commonly used in the built environment is smaller. Scrap wood can contain finish layers that make identification harder. Identification is mostly done visually but is less accurate than under a microscope, only this is a time consuming and expensive process. For certain building products, the use of the same species or combinations of species is important because of the different properties of each species and therefore identification is important.

6.1.5 UNCERTAINTY OF SUPPLY STREAM

The supply of scrap wood is not a constant stream, as is the case with virgin wood. The supply of scrap wood comes in large quantities at peak times. The supply comes from the (circular) demolition of buildings, this does not happen gradually and constantly, but from time to time. The quantity and quality of scrap wood varies from one demolition site to another, because each building differs in quantity and quality of wood, wood species and dimensions, due to differences in size, year of construction and materials used. In addition, at each demolition site, a certain amount of wood is too damaged or deteriorated. The consistency of the scrap wood from a demolition case is therefore unknown until the demolition is complete. For example, Rik Ruigrok from Herso (personal communication, March 16, 2023) said that there was sometimes a big difference between what he was told he would get from a demolition site and what he actually got. The usable quantity was usually much smaller, and the dimensions sometimes smaller, due to breakage and damage during the demolition process. So the supply of scrap wood is uncertain, which is another barrier, but the wood that is available is mostly reusable or remanufacturable.

6.1.6 VARYING CONSISTENCY

Every building is different and therefore the consistency of scrap varies greatly. Scrap wood consists of a wide variety of dimensions, qualities, species and mechanical properties. This results in a time-consuming process of sorting, identifying and testing scrap wood, which in turn results in higher costs. This, combined with the uncertain supply stream, also means that certain species and/or dimensions may not be available at any given time. The uncertain supply stream also makes it almost impossible to know when this scrap wood will be available.

6.1.7 LEGISLATION

Wood building products must meet certain performance requirements (Huuhka, 2018). As mentioned above, there is a lack of specific grading rules for the reuse of scrap wood. There is also a lack of legislation on liability and warranty for the reuse of scrap wood. As a result, there is too much uncertainty surrounding scrap wood. In the case of malfunction or, for example, flooding, some insurance companies do not consider these products valuable and refuse to pay compensation (Gemax B.V., 2020). This makes people more reluctant to use scrap wood (Huuhka, 2018; Sloopcheck, 2022). Products made from reused wood don't necessarily come with a guarantee, whereas new products do.

6.1.8 SUSTAINABILITY

Lastly, sustainability in itself is not a barrier, but rather the question of whether it is worthwhile to reuse scrap wood. The process of reusing scrap wood should be more sustainable than other circular processes for scrap wood. Reusing scrap wood extends the sequestration of CO2 in the wood, but the processes needed to reuse scrap wood should not emit more than is sequestered or emitted by other circular processes.

6.2 POSSIBLE IDEAS

In order to make reusing scrap wood a common practice solutions need to be found for the barriers. Some possible ideas on how to solve the mentioned barriers mentioned are discussed below. The solutions are not necessarily the only solution, but the solution give an idea on what the possibilities are.

6.2.1 PROFIT & COST

The biggest barrier is money, divided into profit & cost. Without the chance of reusing scrap wood being profitable, companies are not motivated to begin that process. Solutions for this barrier contain solutions for "cost" and "profit", separately and overlapping. Some solutions are also applicable for other barriers.

The time consuming process has a large impact on the barrier costs, because the manual labour results in high labour costs. There is a lack of mechanical processes that can quicken the process. Therefore the solution to reduce labour costs is develop those mechanical processes to reduce the time to sort, identify and test. Lower costs results in the possibility to make a (higher) profit.

Demounting materials from a building during circular demolition is also a time consuming process and therefore also results in higher (labour) costs. The demolition contractor goes mostly for the cheapest option, and will therefore choose traditional demolition over circular demolition. To solve this issue, circular demolition and dividing all the materials at the demolition process should be a requirement by law, so the contractor is forced to go this route, and they also should be accountable for the costs, not the demolition companies. The sustainable route takes more time and can have higher costs (at the beginning, but eventually, when the sustainable route becomes the "new normal" or the standard option people will get used to the higher prices.

Another consequence of the rise in demolition costs is that the decision of demolishing a building would be more carefully considered. Maybe, instead of demolishing a building it can better be renovated, in terms of costs. Demolition has a higher impact on the environment than renovation, because all the CO2 that was needed to produce the materials and construct the building would be lost instead of saved.

In terms of profit, a solution is granting subsidies for the reuse of scrap wood, so the price of scrap wood products can compete with other circular strategies and virgin wood products.

6.2.2 TIME CONSUMING PROCESS

The time consuming process of collection, sorting and processing scrap wood needs to decrease. There are multiple solutions to decrease time consuming process. The collection process during demolition will be elongated but will result in an overall decrease of time. If scrap wood is carefully collected from a building and already separated from other materials, such as metal connectors, more clean and whole scrap wood will be available. This will result in a shorter processing stage, because less metal and other materials, and less damaged parts have to be removed.

When scrap wood is already thoroughly sorted at the demolition site by circular strategies and aspects, the sorting at other locations will be easier. When the wood species of a product of a building is known, probably the other similar product have the same wood species, therefore less scrap wood has the identified by wood species.
After sorting at the demolition site the remanufacturable scrap wood could go to a processing hub, where the scrap will be processed into remanufacturable pieces, as mentioned in 5.3.5.Also, as mentioned in the solution for profit & cost, the development of mechanical processes for identifying, sorting and testing can quicken the whole process and decreasing the labour costs.

6.2.3 LACK OF MECHANICAL PROCESSES

Another barrier is the lack of mechanical processes to sort, identify and test scrap wood. As previously mentioned, these mechanical processes need to be developed to quicken the process. For these one or separate machines can probably be developed. Although the machines will probably require some investment that needs to be earned back. Testing scrap wood on mechanical properties happens for every individual piece manually or mechanically and is a time consuming process. A solution is using scrap wood in products where the mechanical properties matter less. The mechanical properties matter less in non-load bearing constructions and wall and ceiling panelling and floors.

6.2.4 IDENTIFICATION OF WOOD SPECIES

The identification of wood species is important because certain wooden building products rely on the use of specific wood types or species and in certain products the same wood species need to be used throughout the whole product. There are a few possible solutions that can help the reuse of scrap wood in terms of identification.

For building products where the wood type and/or species matters, every scrap wood piece needs to be identified. The identification can either happen at the demolition site or at a processing facility. The former location is better as was mentioned in 6.1.2, because throughout a building the same wood species is probably used for the same building products. The identification is mostly done visually and can be done through a microscope, but a possible quicker option would be a machine that can mechanically identify the wood species of the scrap wood pieces and sort them.

Another suggestion is using scrap wood in products where the wood specie matter less. Then the scrap wood does not have to be identified and/or tested, which also quickens the process. At the moment this happens for the recycling of scrap wood, where shredded scrap wood of mixed wood species are manufactured into OSB board and chipboard.

6.2.5 UNCERTAINTY SUPPLY

The uncertainty of the supply stream of scrap wood is a barrier that can't be solved in the sense that the supply stream can become certain. The solutions are more based on handling the uncertainty.

This uncertainty of the supply stream become an issue when companies rely on the scrap wood stream. The uncertainty in the supply stream makes it hard for the companies to have an indication of possible profit and accepting assignment. So, therefore it would be better if companies not only use scrap wood but also virgin wood. The scrap wood content in products would then be a certain percentage depending on the availability of scrap wood, for example a CLT panel can consist of 50% scrap wood and 50% virgin wood.

In the current society sustainability is becoming more and more a "popular" and common practice. Buildings and other products can try to get sustainable labels to prove they are sustainable. Sometimes, this will result in trying to do everything to get a label instead of trying to be sustainable as possible. The issue with creating products that are part scrap wood and part virgin wood is that some clients don't want those products because it sounds less sustainable than 100% scrap wood products. So those combined products are less likely to be bought. But when not enough scrap wood is available, this becomes an issue because 100% scrap wood products can not be produced. This is a mindset issue. One should not require fully reused products to get a sustainable label but they should see what's available and try to make a sustainable product. In short, it should not be focussed on labels but on actual sustainability.

6.2.6 VARYING CONSISTENCY

The barrier of the varying consistency can also be seen as a possibility, because the different available scrap wood species can be used in many different products. All products also require different dimensions, quality and wood species. The scrap wood then needs to be sorted as thoroughly as possible. Research can be done about mixing certain wood species in building products, so the varying consistency can be less thoroughly sorted. These building products from scrap wood needs to be developed and tested.

A problem with the wide variety is the sorting process, because it can be sorted by either one aspect or more. For example, scrap wood can be sorted only by wood species, or by wood species and dimensions or also by quality. A sorting system needs to be developed to maximize the reuse possibilities of the varying scrap wood consistency. This sorting system can differ, depending on which products are more manufactured. Mechanical sorting machines could quicken the whole process.

6.2.7 LEGISLATION

One of the biggest barriers that needs to be fixed by the government is legislation. The lack of legislation specifically for the reuse of materials un-motivates companies to start reusing materials. The lack of rules and grading tests results in more scrap wood being rejected for reuse and lack of development and examples in how scrap wood can be reused. The current legislation for building products only use virgin wood. So, in terms of legislation is developing grading tests for the of scrap wood and laws about warranties and who is responsible.

6.2.8 SUSTAINABILITY

Lastly, one solution for sustainability is decreasing the transport distance and amount of different routes, because transport is a large contributor to carbon emissions emitted by wood. Virgin wood is transported from other countries and scrap wood locally, so the transport distance is already much shorter. The development of processing hubs spread throughout the Netherlands can also reduce transport distance, because multiple processes happen at the processing hub.

6.2.9 DIVISION OF SOLUTIONS IN THE REUSE CHAIN

Most barriers have solutions with the highest impact at the beginning of the chain, at the demolition phase. Other solutions have an impact on the whole process. The barriers with their solutions can be separated into two categories:

1. Barriers that can be solved by development of methods, legislation and/or machines
2. Barriers that can have multiple solutions within the reuse of scrap wood as a building product

The first type of solution consists of the barriers: time consuming process, lack of mechanical processes, difficulty of wood identification, legislation and lastly lack of storage. The general solution is developing a step, a link in the reuse chain where all the scrap wood is gathered. This step will be placed after the demolition phase. For this link new mechanical methods and machines have to be developed to not only quicken and simplify the whole process but also to motivate companies to start adding the reuse of scrap wood and other materials into their production processes. Legislation should provide laws that also motivate companies and ensure that certain things need to happen.

The second type of solutions have to do with how the scrap wood is handled to maximize the reuse and remanufacturing of scrap wood. Under this type the barriers uncertainty of supply and wide variation apply, or in other words the uncertain supply stream of a wide varying amount of wood. For all the variations in and differences between the scrap wood other solutions apply. For example, high quality scrap wood can be used for high quality products or visible products. Strong scrap wood can be used for load-bearing products while weak scrap can better be used for non load-bearing products. When the sorting is hard or impossible, the scrap wood can better stay mixed an shredded for recycling. Some scrap can be used for building products, other are better other products. The different solutions apply for different aspects. There needs to become a system where and how is decided how the scrap wood is used and sorted. There is some hierarchy: scrap wood products that can be reused should reused. Scrap wood that still has usable dimensions and is in a good enough quality should be remanufactured into new building products. If that’s not possible the scrap wood might be suitable for other products. Only when those options aren’t optional the scrap wood can be recycled and shredded for OSB board. Lastly, what’s left can be used for incineration.

7

CASE STUDY CLT

The previous chapters have provided an insight into scrap wood and why scrap wood pieces (and products) are not commonly reused. This chapter discusses the incorporation of scrap wood into building products through a case study: CLT. Firstly, some background information on CLT is discussed and then why CLT was chosen as a case study. In the third and fourth paragraphs, the manufacturing process of CLT from virgin wood and its mechanical properties are discussed in order to identify some important factors for the production of CLT from scrap wood. These factors and six scenarios of CLT panels with varying levels of scrap wood content are discussed in the fifth section. Next, the sustainable impact of replacing virgin wood with scrap wood in a CLT is discussed through calculations of carbon emission savings using the example of a terraced house. Finally, it discusses the sustainable benefits of using scrap wood and whether it is worth doing.

7.1 WHAT IS CLT?

CLT is a structural wood building product that is mainly used for walls, floors and roofs in houses, apartment buildings, high-rise buildings, schools, halls, sports arenas, etc. Gustafsson et al. (2019) explain the basics of CLT in 'The CLT handbook', and this information was used in this case study. CLT consists of an uneven number of layers glued perpendicular to each other. The most common number of layers is 3, 5 and 7, but there can be up to 25 layers. A layer consists of several planks or lamellas of varying widths between 40 and 300 mm and equal thickness per layer, mostly varying between 20 and 60 mm (up to 80 mm), resulting in a total thickness between 60 and 540 mm and varying widths, see Figure 74. The lamellas are elongated by finger-jointing shorter planks. Although the thickness of each layer can vary, the cross-section of CLT is usually symmetrical, see Figure X. This is important to prevent the risk of moisture movement and deformation. Appendix 9 shows some commonly used thicknesses for 3 and 5 layers respectively. As can be seen, the different thicknesses per layer are still symmetrical across the panel.

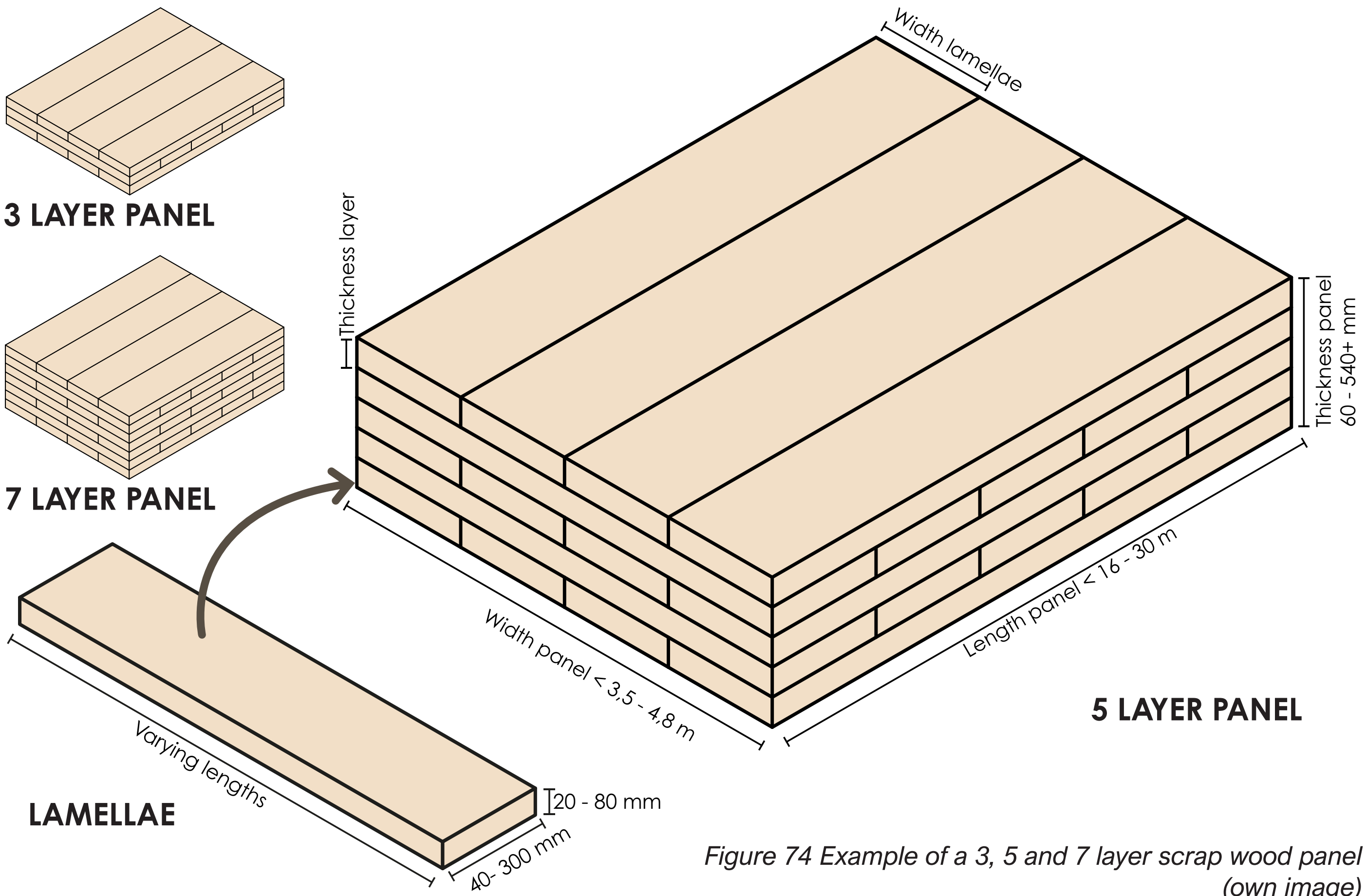


Figure 74 Example of a 3, 5 and 7 layer scrap wood panel (own image)

CLT is usually made from softwood species such as spruce or pine, but other softwood and hardwood species are also possible. CLT panels are prefabricated in accordance with the NEN-EN-16351 standard. The most common dimensions are 16 m x 3.5 m, but they can be up to 30 m x 4.8 m, depending on the manufacturer and transport possibilities (Gustafsson et al., 2019).

CLT is a relatively new construction method, first produced in Austria in the 1990s, but it is gaining popularity due to the use of the renewable material wood, its lightweight construction, prefabrication and easy, fast, dry, clean and silent on-site assembly. A CLT structure (+/- 470 kg/m3) is about 5 times lighter than a concrete structure (+/- 2700 kg/m3) for a similar load-bearing capacity (Vos et al., 2021). The large panels with perpendicular layers result in stiff panels that are good for the stability of a building, have a high load-bearing capacity and are easier to transport and assemble into the building than concrete and steel. During prefabrication, the panels can be customised, with holes for windows, doors and plumbing cut out using a CNC machine. This process increases the flexibility of the design, reduces the construction time on site and creates less noise and dust (Gustafsson et al., 2019).

In addition to these advantages of CLT, it also has some sustainable advantages, mainly due to the use of wood. CLT has quite good reusability due to dry joints. CLT is (part of) the construction of a building which has a lifespan of 20-75+ years. After the first life cycle, the CLT construction can be reused, extending the life of the CLT by another 20-75 years. The CLT can sometimes be reused again or otherwise recycled into products such as OSB or particleboard, adding another life cycle (Brandner et al., 2016; Gustafsson et al., 2019). Over its lifetime, CLT stores CO2 in the wood, approximately 0.9 tonnes CO2/m3 of softwood (Vos et al., 2021). In the meantime, more trees have grown back than were harvested, resulting in a possible negative CO2 impact. Finally, energy can be recovered from the CLT panels through incineration, releasing the sequestered CO2 (Brandner et al., 2016; Gustafsson et al., 2019).

Glue content

A CLT panel consists of +/- 1% glue. The glue connects the perpendicular layers to each other and to the lamellae in the longitudinal direction by finger-joints. Some manufacturers also glue the edges of the lamellas to increase the rolling shear strength, which results in a higher glue content. This is most commonly done in flooring panels where high rolling shear strength is essential. The glue is not a sustainable component of CLT as it is not renewable and reusable. Although CLT can be reused several times and then recycled into OSB or particleboard, the glue also ensures that the layers cannot be taken apart. The most commonly used glues today are MUF (melamine formaldehyde) and PUR (polyurethane). MUF contains formaldehyde, a material that is harmful to health when used in large quantities, so the use and handling of this glue is strictly regulated. PUR is the most commonly used glue for CLT and does not contain formaldehyde. So the glue itself is not bad for the environment (Klaassen & Kloppenburg, 2021; Van Der Lugt, 2021). There is also CLT without glue, where the layers are bonded with wooden dowels and is actually called Dowel Laminated Timber (DLT) (De Vree, n.d.).When hardwood species are used, a different type of glue is needed because hardwood species react differently to glue. This also applies to gluing hardwood to softwood (Gustafsson et al., 2019).

MPG

CLT scores relatively well in the MPG due to the use of wood. However, as discussed in 2.3, the MPG does not take into account the temporary CO2 sequestration capacity of wood, and CLT is assumed to be incinerated at the end of its life cycle rather than reused, so the MPG of CLT can be higher than for a concrete building, see Figure 19 on page 24X. CLT performs much better when CO2 sequestration is considered, and may even have a negative CO2 impact during the use phase, as CLT contains a lot of wood and therefore stores a lot of CO2. The production of CLT produces much less CO2 than is stored.

Figure 75 shows an example of an MPG calculation for CLT compared to concrete, taking into account temporary CO2 sequestration. The figure shows the CO2 emissions /m3 over different life stages of CLT. As can be seen, CLT still has a negative impact on CO2 emissions at the end of its life cycle. This occurs when incineration is used as an energy recovery that replaces the use of fossil fuels, resulting in overall lower CO2 emissions because sequestered CO2 is emitted instead of more CO2 from those fossil fuels (Van Der Lugt, 2021). Concrete only contributes to CO2 emissions because it is a non-sequestering product.

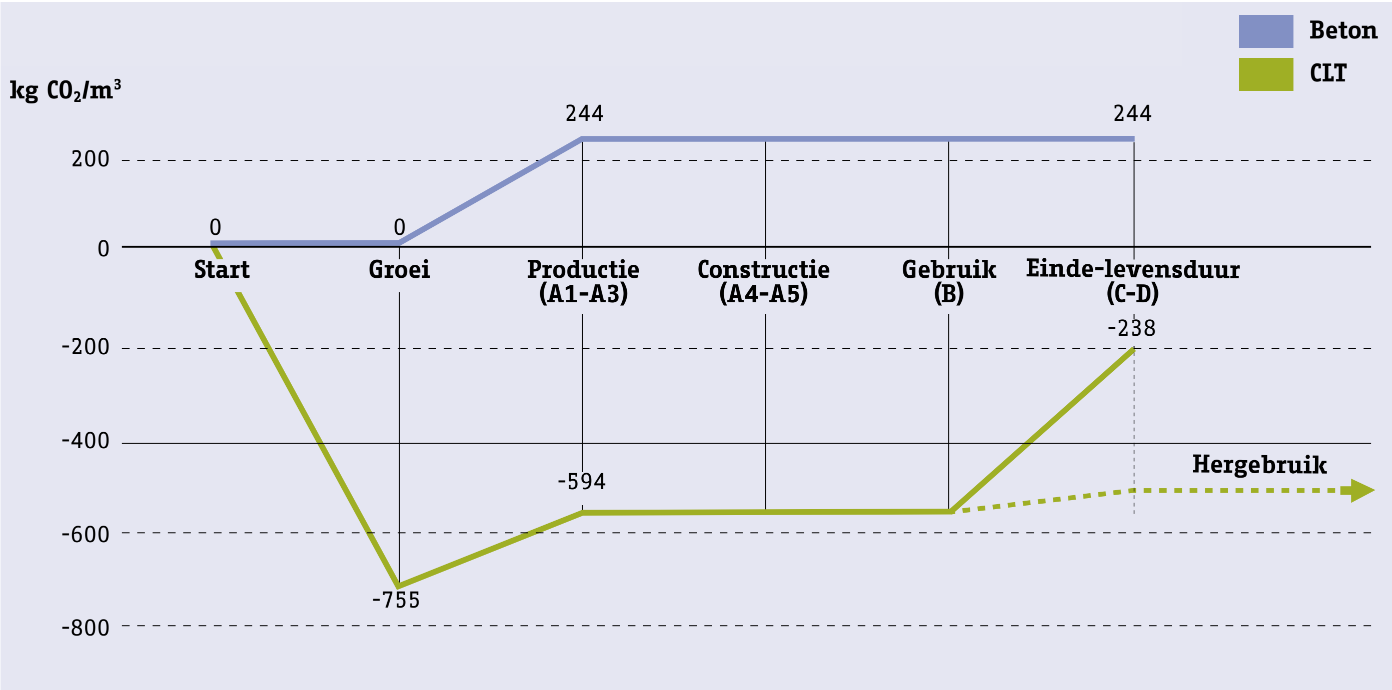


Figure 75 MPG comparison of concrete and CLT with temporary CO2 sequestration (Van Der Lugt, 2021c)

So CLT is a building product that can replace concrete and steel structures, with some advantages in terms of CO2 emissions, weight, production, transport and manufacturing. The use of quite a lot of the renewable material wood and the ability to cascade CLT over a number of life cycles, thus extending the life span, results in long and high CO2 sequestration, making CLT quite sustainable, except for the glue content. CLT can therefore contribute to the goals of circularity and sustainability.

CLT can vary in width, thickness and length of the lamellae and panels. Although spruce is the most commonly used species, other species can also be used. These aspects result in the possibility of using different pieces of wood in CLT.

7.2 REASONS TO INTRODUCE SCRAP WOOD INTO CLT

The variety of wood pieces and the possibility of using different types of wood in CLT is one of the reasons why scrap wood may be suitable for use in CLT. Scrap wood consists of all kinds of dimensions from different species. All dimensions of a CLT lamina can vary: width, length and thickness, even between the lamina in one layer, except thickness. This can only vary between different layers as long as the cross section remains symmetrical. So the different pieces of scrap wood can be used together as lamellas.

Another reason is the long life of CLT and the ability to reuse and recycle CLT. The lifespan of the wood can therefore be extended, delaying the emission of the sequestered CO2. CLT also contains a lot of wood, so a lot of scrap wood can be used and a lot of CO2 can be sequestered in CLT buildings. It contains the most amount of sequestered CO2 of all wooden construction elements, due to it consisting out of panels instead of columns and beams. Because wood is a sustainable construction material, the demand for timber buildings will increase, so the demand for wood will increase. CLT is therefore a popular and thus a higher price ca be demanded, resulting in the possibility to make CLT panels from scrap wood possible, when the costs for processing stays high. Scrap wood can also partly cover this increase in demand.

7.3 MANUFACTURING OF CLT

CLT consists of an uneven number of layers glued perpendicularly to each other in custom sizes. In Europe, the production of CLT must follow the EN 16341 standard, which ensures the quality and safety of the CLT panel (production) (Gustafsson et al., 2019). This standard also contains a list of wood species that are currently allowed to be used in CLT (EN-16341, 2021). The manufacturing process is as follows, see also Appendix 10. Timber lamellas are cut from tree trunks at the sawmill, dried and strength graded according to EN 14801-1. The lamellas are sorted according to their thickness. An important factor is the moisture content, which must be similar for adjacent lamellas, with a maximum difference of 5% between lamellas. The moisture content is 12% (+/- 3%). The best moisture level is the equilibrium moisture level of the final location of the CLT, which varies around the world. If there is a difference in the moisture level between the lamellae, there will be different shrinkage or expansion rates, resulting in splitting of the wood (Gustafsson et al., 2019).

At the factory, the lamellas are first elongated by finger-jointing. There are lamellas required for the length (< 30 m) and the width (< 4.8 m) of a panel. Lamellas of similar thickness are then planed on all sides. The lamellas are placed adjacent to each other to form panels. There are two options: edge gluing, where the sides of the lamella are glued to the adjacent lamella, or no edge gluing. The former results in a higher rolling shear strength than the latter, although it requires more glue. The lamellas are covered with a layer of glue and pressed together at an angle of 90 degrees until the required number of layers is achieved. The whole panel is pressed together until the glue has set. There are two types of pressing: vacuum and hydraulic, the former is more consistent but at a lower pressure, the latter is at a higher pressure and consists of hot or cold pressing. Before the panels are transported to the site, a CNC machine is used to cut the necessary holes for windows, doors, installation, pre-drilled holes, joints and fasteners. The machine also cuts a sample to be tested for strength and quality. The construction of CLT panels means that holes can be drilled almost anywhere without compromising strength (Gustafsson et al., 2019).

7.4 MECHANICAL PROPERTIES OF CLT

A CLT panel consists of an uneven number of perpendicularly glued layers. This construction reduces the possibility of overall contraction and expansion, contributes to the load bearing capacity and stresses, and compensates for other properties and variations of the wood. The result is a product with high load-bearing capacity and stiffness (Gustafsson et al., 2019). The outer layers of a panel are called surface layers and are mostly parallel to the main direction of loading. The layers perpendicular to the surface layers are the transverse layers. The layer in the centre is called the middle layer, which can be either a transverse layer in a panel with 3, 7, 11, etc. layers, or a load-bearing layer in a panel with 5, 9, 13, etc. layers. Each lamina has a certain width and thickness, with the same thickness per layer, see Figure 76. The width of the lamina is not important for the load-bearing capacity, but for ease of manufacture it is usually the same width throughout the panel.

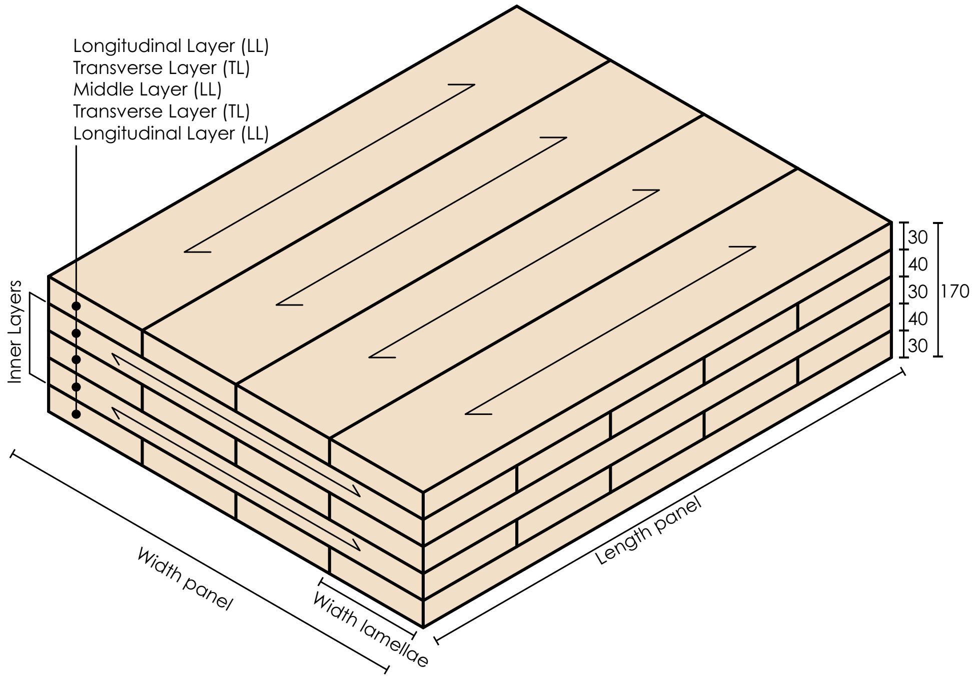


Figure 76 Consistency of a CLT panel (own image)

7.4.1 STRESSES IN A PANEL

A CLT panel can be load-bearing in one or more directions. A CLT panel can take higher loads perpendicular to the main direction of load than loads in the main direction where the panel is less stiff. The load bearing layers and are parallel to the main direction of load and must be strong enough to carry the load, which is indicated by the strength class. The strength class and dimensions influence the stiffness of the panel.

The transverse layers do not carry the load and can therefore have a lower strength, but are crucial for deformation and stress calculations. The surface layers are most sensitive to tensile strength and the transverse layers to rolling shear strength (Gustafsson et al., 2019).

In a panel with a load in one direction, the surface layers are parallel to the load. An example is a wall with a vertical load, so the load is parallel to the CLT panel and therefore the panel is loaded in plane. The load causes stresses in the CLT panel, with the highest stresses in the surface layers. The surface layers must therefore have the highest strength. Towards the middle, each subsequent parallel layer has less stress and can therefore be less strong, especially in the middle layer (Gustafsson et al., 2019), see Figure 77. A CLT wall does not necessarily have to be load-bearing, but can also function as an (internal) partition. In this case, the strength of the layers is less important.

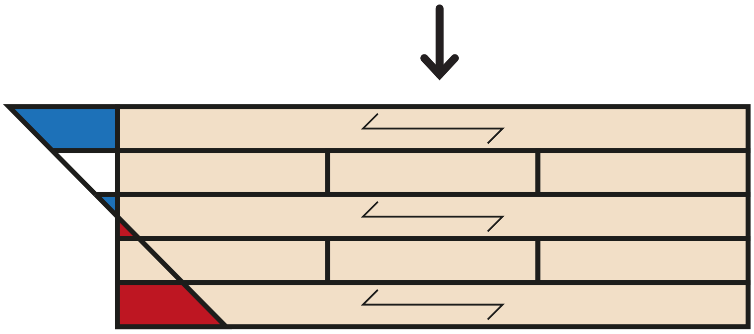


Figure 77 Stresses in a CLT panel loaded in plane (own image)

The rolling shear strength of the transverse layers is the main contributor to the shear capacity of floors and roofs. A floor takes vertical loads perpendicular to the slab, such as self-weight, imposed load and sometimes snow load, and horizontal loads, such as wind load, and transfers these loads to the supports, which may be a load-bearing wall or columns. Thus, a floor (or roof) is loaded out of plane (Gustafsson et al., 2019).

The thickness and strength of the lamellae affect the load distribution. In a floor slab, the main load is not parallel to the slab, so the surface layers are mostly parallel to the span direction of the floor slab and, together with the parallel layers, have lamellae with the highest strength class. Instead of bending stress, deflection or vibration are the most important values to consider (Gustafsson et al., 2019). The out-of-plane load causes a higher risk of shear failure (Brandner et al., 2016). Therefore, the rolling shear strength of the transverse layers is more important in a floor slab than in a wall. To ensure a higher rolling shear strength, a certain ratio between the width and thickness of a lamella is required: width ≥ 4 * thickness (Brandner et al., 2016), for example, a lamella with a thickness of 20 mm must have a width of at least 80 mm. As mentioned in the manufacturing phase, the lamellas can be edge glued, which increases the rolling shear strength. Tongue and groove joints contribute to the risk of shear failure (Gustafsson et al., 2019).

7.4.2 OTHER MATERIALS IN CLT

According to Brandner et al. (2016), one of these layers could also be substituted with other wood-based panels such as OSB (oriented strand board), plywood, LVL (laminated veneer lumber) or multilayer solid wood panels, but then the panel needs to be tested for its properties. Hardwood layers could also be used to improve the mechanical properties of CLT. A hardwood layer, e.g. of birch, poplar or ash, is stiffer and improves the bending stiffness through the transverse layers (shear) or the surface layers (Brandner, 2013), but a different glue has to be used.

7.4.3 STRENGTH CLASS

The lamellas must have a certain strength class, especially the load-bearing layers, to be able to carry the load. The strength class varies between C14-C30, graded according to the standard NEN-EN 14081-1 (Gustafsson et al., 2019). In NEN-EN 338 (2016) the different strength classes for structural timber are shown together with the properties for each strength class. In NEN-EN 1912 (2012) there is a table with the species that can be used per strength class. Most hardwood species have a much higher strength class than softwood species (NEN-EN 338, 2016). C24 is most commonly used in a homogeneous CLT panel. The species that can have a C24 strength class are: spruce, fir, pine, Douglas fir, poplar and larch. In combined layup panels, the panels parallel to the load are C24 timber boards and the transverse layers can be C16/C18 (Brandner et al., 2016) or C30 for the surface layers and C14 for the transverse layers (Gustafsson et al., 2019). The surface layers in panels loaded in one plane may have a higher strength class than other parallel layers. During the manufacturing process, therefore, several panels with different strength classes and/or thicknesses are produced and stacked on top of each other. The properties of a CLT panel depend on the number of layers and their strength classes and thicknesses.

7.4.4 OTHER MECHANICAL PROPERTIES

In addition to its load-bearing capacity and low weight, CLT has a relatively good thermal conductivity compared to concrete and steel: an average of 0.12 - 0.13 W/(m °K), depending on the type of wood used. CLT can be considered as a solid wood with small temperature variations. The thermal capacity is 1600 J/(kg °K) (Gustafsson et al., 2019).

In terms of fire safety, CLT is fairly fire resistant. It is flammable, but it takes some time to ignite and then burns slowly at a rate of 0.6 - 1.1 mm/minute. The CLT forms a char layer on the burned side, which protects the inner layer of the CLT. This ensures that the load-bearing capacity can be maintained in combination with other materials (Gustafsson et al., 2019).

7.4.5 CONCLUSION

In short, the most important properties are bending strength in the load-bearing layers and rolling shear strength for the transverse layers. The latter is particularly important for floor slabs, as the load is perpendicular to the CLT panel. This can be improved by gluing the edges of the lamellas, with a ratio of 4:1 between width and thickness.

The load-bearing capacity is determined by the strength class, which is usually the same throughout the panel (C24), but can vary. The lamellae with the highest strength class are then the surface layers, as this is where most stresses occur. The other layers may have a lower strength class, especially the transverse layers, because they do not contribute to the load bearing but to the rolling shear strength. The layers in a panel can be replaced by other wood-based materials or hardwood to improve strength.

7.5 SCENARIOS OF SCRAP WOOD IN CLT

The consistency of CLT and its main properties have been discussed. In this section, scrap wood will be implemented in a CLT panel with a number of different configurations. The scenarios consist of different quantities of scrap wood incorporated into a panel. First, some assumptions and criteria are discussed. The assumptions refer to the problems of incorporating scrap wood into CLT and apply to all scenarios unless otherwise stated. These problems also apply to the general reuse of scrap wood in building products and solutions have already been mentioned. To avoid repetition of the same issues in each scenario, the assumptions are mentioned in advance and should be kept in mind when reading the scenarios.

The scenarios are tested against a set of criteria related to the production of a CLT panel on a scale of 1 to 5, where 1 means that the criteria is not important for this scenario and 5 means that it is very important. The criteria are: wood species, dimensions, mechanical properties (bending strength, stiffness, rolling shear strength) and manufacturing process.

A brief overview of the scenarios is then given, followed by a discussion of each scenario according to the criteria. Finally, a summary table of each scenario against each criterion is shown and a conclusion for the best option(s) is discussed.

7.5.1 CRITERIA & ASSUMPTIONS

7.5.1.1 Wood species

A CLT is usually manufactured from the same wood species, in Europe mostly from the softwood species spruce and pine (Gustafsson et al., 2019). The wood species vary between all scrap wood, even between the same type of building products, see Chapter 4. Identifying the species of wood can be difficult, but is important because each species has different properties. This aspect can therefore cause some difficulties for use in CLT. The scenarios assume that there is enough scrap wood of the same species for at least one layer, but not necessarily for all layers.

The use of a different wood species in a layer is allowed in some layers of the panel, as mentioned above. To minimise the risk of warping and moisture movement, the cross section of the CLT panel must be symmetrical in thickness and strength class. There is no mention of whether the species of wood should be symmetrical. This needs to be researched.

The criteria is:

- Importance of same wood species/having enough scrap wood of the same wood species

7.5.1.2 Dimensions

The dimensions of scrap also vary considerably. Although scrap wood may consist of dimensions that are between the commonly used widths and thicknesses of lamellas of virgin wood, the exact same commonly used dimensions may not be available for scrap wood. Larger pieces of scrap wood can be processed into standard dimensions, but there may also be smaller dimensions than commonly used. Scrap wood dimensions can be a problem for the lamellas in the transverse layers of floor slabs, due to the higher risk of shear failure. These lamellas must have a ratio of width : 4 * thickness. The available scrap wood dimensions can be processed to dimensions with this ratio, but may result in thinner lamellas. To achieve sufficient strength for load-bearing CLT panels, thinner layers are likely to result in more layers in a panel than in virgin wood CLT. Scrap wood may therefore be more suitable for panels that are loaded in one plane, such as walls. The scenarios are based on the assumption that there is sufficient scrap wood available, but that the dimensions may vary from the standard. The dimensional issues are discussed for each scenario.

The criteria is:

- Importance of dimensions for the ratio

7.5.1.3 Mechanical properties

Strength class

The mechanical properties of the scrap wood are unknown, just as the species, but important to know for use in CLT, especially the bending strength for the strength class (Llana et al., 2022). Each piece of scrap wood must therefore be graded mechanically to indicate the strength class, as too much scrap wood is rejected by visual grading. It is possible that some scrap may not have the required strength class.

The Eurocode 5 (1995) states that any timber, as long as the bending strength and density are equal to or greater than a certain strength, can have that certain strength class when at least 95% of the mean modulus of elasticity of the strength class is achieved.
The strength class is most important for load-bearing CLT panels, so scrap wood could also be used in non-load-bearing CLT panels where the required strength classes cannot be met, for example in internal partitions. Most of the load is carried in the layers parallel to the main direction of load, so these layers must be the strongest, especially the surface layers. However, in a layer ≤10% of the lamellae are allowed to have a lower strength class according to several technical approvals (Brandner et al., 2016). The strength class in the transverse layers can be lower due to the lower contribution to load bearing. Therefore, scrap wood may be more applicable in these layers.

It is assumed that the strength class of the scrap wood pieces will vary and that some of them will not meet the required strength class for the load-bearing layers. The criteria are:

- Importance of strength class

Moisture

Another important factor is moisture content. Fresh wood is brought to the right moisture content at the sawmill. Scrap wood can have different moisture content because it comes from different environments where the moisture content may be different. According to Woodjoint (personal communication, April 5, 2023), instead of bringing each piece of scrap wood to the right moisture content immediately, the overall moisture content is first raised to a much higher moisture content until it reaches each scrap wood piece, and then the moisture content is lowered to the right level. For CLT production, the moisture content is 12% +/- 3%. It is assumed that all scrap wood has been brought to the same moisture level at the processing stage. Thereefore, there is no criteria for the moisture content of scrap wood.

7.5.1.4 Manufacturing process

One of the main barriers to the reuse of scrap wood is the time-consuming process and high costs. As discussed in Chapter 5, the problems lie at the beginning of the chain, between the collection and processing stages. The remanufacturing of scrap wood would benefit from a processing hub where all scrap wood is collected, sorted, tested and remanufactured into semi-finished products ready for distribution to building product manufacturers. The conversion of scrap wood into CLT panels assumes the existence of such a hub. Because adding all these steps to the CLT manufacturing process has a big impact on these factories. Several different types of processes will have to be added to the factory. It will also result in more waste or transport because not every piece of scrap wood is likely to be suitable for CLT and therefore some scrap wood will be rejected.

The processing hub delivers semi-finished products to the CLT manufacturer. These semi-finished products will still come in different dimensions, species and strength classes, but these have already been taken into account. The challenge will be to implement these variations into the manufacturing process, which will probably require some changes to the machinery and additional storage for all the variations.The CLT should also not rely on scrap wood, but use both virgin and scrap wood to deal with the uncertainty of the scrap wood supply stream.

Another assumption is that there will be processing hubs and CLT factories in the Netherlands, located relatively close to each other, in order to reduce the transport distance between demolition site - processing hub - CLT factory - building site, and thus reduce the CO2 emissions caused by transport. There are currently no CLT factories in the Netherlands, mainly in Germany and Austria, although there are plans to build one in the Netherlands (Houtwereld, 2022). The criteria is:

- Impact on manufacturing process

7.5.1.5 Summary

In short, the assumptions for the implementation of scrap wood in CLT panels are that there is a processing hub where the scrap wood is sorted, tested and processed into semi-finished products. This hub supplies the CLT factory, both located in the Netherlands, with scrap wood of varying species, dimensions and strength classes. The challenge of the scenarios will be how these different pieces of scrap wood are converted into a CLT panel, what the challenges are and where in a building the panels are best suited:

- Load bearing constructions
- Floors & roofs
- Walls

In order to rate and compare the scenarios the scenarios will be graded on the following criteria, all indicated on a scale of 1-5:

- Importance of same wood species/having enough scrap wood of the same wood species.
- Importance of dimensions for the ratio
- Importance of strength class
- Impact on manufacturing process
- Use of varying scrap wood*

*this criteria is added to compare the scenarios with each other in terms of how much different kinds of varying scrap wood pieces can be used.

7.5.2 SCENARIO OVERVIEW

There are six scenarios, all with a different amount of scrap wood into a CLT panel. On the next page are the scenarios shown. In the following sub-paragraphs each scenarios is further explained, potential and hurdles are discussed, the most suitable function is determined and the scenario is graded on the criteria.

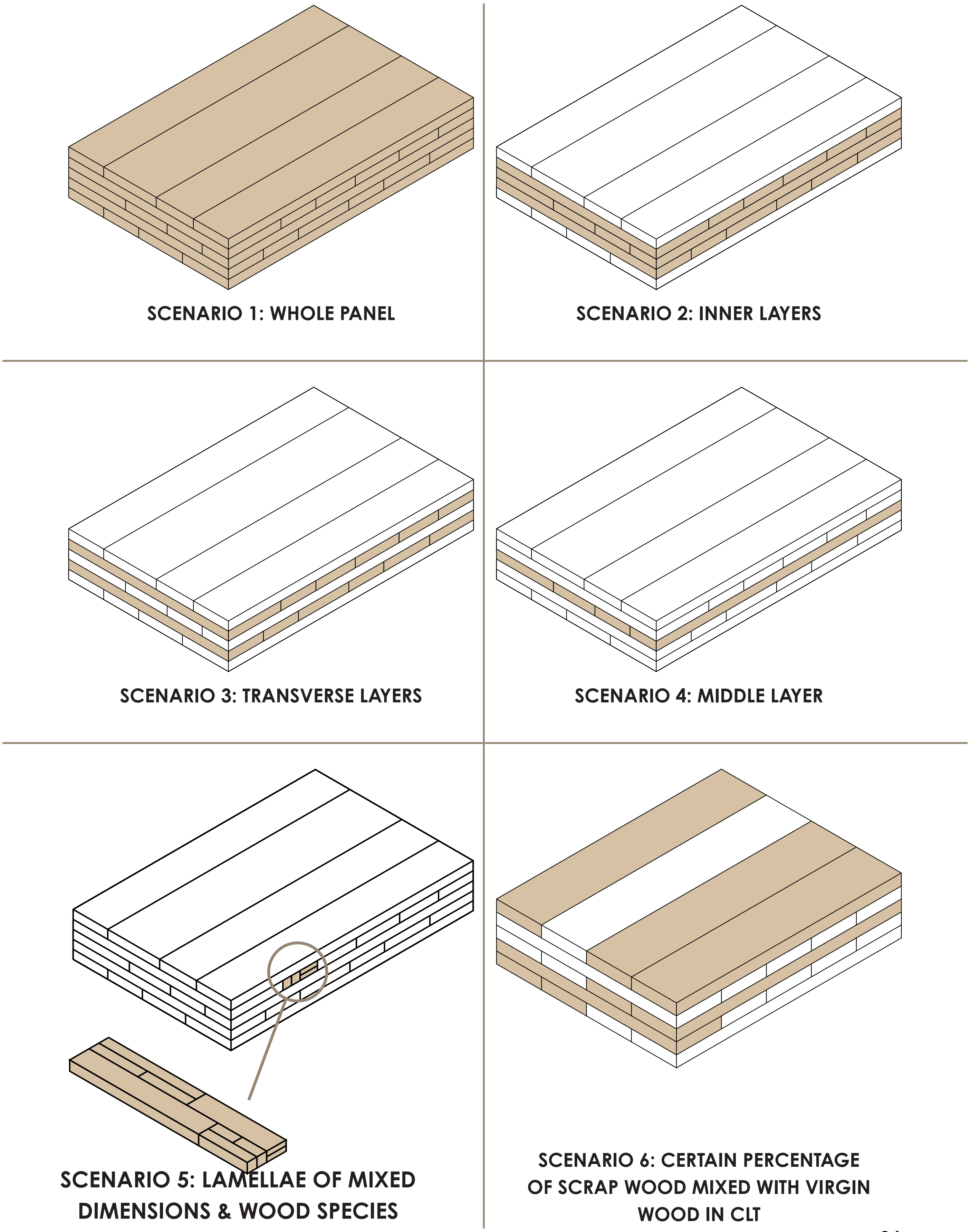


Figure 78 Six scenarios of scrap wood in CLT panels (own image)

7.5.3 SCENARIO 1 WHOLE PANEL

The first scenario consists of a CLT panel that is fully manufactured from scrap wood. This scenario contains the largest amount of scrap wood out of all scenarios. The panel can either consist of:

A: one wood species

B: every layer consists of a different wood species

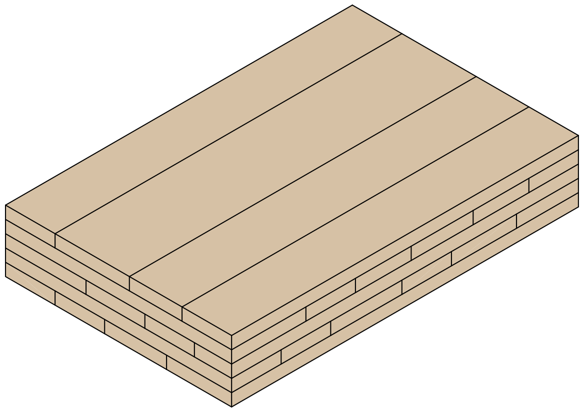


Figure 79 Scenario 1 whole panel (own image)

Option A requires the highest availability of one species. This option is more feasible for the most commonly used species, as there may not be enough scrap to produce multiple panels of less common species. Option B is therefore better for using more varied wood species in CLT panels, but has a greater impact on the manufacturing process. The machines need to be adapted to make layers of different species and the factory needs to be able to store all these different species.

An entire panel of scrap wood can pose some problems for load-bearing structures if the strength class of the scrap wood does not meet the required strength class, especially in the load-bearing layers, such as the surface layers. If there is not enough scrap of the required strength class, more layers can be added to support the load. Although this would involve using more scrap, it would also increase the thickness of the panels, which would occupy more space in a building. If the strength class can be met, the whole panels could be used in load-bearing constructions, but otherwise this scenario is more suitable for non-load-bearing constructions, such as internal walls or non-load-bearing walls.

This scenario also requires scrap wood pieces of the correct ratio for the transverse layers if they are to be used in panels that are loaded out of plane, such as floors and roofs. As mentioned above, the ratio may be available in common dimensions or otherwise thinner lamellas. If the latter is not possible and the ratio cannot be met, this scenario is less suitable for floors and roofs.

So, a full panel of scrap wood uses the most scrap wood, but requires enough scrap wood of the required strength classes for the load-bearing layers of load-bearing panels and the ratio for the transverse-layers in floors and roofs. Use in non-load-bearing structures presents the fewest obstacles. Option A has less impact on the manufacturing process, but Option B uses more different types of wood.

Best suitable for: non load bearing walls

	1	2	3	4	5
Importance of same wood species	●	●	●	●	●
Importance of dimensions for the ratio	●	●	●	●	●
Importance of strength class species	●	●	●	●	●
Impact on manufacturing process	● A	●	●	● B	○
Use of varying scrap wood*:	●	●	●	○	○

7.5.4 SCENARIO 2 INNER LAYERS

One of the problems in Scenario 1 is the need for sufficient scrap wood of the required strength class, which is mostly C24, in the load-bearing structures. The highest stress in a structural panel occurs in the surface layers and therefore these layers require the highest strength class. The inner layers carry less load and can therefore have a lower strength class, especially the transverse layers. So another option is to replace only the inner layers with scrap wood.

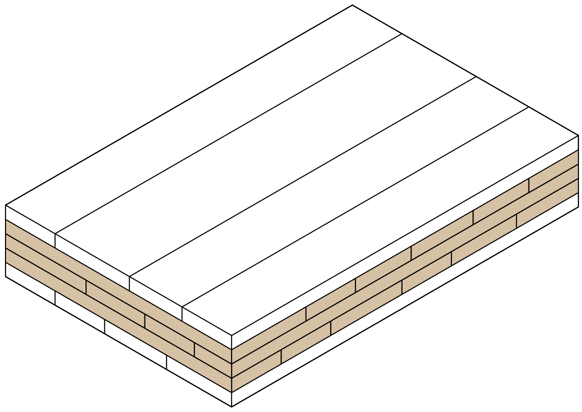


Figure 80 Scenario 2 Inner layers (own image)

In a 3 layer panel, the inner layer is a transverse layer and does not contribute to the load bearing capacity. In a panel with 5 or more layers, the inner layers contain load-bearing layers and therefore these layers must still be of a certain strength class, which can be a lower strength class than the surface layers.

Scrap wood is still used in the transverse layers, so for floor and roof panels the same problem of the correct ratio occurs, resulting in a lower possibility of scrap wood being used in floor and roof CLT panels. The manufacturing process is slightly less affected than in Scenario 1, as there are 2 fewer layers containing (varying) amounts of scrap wood.

In order to improve the strength of a panel, some research has tested whether changing the angle of the transverse layers would have a positive effect on the strength of the panel. For example, Bahmanzad et al (2020) found that setting the transverse layer at a 30 degree angle instead of the 90 degree angle improved the shear strength by 1.5 times, the shear stiffness by as much as 8.3 times and the bending stiffness by 4.3 times in a 3-layer CLT panel. This means that lower quality or lower strength wood can be used. However, the non-perpendicular angle means that more wood has to be cut, resulting in more waste than with perpendicular layers, but if it ensures the use of scrap wood, the amount of wood waste is still reduced.

In short, producing a CLT panel with the inner layers made of scrap wood may be a more suitable option than scenario 1, because the required strength class in the surface layers can be guaranteed with virgin wood. The inner layers parallel to the main load must still have a certain strength class, but this can be lower than the surface layer. The strength of the panel can be increased by placing the transverse layer at an angle other than 90 degrees. However, the uncertainty of obtaining the required ratio makes this scenario less suitable for floor and roof panels.

Best suitable for: (non) load bearing walls

	1	2	3	4	5
Importance of same wood species	●	●	●	●	○
Importance of dimensions for the ratio	●	●	●	●	●
Importance of strength class species	●	●	●	○	○
Impact on manufacturing process	●	●	●	●	○
Use of varying scrap wood*:	●	●	○	○	○

7.5.5 SCENARIO 3 TRANSVERSE LAYERS

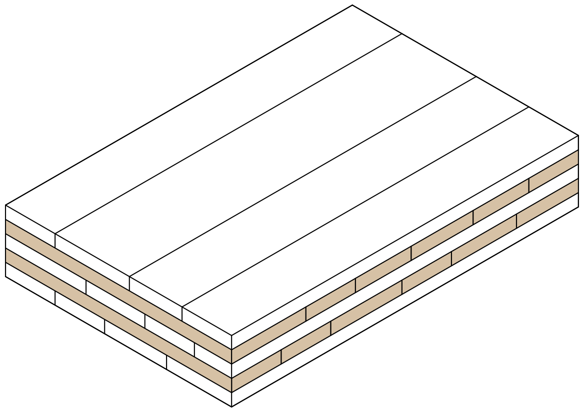


Figure 81 Scenario 3 Transverse layers (own image)

In the third scenario, scrap wood is only used in the transverse layers to eliminate the need for high-strength scrap wood. The most important factor is the rolling shear strength, especially in the floor and roof panels, so the required ratio should be met and the lamellas could be edge glued to make the panels stronger. As discussed in Scenarios 1 & 2, the ratio may not be available, or smaller than usual dimensions may be used. As mentioned in Scenario 2, the angle could be changed to increase the strength of the panel. The impact on the manufacturing process is again slightly less than the previous scenarios as less scrap wood is used in a panel when 5 or more layers are used.

To improve the rolling shear strength of the transverse layers, several studies have been carried out by changing the wood of these transverse layers to other engineered wood products to create a 'hybrid panel'. Besides mentioning some other studies where the layers were replaced with Laminated Strand Lumber (LSL), Laminated Veneer Lumber (LVL) and hardwood, Xu et al. (2021) conducted a study of a hybrid 3-layer CLT panel with 8 different wood products. The surface layers consisted of SPF, which stands for spruce-pine-fir, because these species have such similar properties in the US and Canada that they can be used together (Centrum Hout, 2019). The transverse layer consisted of either SPF or 7 other wood species or products, which were solid birch (hardwood), OSB (oriented strand board), LVL (laminated veneer lumber), compressed wood, plywood, PSL (parallel strand lumber) and GLB (glued laminated bamboo). Of all the wood products, GLB showed the most promising results, with twice the rolling shear properties of SPF. The next most promising product was compressed wood.

Another study of a hybrid three-layer CLT 3 was conducted by David et al. (2017) with different symmetrical configurations of SPF and LSL (laminated strand lumber). The best result was SPF on the surface layers and LSL in the inner layer in terms of bending and shear strength and stiffness. Yang et al. (2021) found the same results, but then for LVL in the transverse layer, although this option needs some further research on the composition when used in a CLT panel that is loaded out of plane, as the bending properties partly degrade.

The use of hardwood in the transverse layer of a softwood CLT panel has a beneficial effect on the rolling shear properties, but the adhesion of the glued layers depends on the species used. This effect has not been tested for the mixing of hardwood and softwood in a CLT panel (Yang et al., 2021).

All these studies show that the replacement of the middle layer, which is also the transverse layer in a 3-layer panel, has a positive effect on the mechanical properties of the CLT panel. All the experiments were carried out with either wood-based products, bamboo or hardwood and not with scrap wood. The wood-based products can be made from recycled wood and therefore from recycled scrap wood. So, although the paper does not mention the effects of scrap wood in CLT, it does show that scrap wood could be recycled and used in CLT panels.

There have been a few studies of hybrid CLT panels using scrap/waste wood. Stenstad et al. (2021) investigated the reuse of scrap wood in CLT and tested 9 prototypes of different configurations of a 3-layer CLT panel for stiffness, bending strength, shear properties, delamination and demolition damage. Prior to CLT production, the scrap wood pieces were mechanically tested for bending strength and modulus of elasticity, and the results were above acceptable levels, meaning that the scrap wood pieces can be used in CLT. The scrap pieces were also visually graded for strength, with more pieces being rejected. Visual grading is less suitable for scrap wood because of the damage in the wood from the demolition part. However, this damage and holes from nails and screws don't contribute to the indication of failure in the tests. The research does not specify the type of wood, softwood or hardwood, and the species, or even whether each piece is of the same species. If these CLT prototypes are tested alongside normal CLT and compared, it may be assumed that the scrap pieces are from the same species as the virgin wood for comparison purposes, which would probably be Norwegian spruce.

Although the CLT pieces passed the test, the scrap wood pieces were placed in the transverse layers because these layers contribute much less to the stiffness of the panel than the perpendicular layers. The transverse layers contribute mainly to the rolling shear strength, but this depends more on the width of the lamellae than on the strength of the wood. Scrap wood does not differ from virgin wood in the delamination tests. The results showed that the use of scrap wood in the transverse layers is very feasible as long as the scrap wood is dry, planed and free of metal (Build-in-Wood, 2022). The overall conclusion of the study was that the challenges were not related to the quality of the scrap wood, but rather to the lack of legislation, standards and better processes for cleaning and grading the strength of the scrap wood pieces, and the uncertainty of the scrap wood stream (Stenstad et al., 2021). The latter could be solved by introducing a scrap wood supply stream into the general CLT production process, but not by relying on this stream.

In order to further develop research on the reuse and recycling of wood, NTI, funded by the Norwegian government and together with 52 partners from (wood) companies to universities and research institutes, founded CircWood (Build-in-Wood, 2022).

Llana et al. (2022) mention three studies that have attempted to construct a 3-layer CLT panel from waste wood: one by Stenstad et al. (2021) mentioned above, and another by Arbelaez et al. (2020), who tested different configurations of virgin and recycled Douglas fir wood. Similar results were found between recovered and new wood in terms of stiffness, bending and shear strength, suggesting the possibility of using waste wood in the core or as a whole panel, but further research with more samples is needed. Finally, Rose et al. (2018) tested 12 three-layer CLT panels, actually CLST (= cross-laminated secondary timber) panels made from recovered wood, for bending and compression. The results were promising, with minimal effects found on compression stiffness and strength, even with respect to damage and ageing of the recovered wood. However, the latter is only true for recovered wood in the transverse layers, as recovered wood has a greater effect on bending stiffness. They therefore propose CLST panels with a combination of new and recovered wood.

In short, a number of studies have been carried out on the substitution of one or more layers with other wood-based materials or waste wood, although all the studies have only been carried out with a 3-layer panel. The studies show that the use of scrap wood in CLT is possible, mainly in the transverse layers, due to the reduction in the bending stiffness of scrap wood, which is necessary for the load-bearing capacity. When scrap wood is used in the outer layers, the ultimate load-bearing capacity is lower than when new wood is used. The other properties such as shear, stiffness, elasticity and compressive strength are similar to virgin wood (Llana et al, 2022). However, all studies note that more research needs to be done on a larger scale before commercialisation (Arbelaez et al., 2020; Rose et al., 2018; Stenstad et al., 2021).

In terms of availability of the required ratio, this scenario is also less suitable for floors and roofs than for (non-) load-bearing walls.

Best suitable for: (non) load bearing walls

	1	2	3	4	5
Importance of same wood species	●	●	●	○	○
Importance of dimensions for the ratio	●	●	●	●	●
Importance of strength class species	●	○	○	○	○
Impact on manufacturing process	●	●	●	○	○
Use of varying scrap wood*:	●	●	○	○	○

7.5.6 SCENARIO 4: MIDDLE LAYER

Scenario four consists of substituting one layer in the panel with scrap wood: the middle layer. The middle layer is either:

A: a transverse layer (panel of 3, 7, 11, etc. layers)
B: a layer parallel to the surface layers (panel of 5, 9, 13, etc layers)

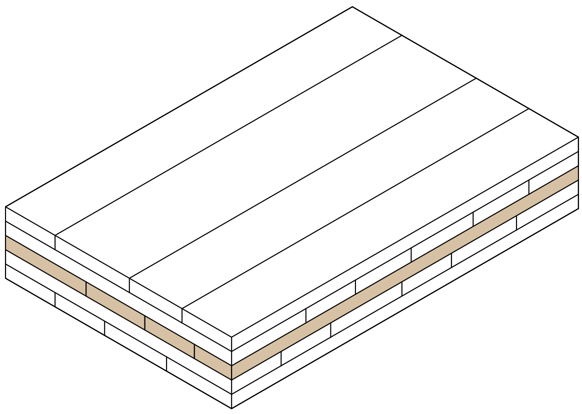


Figure 82 Scenario Middle (own image)

The middle layer has the lowest stresses and can therefore have a lower strength class, especially in option A. The middle layer does contribute to the rolling shear strength, so in a floor or roof panel the availability of the required ratio is still important for option A. Option B is therefore more suitable for floor and roof panels, because the middle layer is not a transverse layer.

As mentioned above, tests have been carried out to replace this layer with hardwood or other wood-based materials, and it has been shown to improve the strength of the panel. Research has also been carried out on replacing the layer with scrap wood, with positive results, but more research is needed. This scenario uses the least amount of scrap wood of all the scenarios discussed and therefore has the lowest impact on the manufacturing process.

Best suitable for:
Option A: (non) load bearing walls
Option B: (non) load bearing walls+ floors & roofs

	1	2	3	4	5
Importance of same wood species	●	●	○	○	○
Importance of dimensions for the ratio	● A	●	●	●	● B
Importance of strength class species	●	○	○	○	○
Impact on manufacturing process	●	○	○	○	○
Use of varying scrap wood*:	●	○	○	○	○

7.5.7 SCENARIO 5: LAMELLAE OF MIXED DIMENSIONS & WOOD SPECIES

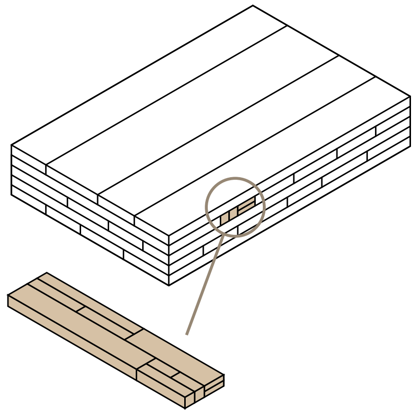


Figure 83 Scenario 5: lamellae of mixed dimensions & wood species (own image)

The next scenario takes a different approach to the previous ones. If the scrap wood consists of smaller pieces and different wood species, one option could be to construct a CLT layer from several smaller pieces, possibly even with 2 layers in the thickness, see figure X for an example, and mix all wood species. This method allows more smaller pieces of wood to be used in a CLT panel, but the ratio is not maintained and much more glue is required. Instead of glue, dowels or other connectors could be an option to reduce the amount of glue. Due to the smaller size of the pieces, the expansion and contraction due to environmental changes may be small enough that species could be used together, eliminating (most of) the species sorting process. This method will require a lot of testing, especially for strength, elasticity/stiffness and delamination. Different configurations need to be tested, such as applying this method to all layers, the inner layers, the transverse layers or the middle layer. The mechanical properties are unknown and probably not strong enough for load-bearing structures, but it could possibly be used in non-load-bearing structures such as partitions. This process requires a complete change in production method, as it is necessary to work out how to glue and stack all sorts of small pieces perpendicular to each other. This is an out-of-the-box idea that is probably not suitable for a standardised and machine-based process, but it is interesting to explore and see the effects of such a process.

Best suitable for: non load bearing walls

	1	2	3	4	5
Importance of same wood species	●	○	○	○	○
Importance of dimensions for the ratio	unknown				
Importance of strength class species	unknown				
Impact on manufacturing process	●	●	●	●	●
Use of varying scrap wood*:	●	●	●	●	●

7.5.8 SCENARIO 6: CERTAIN PERCENTAGE OF SCRAP WOOD MIXED WITH VIRGIN WOOD IN CLT

Lastly, all other scenarios, except for scenario 5, discusses changing a whole layer into a scrap wood layer. Another option could be using a certain percentage of scrap wood into a CLT panel, either

A: separately in one layer

B: combined with virgin wood in a layer

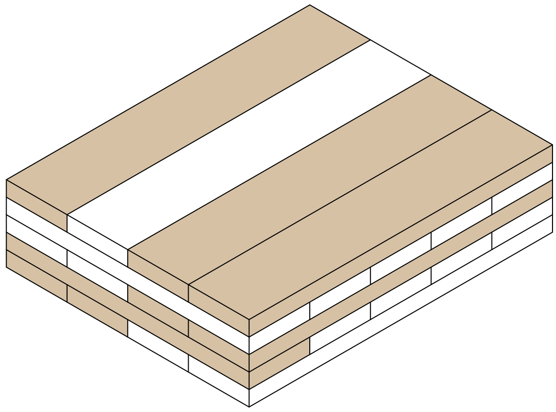


Figure 84 Scenario 6 : Certain percentage of scrap wood mixed with virgin wood in CLT (own image)

Option A is actually scenario 1 to 4. Option B works best with scrap spruce or pine because these are the species most commonly used in virgin CLT panels. The scrap wood and the virgin wood could therefore be mixed in one layer, as long as the strength class is similar. A maximum of 10% of the lamellae in a layer may have a lower strength class (Brandner et al., 2016).
Option B, when different species are mixed in a layer, could also be an option. In terms of bending strength, several wood species may have the same strength class but different mechanical properties. This option should therefore be studied.

The whole panel or a layer could also be made of a different wood species, where new wood and scrap wood are mixed. This option will ensure that more scrap wood can be used. The layers could be made when there is enough scrap of one species. For example, instead of using spruce or pine as the base material, the CLT panel could be made from oak or ash. Studies have shown that CLT can be made from these species.

This option is less dependent on the uncertain supply of scrap wood, as scrap wood is only used when it is available. For example, the panel may contain 50% scrap wood at one time and 10% or 80% at other times. The manufacturing process is only partially affected, depending on the supply. For option B, where spruce or pine scrap wood is used, the only impact is that some dimensions differ from the usual dimensions, especially the width of the lamellas, as the thickness in a layer must be the same for scrap wood and virgin wood.

The most suitable option in this scenario depends on the percentage of scrap used and the layers in which scrap is used. If the same problems occur as in the previous scenarios, such as lack of the required strength class or ratio, then some panels will not be suitable for load-bearing walls and floor or roof panels. However, this scenario has the greatest freedom to choose where the scrap wood is used and can therefore produce panels that are particularly suitable for floors and roofs. The percentage will therefore depend on the amount of scrap wood available.
If option B is chosen and only spruce and pine are used, not all the scrap wood can be used. However, if option A is (also) chosen, this is not necessarily the case.

Best suitable for: (non) load bearing walls and floors & roofs, depending on percentage and location of the scrap wood.

	1	2	3	4	5
Importance of same wood species	●	●	●	●	●
Importance of dimensions for the ratio	●	●	●	○	○
Importance of strength class species	●	●	●	●	○
Impact on manufacturing process	●	○	○	○	○
Use of varying scrap wood*:	●	●	○	○	○

7.5.9 SUMMARY & CONCLUSIONS

The six scenarios fall into two categories: Scenarios 1-4 and Scenarios 5 & 6. Scenarios 1 to 4 describe the method of replacing one of several layers in a CLT panel with a layer of scrap wood, where a layer is made of the same wood species but may differ from the wood species of the virgin wood layers. The number of layers replaced in a panel decreases from Scenario 1 to 4. Scenarios 5 and 6 describe other methods, with Scenario 5 being the most out-of-the-box, mixing all kinds of scrap wood pieces and species in a panel.

Scenario 6 focuses more on using as much scrap wood as possible according to availability, in separate scrap wood layers or combined with virgin wood in one layer, rather than changing specific layers. Therefore, in terms of the quantity of scrap wood substituted in a panel, Scenarios 1 and 5 are the best options because they consist of a whole panel of scrap wood, and Scenario 4 is the worst because it substitutes only one layer. Scenario 6 depends on the percentage of scrap wood, it can be either the best option (100%) or the worst (<1%). The criteria for all scenarios are shown in Table 1.

SCENARIO	1: WHOLE PANEL	2: INNER LAYERS	3: TRANS-VERSE LAYERS	4: MIDDLE LAYER	5: SMALL PIECES	6: % MIXED
Importance of same wood species	5	5	3	2	1	5
Importance of dimensions for the ratio	5	5	5	A: 1, B: 5	?	3
Importance of strength class species	5	3	1	1	?	4
Impact on manufacturing process	A: 1, B: 4	4	3	1	5	1
Use of varying scrap wood*:	3	2	2	1	5	2

1 2 3 4 5

Table 1: summary of criteria for every scenario (ow n image)

In all scenarios, the most important factors for using scrap wood in CLT are the availability of:

- Mechanical properties: strength, stiffness and rolling shear strength
- Aspects: wood species and dimensions, especially ratio

In load-bearing structures, the strength class is important for the load-bearing layers, which are usually the surface layers and all parallel layers, although the required strength class decreases from the surface layers to the middle layer. Therefore, scrap wood is least suitable in the surface layers, but could be used in the other load-bearing layers. This is also the conclusion of some studies by Stenstad et al. (2021), Arbelaez et al. (2020) and Rose et al. (2018). This means that scenario 1 is the least suitable option for the remanufacturing of scrap wood in load-bearing structures, and scenario 3 and 4 are the best. In scenario 2, the scrap wood still requires a certain strength class, but this can be lower than the surface layers and therefore more scrap wood may be suitable.

In panels that are loaded out of plane, such as floor and roof panels, the transverse layers are the most important. Transverse layers do not carry the load and therefore do not need to have a high strength class, but they do have an effect on the rolling shear strength, which can be increased by a ratio of lamella width: 4 * thickness and edge gluing. If the required ratio is not available, Scenarios 1, 2 and 3 are not suitable for floor and roof panels. Scenario 4 is only not suitable if the middle layer is a transverse layer. If the usual ratios are not available, the ratio can still be produced but it may result in thinner lamellae. The effect should be investigated to see if this causes problems.

Scenario 3 is the most researched scenario. Several studies have been carried out on the substitution of the transverse layer of a 3-layer panel, so it also applies to a 3-layer panel of Scenario 2 (inner layers) and Scenario 4 (middle layer). However, the focus of the studies was on the use of scrap wood in the transverse layer and therefore applies most to Scenario 3. The substitution with other wood-based materials, hardwood or waste wood shows positive results, although the strength of the panel for the substituted waste wood needs further testing and research.

By assuming the presence of a processing hub, there is little impact on the manufacturing process. More substituted layers in a panel result in higher impacts. Scenario 5 has the highest impact, followed by scenario 1. Scenario 4 has the lowest impact, but also uses the least amount of scrap wood. There is a relationship between the amount of scrap wood substituted in a panel and the impact on the manufacturing process and suitability for building products, see Figure 85. However, the amount of scrap wood in a panel is the lowest in Scenario 4, but a lot of houses (900,000) need

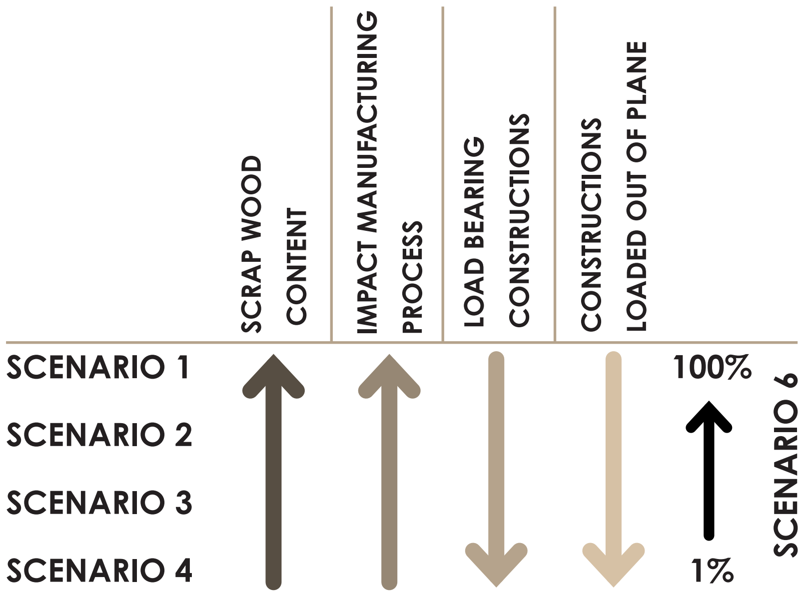


Figure 85: Relation between the scrap wood content and impact on manufacturing process and suitability for construction elements (own image)

to be built by 2030. If some of these houses are built with CLT, which is likely due to the increasing demand for wood, a substantial amount of scrap wood can still be used. There is an annual production of 400-500 kton of scrap wood, and although not all scrap wood is reusable or remanufacturable, the conversion of scrap wood into CLT can reduce the production of scrap wood.

Altogether, the use of scrap wood seems to be a possible option. Each scenario could be used in non-load-bearing structures and in load-bearing structures if the right properties and dimensions of scrap wood are available, with the probable exception of scenario 5, which needs to be thoroughly tested first. From scenario 1 to 4, scenario 3 is the best tested and seems the most likely to be used in load-bearing structures, at least for 3-layer panels. In terms of the manufacturing process and the uncertainty of the supply stream, Scenario 6 is the most suitable option, as the proportion of scrap wood in a CLT panel depends on the availability of scrap wood with the required properties.

7.6 SUSTAINABLE GAIN OF SCRAP WOOD IN CLT

7.6.1 CASE STUDY MODEL

The 6 scenarios contain a certain percentage of scrap wood ranging from 1% to 100%. The percentage of scrap wood in a CLT panel varies depending on the building element (wall or floor), which depends on the mechanical properties of the scrap wood and the availability of sufficient scrap wood. The aim of substituting scrap wood for virgin wood is to contribute to reducing the environmental impact of the C&D industry by reducing CO2 emissions and waste production. Studies have shown that scrap wood can be incorporated into CLT. But is the CO2 reduction valuable enough to start incorporating scrap wood into CLT products? To understand the environmental impact of substitution, the reduction in CO2 emissions is calculated using a case study model of a 3-storey CLT terraced house with a flat roof, see figure 86.

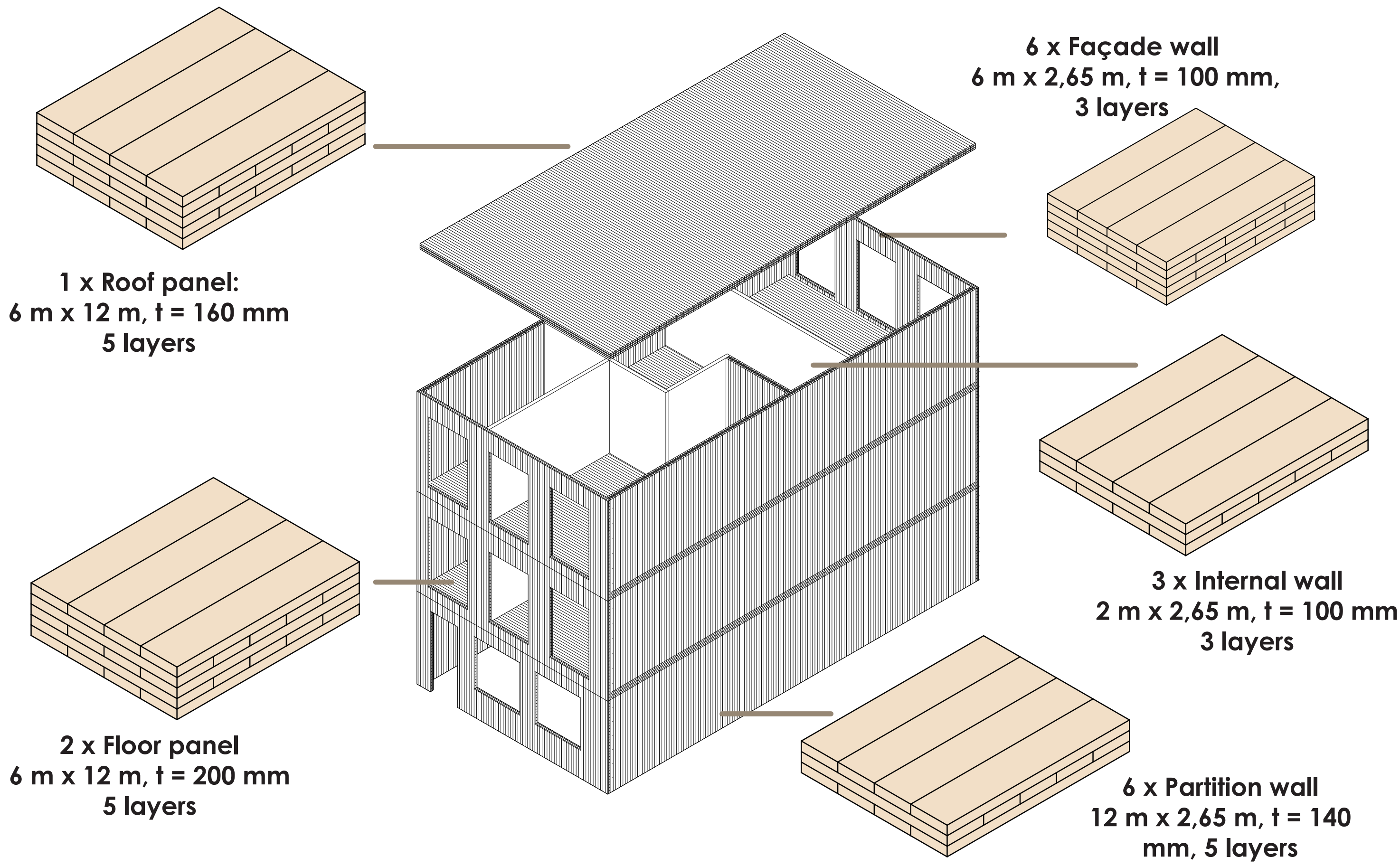


Figure 86 CO2 storage and emissions of CLT (Van Der Lugt, 2021)

The building has a floor area of 6 m x 12 m and a floor to ceiling height of 2.65 m. The foundation floor is made of concrete, because concrete is better at fencing off moisture from the ground (Vos et al., 2021). The parameters for the CLT building are given in Table 2. Note that the thickness of each layer in a panel shown in the table is a possible option, the thicknesses of the layers can differ as long as the total thickness of the panel remains the same and the cross section remains symmetrical, e.g. 30-40-30 can also be 40-20-40. Changing the thickness configurations does not affect the total volume of a CLT and therefore not the total volume of CLT in a building, but it can affect the volume of scrap wood used in the scenarios. This then affects the percentage of CO2 emissions saved by replacing virgin wood with scrap wood. The different thicknesses of scrap wood available may also result in other, less common, configurations of layer thicknesses.

Component	Width	Height/ Length	Factor	Area panel	Amount of layers	Thickness of each layer					Thickness panel	Volume of a panel	Amount of panels	Total volume
	[m]	[m]	[%]	[m2]		[mm]					[m]	[m3]		[m3]
Partition wall	12	2,65		31,8	5	40	20	20	20	40	0,14	4,45	6	26,7
Façade wall*	6	2,65	50%	7,95	3		30	40	30		0,10	0,80	6	4,8
Internal wall	40	2,65		106	3		30	40	30		0,10	10,60	1	10,6
Stability wall	2	2,65		5,3	5	40	20	20	20	40	0,14	0,74	3	2,2
Floor	6	12		72	5	40	40	40	40	40	0,20	14,40	2	28,8
Roof	6	12		72	5	40	20	40	20	40	0,16	11,52	1	11,5
Total														84,6

*50% of wood in the façade

Table 2_Parameters of case study model (own table)

The stored carbon emissions are calculated from the volume of CLT used in the building per component, see Table X. First, the area [m2] of a panel is calculated by multiplying the width by the height (for floors and roof: length). For the façade panel, a factor of 50% is added because of the openings in the façade. The internal wall width of 40 m is the total length of the internal wall in the building and is calculated as one long panel. Then the area [m2] of a panel is multiplied by the thickness of the panel to calculate the volume [m3] of a panel. For each component, the volume is multiplied by the number of panels in the building to give the total volume of the component in the building. The total volume of the CLT is **84,6 m3.**

7.6.2 CARBON SAVINGS OF CLT FROM SCRAP WOOD

7.6.2.1 Calculations for base model of virgin wood

CLT panels from virgin wood are mostly made from the soft wood species: spruce. On average, softwood stores 0,9 ton CO2 /m3 wood, but for CLT the capability of CO2 storage is a bit lower: 0,759 ton CO2/m3. The storage capability of CLT is lower than the average storage capability of softwood. This is probably partly due the lower storage capability of spruce than other softwood species and partly the 1% glue content. In the calculations of the carbon savings in this case study the storage capability of CLT is used: **0,759 ton CO2/m3**. The total stored CO2 is calculated by multiplying the volume of CLT x storage capability:

Total CO2 stored in case study model: 84,6 m3 x 0,759 CO2/m3 = **64,2 ton stored CO2.**

The production of CLT also emit some CO2, but the amount of CO2 emitted is lower than the stored CO2, see figure 87. The total amount of CO2 that is emitted during production and installation (A1-A5) of virgin wood is according to Van der Lugt (2021):

Total emitted CO2 of production = 79+14+7+5 = 105 kg CO2 /m3 CLT = **0,105 ton CO2 / m3**

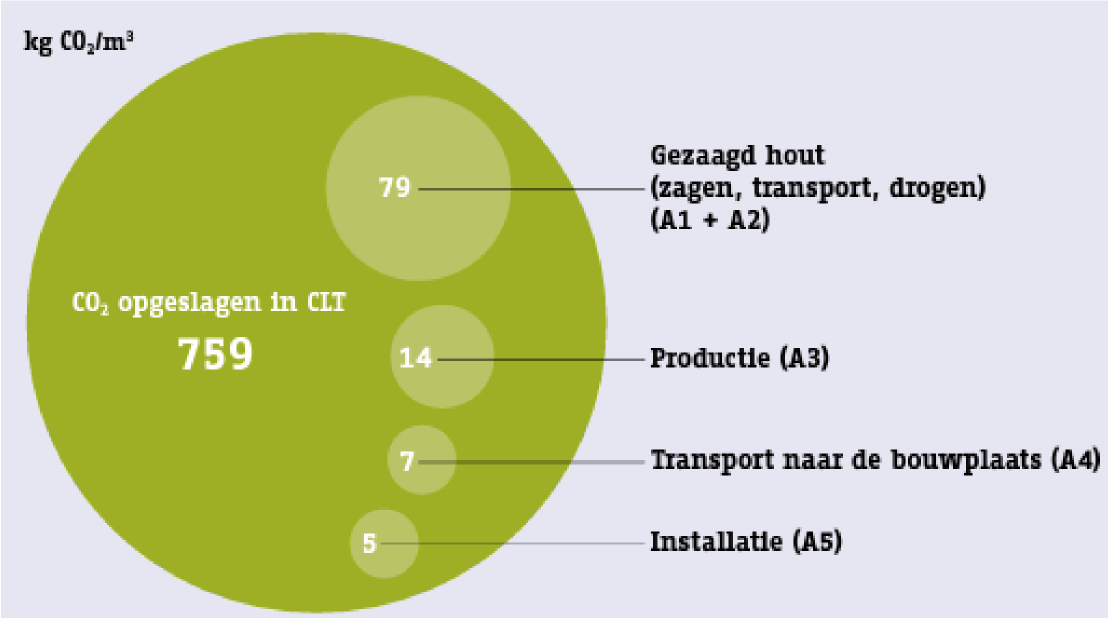


Figure 87 CO2 storage and emissions of CLT (Van Der Lugt, 2021)

The emitted CO2 during production is only 14% of the stored CO2 in CLT. For the case model of virgin wood this means that for the total volume:

84,6 m3 x 0,105 CO2/ m3 = **8,9 ton CO2 is emitted**

This amount needs to be substracted from the total amount of stored CO2 to show the amount of CO2 that is saved from being emitted:

64,2 ton stored CO2 - 8,9 ton emitted CO2 = **55,3 ton saved CO2**.

Besides the CO2 storage capability of wood, extra carbon emissions are saved by substituting traditional building materials (TBM), such as concrete and steel, with wood. The production of concrete and steel emits CO2. When TBM are substituted for CLT the CO2 emissions from the product are not emitted, and therefore these CO2 emissions are avoided from being emitted.
The EU has a rule of thumb that for every m3 softwood used around **0,75 ton CO2** emissions will be **avoided** (Van Der Lugt, 2021). For the case study of virgin wood the volume needs to be multiplied by 0,75 ton CO2 to calculate the avoided emissions:

84,6 m3 x 0,75 CO2/ m3 = **63,5 ton CO2 is avoided.**

The total amount of saved and avoided CO2 emissions, compared to TBM is: saved CO2 + avoided CO2 - emitted CO2 of production (A1-A5) So, the total saved CO2 emissions compared to TBM of the case study of virgin wood is:

64,2 + 63,5 - 8,9 = **118,8 ton CO2.**

This calculation is shown in table X. The CO2 emissions of production and avoided CO2 emissions by substitution of TBM with CLT is also calculated per component.

7.6.2.2 Calculations for CO2 savings of CLT from scrap wood

Below, these calculations are applied for the 6 scenarios. It must be noted that in these scenarios the focus will be on the saved CO2 emissions by substituting virgin wood wilt scrap wood. So, first the stored CO2 in scrap wood will be calculated.

Normal CLT residential building

Component	Area panel [m2]	Amount of layers	Thickness of each layer [mm]					Total thickness layers [m]	Volume of layers in 1 panel [m3]	Amount of panels	Total volume of layers [m3]	CO2 storage [ton CO2]	CO2 emissions of production (A1-A5) [ton CO2]	CO2 saved by substitution traditional building materials [ton CO2]
Partition wall	31,8	5	40	20	20	20	40	0,14	4,45	6	26,7	20,3	2,8	20,0
Façade wall*	7,95	3		30	40	30		0,1	0,80	6	4,8	3,6	0,5	3,6
Internal wall	106	3		30	40	30		0,1	10,60	1	10,6	8,0	1,1	8,0
Stability wall	5,3	5	40	20	20	20	40	0,14	0,74	3	2,2	1,7	0,2	1,7
Floor	72	5	40	40	40	40	40	0,2	14,40	2	28,8	21,9	3,0	21,6
Roof	72	5	40	20	40	20	40	0,16	11,52	1	11,5	8,7	1,2	8,6
Total											**84,6**	**64,2**	**8,9**	**63,5**
											Total saved CO2:**	**55,3**	**ton CO2**	
											Total saved CO2 compared to traditional building materials:	**118,8**	**ton CO2**	

*50% of wood in the façade

Table 3_Saved CO2 calculations of CLT from virgin wood (own table)

This is done by multiplying the volume of scrap wood times the storage capability:

Stored CO2 in scrap wood = Volume scrap wood [m3] x 0,759 [ton CO2/m3].

CLT from scrap wood still has to be manufactured, but does not emit CO2 during A1 + A2, because this has already happened. The CO2 emissions of the production of CLT from scrap wood is therefore A3-A5: 14+7*+5 = 26 kg CO2/m3 = 0,026 ton CO2/m3. The total is subtracted from the stored emissions.

Emitted CO2 of scrap wood is = volume scrap wood [m3] x 0,026 [ton CO2/m3]

**The existence of a Dutch CLT manufacturer will be taken into account in these scenarios, where CLT will be produced from virgin wood AND scrap wood. The amount of CO2 emissions of A4 might therefore not be the most accurate, because CLT is manufactured in other countries and therefore have a longer transport distance, which means higher CO2 emissions than CLT from a Dutch manufacturer. But for this calculation this amount of 7 kg CO2/m3 will still be used.*

The **total saved emissions of scrap wood** are then:

Stored CO2 in scrap wood - Emitted CO2 of scrap wood

The avoided CO2 emissions by substituting virgin wood with scrap wood will be calculated in comparison to the use of virgin wood AND the use of TBM. The use of 100% virgin wood is called scenario 0: the base of this case study.

Scenario 0:

- Stored CO2: 64,2 ton CO2
- Emitted CO2: 8,9 ton CO2
- Avoided CO2: 63,5 ton CO2

The first comparison is between virgin wood and scrap wood. When scrap wood is used instead of virgin wood CO2 emissions are avoided. The stored CO2 of CLT from virgin wood is still stored in a forest or with the rising demand of wooden buildings, more of those wooden buildings can be built without increasing the production of virgin wood from the forests, keeping the harvesting of wood at the same rate. So, although the CO2 is already stored, the substituting with scrap wood prevents harvesting of those trees and therefore more trees are growing that absorb even more CO2. The substituting also avoids the emissions of production of CLT from scrap wood. Therefore the amount of extra saved CO2 is 64,2 - 8,9 is 55,3 ton CO2. This is the base and is set at 100%. The amount of saved CO2 of CLT from scrap wood is then added to the 55,3 ton CO2 and divided by 55,3 ton CO2 to show a percentage on how much extra CO2 is saved =

(Total saved CO2 scrap wood + 55,3 ton CO2)/55,3 ton CO2 * 100%

The same method will be applied for the second comparison with the substitution of traditional building materials with scrap wood, only here the value of 118,8 ton CO2 is used. This amount of CO2 is already saved by substituting TBM with virgin wood, so when that is substituted with scrap wood, all saved CO2 are extra saved CO2 emissions. The total amount of saved CO2 emissions by substituting TBM and virgin wood with scrap is added together: total saved CO2 scrap wood + 118,8 ton CO2. The comparison formula, which shows the extra savings, is then =

(Total saved CO2 scrap wood + 118,8 ton CO2)/118,8 ton CO2 * 100%

The scenarios are not necessarily applicable to all components. The most suitable components for each scenario were discussed in the previous paragraph. Finally, for each scenario, the total amount of additional CO2 emissions saved is calculated by substituting only the most suitable components.

7.6.3 SCENARIO 1 WHOLE PANEL

In scenario 1 the whole CLT panel is constructed from scrap wood. So that means that the total volume and total stored CO2 is equal to a CLT panel of virgin wood: volume of 84,6 m3 and 64,2 ton stored CO2, see table 4. The CO2 emissions of production is less due to the absent CO2 emission of harvesting wood: 2,2 ton CO2. Therefore the total amount of saved CO2 emissions is 64,2 - 2,2 = 62,0 ton CO2.

														Partly substition	
Component	**Area panel** [m2]	**Amount of scrap wood layers**	**Scrap wood layers** [mm]					**Total thickness scrap wood layers** [m]	**Volume of scrap wood layers in 1 panel** [m3]	**Amount of panels**	**Total volume of scrap wood layers** [m3]	**CO2 storage** [ton CO2]	**CO2 emissions of production (A1-A5)** [ton CO2]	**CO2 storage** [ton CO2]	**CO2 emissions of production (A1-A5)** [ton CO2]
Partition wall	31,8	5	40	20	20	20	40	0,14	4,45	6	26,7	20,3	0,7		
Façade wall*	7,95	3		30	40	30		0,1	0,80	6	4,8	3,6	0,1	3,6	0,1
Internal wall	106	3		30	40	30		0,1	10,60	1	10,6	8,0	0,3	8,0	0,3
Stability wall	5,3	5	40	20	20	20	40	0,14	0,74	3	2,2	1,7	0,1		
Floor	72	5	40	40	40	40	40	0,2	14,40	2	28,8	21,9	0,7		
Roof	72	5	40	20	40	20	40	0,16	11,52	1	11,5	8,7	0,3		
Total											84,6	**64,2**	**2,2**	**11,7**	**0,4**
											Total saved CO2:**	**62,0**	**ton CO2**	**11,3**	**ton CO2**
											Total saved compared to TBM:	**180,8**	**ton CO2**	**130,1**	**ton CO2**

*50% of wood in the façade

**CO2 storage - CO2 emissions caused by production (A1-A5)

Table 4_Saved CO2 calculations of scenario (own table)

By substituting a whole panel with scrap wood a total of 62,0+55,3 = 117,3 ton CO2 is saved which is an increase of 117,3 / 55,3 * 100% = 212,2%. So more than double the amount of scrap wood is saved. Compared to the substitution of TBM the avoided CO2 emissions are 118,8 + 62,0 = 180,8 ton, which is an increase of 180,8/118,8 * 100 = 152,2%.

As mentioned in 7.5.3 the substitution of scrap wood into a whole panel is less suitable for load bearing components and floor and roof panels, but more suitable for non-load bearing elements, such as the internal walls and façade walls. So, when whole panels of scrap wood CLT are only used in those walls the total carbon savings in comparison to virgin wood is 3,6 + 8,1 = 11,7 ton CO2, where 0,1 + 0,3 = 0,4 ton CO2 needs to be subtracted due to production: 11,7 - 0,4 = 11,3 ton of saved CO2 emissions, see the right column of the Table. Compared to virgin wood, (11,3+55,3)/55,3 * 100% = 120,4% more CO2 emissions are saved, and compared to substitution of TBM = 118,8 + 11,3 = 130,1 is saved, which is an extra savings of 130,1/118,8 = 109,5%.

7.6.4 SCENARIO 2 INNER LAYERS

In this scenario, the surface layers do not contain scrap wood, and therefore need to be omitted from the calculation. In a three layer panel this means only one layer consists of scrap wood and the 5 layer panel of 3 layers, as is shown in table 5. The total volume of scrap wood is 41,6 m3, which is 49% of the total volume of the case study. The total amount of CO2 that is stored in the scrap wood is 31,6 ton. The production of those layers emits 1,1 ton CO2, so a total of 31,6 - 1,1 = 30,5 ton CO2 is saved by the substitution virgin wood with scrap wood. This is (30,5+55,3) / 55,3 * 100% = 155,1% more CO2 is saved. In relation to the TBM this is an extra saving of 30,5 + 118,8 = 149,3 ton CO2, which is 125,7% more than CLT from virgin wood.
These panels are more likely to be used in load-bearing constructions, due to the surface layers consisting of virgin wood with a high strength class. The needed ratio in the floors slabs can cause these panels to be unable to be used in floors and and roofs. So when only these panels are used in walls the total amount CO2 stored is 14,1 ton and with the production subtracted 14,1 - 0,5 = 13,6 ton CO2 is saved. This is tan extra CO2 saving of (13,6+55,3)/55,3 * 100% = 124,6% compared to virgin wood and 132,4/118,8 * 100% = 111,4% compared to traditional building materials.

												Partly substition	
Component	**Area panel** [m2]	**Amount of scrap wood layers**	**Scrap wood layers** [mm]			**Total thickness scrap wood layers** [m]	**Volume of scrap wood layers in 1 panel** [m3]	**Amount of panels**	**Total volume of scrap wood layers** [m3]	**CO2 storage** [ton CO2]	**CO2 emissions of production (A1-A5)** [ton CO2]	**CO2 storage** [ton CO2]	**CO2 emissions of production (A1-A5)** [ton CO2]
Partition wall	31,8	3	20	20	20	0,06	1,91	6	11,4	8,7	0,3	8,7	0,3
Façade wall*	7,95	1		40		0,04	0,32	6	1,9	1,4	0,0	1,4	0,0
Internal wall	106	1		40		0,04	4,24	1	4,2	3,2	0,1	3,2	0,1
Stability wall	5,3	3	20	20	20	0,06	0,32	3	1,0	0,7	0,0	0,7	0,0
Floor	72	3	40	40	40	0,12	8,64	2	17,3	13,1	0,4		
Roof	72	3	20	40	20	0,08	5,76	1	5,8	4,4	0,1		
Total									41,6	**31,6**	**1,1**	**14,1**	**0,5**
									Total saved CO2:**	**30,5**	**ton CO2**	**13,6**	**ton CO2**
									Total saved compared to TBM:	**149,3**	**ton CO2**	**132,4**	**ton CO2**

*50% of wood in the façade
**CO2 storage - CO2 emissions caused by production (A1-A5)

Table 5_Saved CO2 calculations of scenario 2 (own table)

7.6.5 SCENARIO 3 TRANSVERSE LAYERS

When only the transverse layers consists of scrap wood the 3 layers also consists of 1 layer of scrap wood and the 5 layer panel has two transverse layers of scrap wood. The total volume of scrap wood is now 28,8 m3, which is 34% of the total volume. This volume stores 21,9 ton CO2 in the transverse layers, see table 6. The production of these layers emits 0,7 ton CO2, so a total of 21,9-0,7 = 21,1 ton CO2 is saved. In comparison to virgin wood transverse layers (21,1+55,3)/55,3 * 100% = 138,2% CO2 is saved. When looking at the TBM this is a saving of 139,9/118,8 = 117,8%.

Scenario 3 can have the same problem as in scenario 2 where the dimensions of the scrap wood lamellae are not the correct ratio and therefore not fit for floor and roof slabs. So when these transverse layers are only applied in wall components 10,9 ton CO2 is stored and with production the total saving is 10,9 - 0,4 = 10,6 ton CO2 (outcome is “incorrect” due to rounded numbers). This is an increase in total savings of (10,6+55,3)/55,3 = 119,1% pertaining to virgin wood and 129,4/118,8 = 108,9% pertaining to traditional building materials.

									Partly substition		
Component	**Area panel**	**Amount of scrap wood layers**	**Scrap wood layers**	**Total thickness scrap wood layers**	**Volume of scrap wood layers in 1 panel**	**Amount of panels**	**Total volume of scrap wood layers**	**CO2 storage**	**CO2 emissions of production (A1-A5)**	**CO2 storage**	**CO2 emissions of production (A1-A5)**
	[m2]		[mm]	[m]	[m3]		[m3]	[ton CO2]	[ton CO2]	[ton CO2]	[ton CO2]
Partition wall	31,8	2	20 20	0,04	1,27	6	7,6	5,8	0,2	5,8	0,2
Façade wall*	7,95	1	40	0,04	0,32	6	1,9	1,4	0,0	1,4	0,0
Internal wall	106	1	40	0,04	4,24	1	4,2	3,2	0,1	3,2	0,1
Stability wall	5,3	2	20 20	0,04	0,21	3	0,6	0,5	0,0	0,5	0,0
Floor	72	2	40 40	0,08	5,76	2	11,5	8,7	0,3		
Roof	72	2	20 20	0,04	2,88	1	2,9	2,2	0,1		
Total							28,8	**21,9**	**0,7**	**10,9**	**0,4**
							Total saved CO2:**	**21,1**	**ton CO2**	**10,6**	**ton CO2**
							Total saved compared to TBM:	**139,9**	**ton CO2**	**129,4**	**ton CO2**

Table 6_Saved CO2 calculations of scenario 3 (own table)

7.6.6 SCENARIO 4 MIDDLE LAYER

Scenario 4 has the lowest amount of scrap wood in this case study when looking at substituting layers in a CLT panel, so between scenario 1-4. Only the middle layer is from scrap wood. The total volume of scrap wood is down to 18,9 m3, which is 22% of the total volume. The total CO2 emissions stored in those layers are 14,4 ton, and the production emits 0,5 ton CO2, so a total of 13,9 ton CO2 is saved with this scenario, see table 7. In relation to virgin wood this is a saving of (13,9 + 55,3)/55,3 * 100% = 125,1%. The total amount of savings in relation to TDM is 132,7 ton CO2, which is a rise of 111,7%.

The middle layer barely contributes to the load-bearing capacity of a 5 layer panel, but does contribute to the rolling shear strength as a transverse layer in a 3 layer panel. Because less scrap wood is used the change of the availability of the right ratio is higher, so there is a bigger change that this technique could be used in the whole building. In a 5 layer floor or roof panel the middle layer is not a transverse layer, so this scenario can be applied in every component. Therefore the stored, emitted and saved CO2 is equal to the amounts already mentioned, and thus also the percentage of CO2 savings.

									Partly substition		
Component	**Area panel**	**Amount of scrap wood layers**	**Scrap wood layers**	**Total thickness scrap wood layers**	**Volume of scrap wood layers in 1 panel**	**Amount of panels**	**Total volume of scrap wood layers**	**CO2 storage**	**CO2 emissions of production (A1-A5)**	**CO2 storage**	**CO2 emissions of production (A1-A5)**
	[m2]		[mm]	[m]	[m3]		[m3]	[ton CO2]	[ton CO2]	[ton CO2]	[ton CO2]
Partition wall	31,8	1	20	0,02	0,64	6	3,8	2,9	0,1	2,9	0,1
Façade wall*	7,95	1	40	0,04	0,32	6	1,9	1,4	0,0	1,4	0,0
Internal wall	106	1	40	0,04	4,24	1	4,2	3,2	0,1	3,2	0,1
Stability wall	5,3	1	20	0,02	0,11	3	0,3	0,2	0,0	0,2	0,0
Floor	72	1	40	0,04	2,88	2	5,8	4,4	0,1	4,4	0,1
Roof	72	1	40	0,04	2,88	1	2,9	2,2	0,1	2,2	0,1
Total							18,9	**14,4**	**0,5**	**14,4**	**0,5**
							Total saved CO2:**	**13,9**	**ton CO2**	**13,9**	**ton CO2**
							Total saved compared to TBM:	**132,7**	**ton CO2**	**132,7**	**ton CO2**

Table 7_Saved CO2 calculations of scenario 4 (own table)

7.6.7 SCENARIO 5: LAMELLAE OF MIXED DIMENSIONS & WOOD SPECIES

This scenario consists of mixed lamellae in terms of dimensions and wood species, the latter possibly consisting of hardwood and softwood species mixed together. Each wood species has different carbon storage capabilities and therefore the actual CO2 storage differs more than the other scenarios, but for this calculation the same factor of 0,759 is used. Therefore the stored CO2 is the same as in the previous scenarios, when those different configurations of substitution are also applied in this scenario.

The production of this method will also require more glue to put all those pieces together and other machine operations to stack the mixed layers perpendicular onto each other, so the CO2 emissions caused by this kind of production can either be lower or higher. For the calculation of CO2 emissions of production (A3-A5) of 26 kg CO2/m3 is used. This means that the results of CO2 storage and savings are equal to scenario 1 - 4. These amounts are summarized in table 8.

Scenario 5: Lamellae of mixed dimensions & wood species

Component	Area panel	Amount of scrap wood layers	Scrap wood layers					Total thickness scrap wood layers	Volume of scrap wood layers in 1 panel	Amount of panels	Total volume of scrap wood layers	CO2 storage			
											Scenario:	*Whole panel*	*Inner layers*	*Transverse layers*	*Middle layer*
	[m2]		[mm]					[m]	[m3]		[m3]	[ton CO2]	[ton CO2]	[ton CO2]	[ton CO2]
Partition wall	31,8	5	40	20	20	20	40	0,14	4,45	6	26,7	20,3	8,7	5,8	2,9
Façade wall*	7,95	3		30	40	30		0,1	0,80	6	4,8	**3,6**	1,4	1,4	1,4
Internal wall	106	3		30	40	30		0,1	10,60	1	10,6	**8,0**	3,2	3,2	3,2
Stability wall	5,3	5	40	20	20	20	40	0,14	0,74	3	2,2	1,7	0,7	0,5	0,2
Floor	72	5	40	40	40	40	40	0,2	14,40	2	28,8	21,9	13,1	8,7	4,4
Roof	72	5	40	20	40	20	40	0,16	11,52	1	11,5	8,7	4,4	2,2	2,2
Total											**84,6**	**64,2**	**31,6**	**21,9**	**14,4**
											CO2 of production:	**2,2**	**1,1**	**0,7**	**0,5**
											Total saved CO2:**	**62,0**	**30,5**	**21,2**	**13,9**
											% virgin wood:	**212,1%**	**155,0%**	**138,3%**	**125,0%**

*50% of wood in the façade

**CO2 storage - CO2 emissions caused by production (A1-A5)

Table 8_Saved CO2 calculations of scenario 5 (own table)

This scenario is quite out-of-the-box and the mechanical properties should be tested If this method can not contribute load-bearing capacities and rolling shear strength, the whole panel scenario can be applied in non-load bearing walls such as the partition walls, 8,0 ton CO2, and possibly façade walls, 3,6 ton CO2. The total CO2 emissions stored will then be 11,6 ton CO2 and the production emits 0,1 + 0,3 = 0,4 ton CO2 (from table X). So the total CO2 that will be saved is 11,2 ton with this scenario, which is in comparison to virgin wood, (11,2+55,3)/55,3 = 120,4% CO2 emissions are saved and compared to TBM: 130,1/118,8 = 109,5%.

7.6.8 SCENARIO 6: CERTAIN PERCENTAGE OF SCRAP WOOD MIXED WITH VIRGIN WOOD IN CLT

The last scenario contains adding a certain percentage of scrap wood in a CLT panel, either in a layer, which will have the results from scenario 1-4, or mixed with virgin wood in the layers. The last option is shown in table 9, as the results of the former can be extracted from the other scenarios. The percentages decrease from total (= 100%) to 75%, 50%, 25%, 10% and 1%. The latter is to show what the impact of a percent is on the substitution with scrap wood. To calculate the percentages the thickness of each layer is not taken into account, but the total thickness of all layers, because with this method the thickness of each layer does not matter. As can be seen a 1% scrap wood content only results in a 101,1% extra savings of CO2 emissions compared to virgin wood and 100,5% to compared to TBM. A 10% scrap wood content is already an extra saving of 111,2% compared to virgin wood and 105,2% compared to TBM. The rise in savings is 10 times the rise of 1%, so there is a linear relation. So, a very small amount of scrap wood content barely contributes to the extra CO2 savings and therefore is not really profitable. But with larger scrap wood contents quite a lot of extra CO2 emissions can be saved by using scrap wood instead of virgin wood.

Component	Area panel [m2]	Amount of scrap wood layers	Scrap wood layers [mm]					Total thickness scrap wood layers [m]	Volume of scrap wood layers in 1 panel [m3]	Amount of panels	Total volume of scrap wood layers [m3]	Total CO2 storage [ton CO2]	Percentage of scrap wood: *75%* [ton CO2]	*50%* [ton CO2]	*25%* [ton CO2]	*10%* [ton CO2]	*1%* [ton CO2]
Partition wall	31,8	5	40	20	20	20	40	0,14	4,45	6	26,7	20,3	15,2	10,1	5,1	2,0	0,2
Façade wall*	7,95	3		30	40	30		0,1	0,80	6	4,8	3,6	2,7	1,8	0,9	0,4	0,0
Internal wall	106	3		30	40	30		0,1	10,60	1	10,6	8,0	6,0	4,0	2,0	0,8	0,1
Stability wall	5,3	5	40	20	20	20	40	0,14	0,74	3	2,2	1,7	1,3	0,8	0,4	0,2	0,0
Floor	72	5	40	40	40	40	40	0,2	14,40	2	28,8	21,9	16,4	10,9	5,5	2,2	0,2
Roof	72	5	40	20	40	20	40	0,16	11,52	1	11,5	8,7	6,6	4,4	2,2	0,9	0,1
Total											**84,6**	**64,2**	**48,2**	**32,1**	**16,1**	**6,4**	**0,6**
											CO2 of production:	**2,2**	**1,7**	**1,1**	**0,6**	**0,2**	**0,0**
*50% of wood in the façade											**Total saved CO2**:**	**62,0**	**46,5**	**31,0**	**15,5**	**6,2**	**0,6**
**CO2 storage - CO2 emissions caused by production (A1-A5)											**% virgin wood:**	**212,1%**	**184,1%**	**156,0%**	**128,0%**	**111,2%**	**101,1%**
											% TBM:	**152,2%**	**139,2%**	**126,1%**	**113,1%**	**105,2%**	**100,5%**

Table 9_Saved CO2 calculations of scenario 6 (own table)

Figure 88 shows the percentages of extra CO2 savings compared to the substitution of virgin wood and the substitution of traditional building materials of scenario 6. In this graph can be seen that the substitution of 100% has the highest impact, with a total **extra** savings of 112,1% compared to virgin wood and 52,2% compared to TBM. Virgin wood already saves CO2 emissions and is 100%. Everything above is extra, so 212,1% becomes 112,1%. A decrease of scrap wood content is proportional to the decrease is CO2 savings.

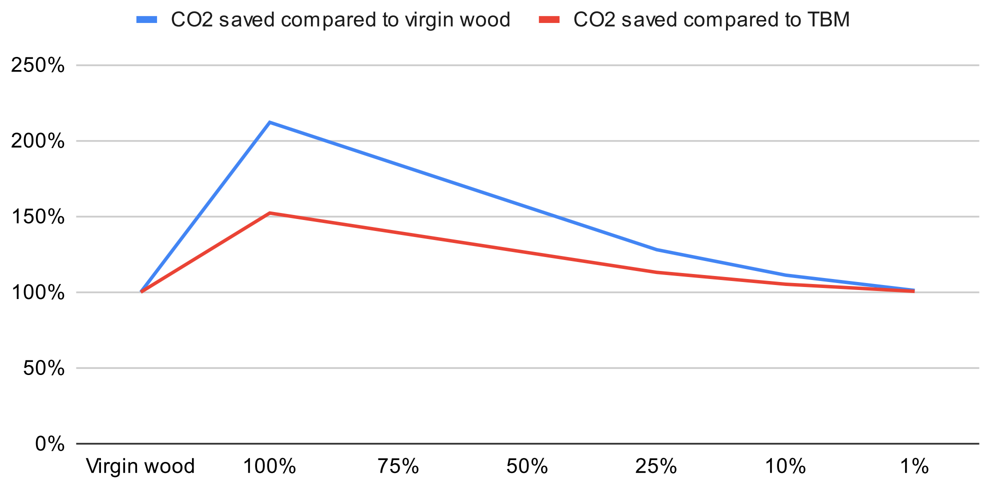


Figure 88_Comparison of saved CO2 emissions by substitution of scrap wood of virgin wood an TBM (own table)

7.6.9 CONCLUSION

In short, the total stored CO2, emitted CO2 by production, total saved CO2 in comparison to virgin wood and to traditional building materials have been calculated for each scenario. The substitution of virgin wood with scrap wood saves extra CO2 emissions, because the CO2 stored in scrap wood would otherwise be emitted and virgin wood can either be used elsewhere or not be harvested from forests, so extra CO2 is and stays absorbed. Therefore the substitution of scrap wood in CLT panels can lead to significant extra reductions in CO2 emissions compared to using virgin wood, with highest extra savings of 112% in scenario 1 (100% scrap wood panel).

The scenarios are divided into scenario 1-4, where one or more layers are substituted and scenario 5 & 6, where a certain amount of scrap wood is inserted into a CLT panel, either with one of the methods of scenario 1 to 4 or to mix scrap wood and virgin wood together in the layers. So when scenario 1 to 4 are compared, the amount of CO2 saved decreases with each following scenario due to the decrease of scrap wood content into the CLT panels. In figure 89 the total volume in the building and amount of stored CO2, and saved CO2 emissions each scenario (0-4) is shown.

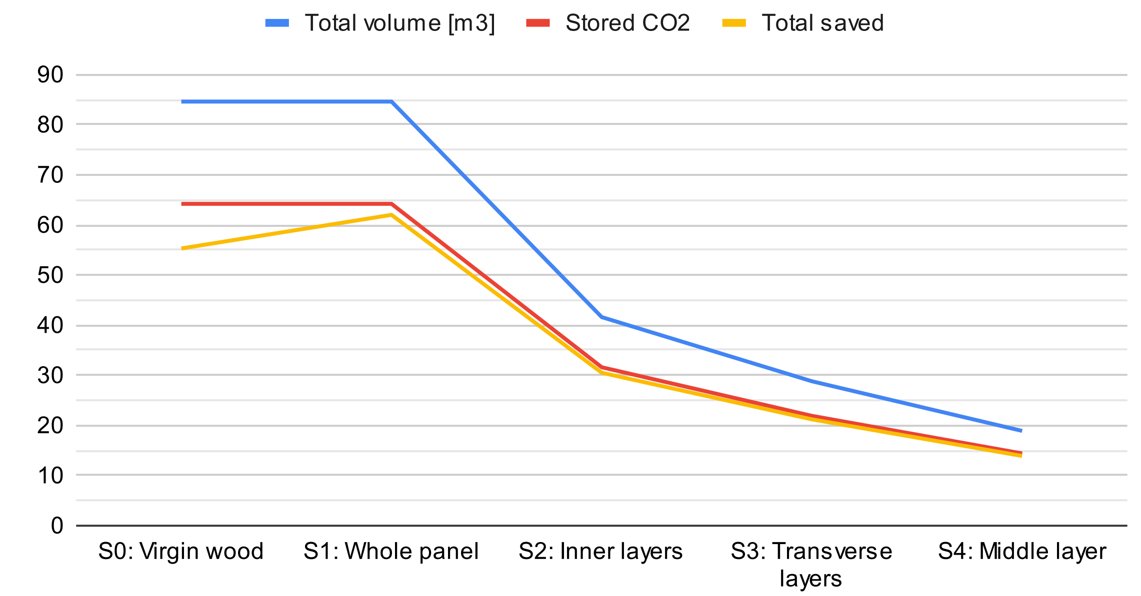


Figure 89_Comparison of the scenarios by total volume, stored CO2 and saved CO2 (own image)

As can be seen, Scenario 1 shows an increase of saved CO2 emissions compared to virgin wood, because CO2 emissions of harvesting wood (A1-A3) can be omitted. The difference between the stored CO2 and total saved CO2 is the deduction of CO2 emissions caused by production. This difference decreases more when the volume of scrap wood decreases. This volume decreases significantly between Scenario 1 and scenario 2. Therefore the the total amount of saved CO2 also decreases significantly. This graphs also applies for scenario 5, which involves using lamellae of mixed dimensions and wood species.

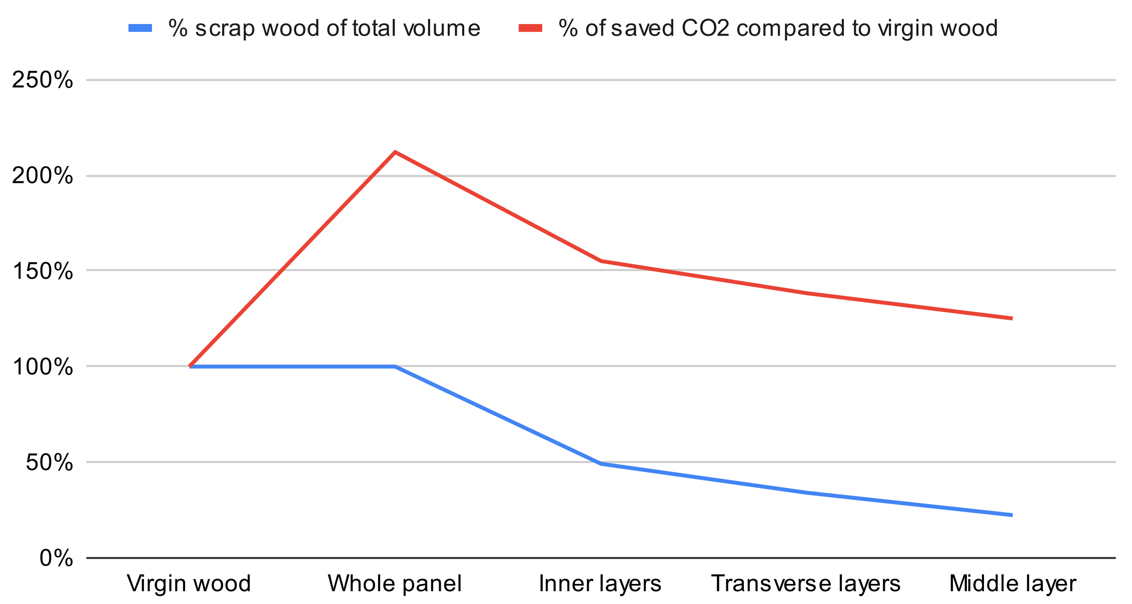


Figure 90_Comparison of the scenarios by total volume and total saved CO2 emissions compared to virgin wood (own image)

Figure 90 shows the relation between the percentage of scrap wood per scenario and the amount of CO2 that is saved by substituting virgin wood with scrap wood. The graph shows that all scenarios have a positive impact on the extra CO2 savings, but the impact decreases for each following scenario because of the decrease of scrap wood content. It can be concluded that in terms of CO2 savings the most sustainable option is scenario 1, but this is not always possible due to the unavailability of certain mechanical properties and consistency of scrap wood. The possible applied scenario is therefore dependent on the availability of these aspects. In terms of CO2 savings and the decrease of scrap wood, the highest scrap wood content in a panel should be tried to achieve. If scenario 1 is not possible, then try scenario 2 and then scenario 3 etc.

These aspects will also determine for which components in the building the scrap wood CLT panels can be used. When the right dimensions for the ratio are not available the substitution of scrap wood is not suitable for floor and roof panels, only for S4, in the middle layer for a CLT panel of 5 layers, because then the middle layer is not a transverse layer. If the right strength class is not available the scrap wood can be used in load-bearing layers, especially on the surface layers. Then the transverse layers scenario (S3) is the most suitable. When the strength class that is needed for the load bearing layers that are not the surface layers can be reached with scrap wood, then the scenario 2 is also suitable. From all four scenarios, scenario 4 (middle layer) is the most suitable and therefore the most possible option, but implements the lowest amount of scrap wood.

So, in order to see what the environmental impact of saved CO2 emissions in a terraced house when the most suitable scenarios are applied per component, a calculation was done, see table 10. In this calculation the facade walls and internal walls consist of a whole panel of scrap wood, because those panels are not load-bearing. The partition walls and stability walls are load-bearing and therefore scenario 2 (inner layers) is applied. The floor and roof slap consist of 5 layers and therefore scenario 4 is the most suitable. The scrap wood content in this case study is 36,4 m3, which is 43% of the total volume. The total amount of saved CO2 emissions is 26,7 ton CO2. This is an saving of 148,2% compared to virgin wood and 122,5% compared to TBM. So an **extra** 48,2% of CO2 emissions are saved by using 43% of scrap wood in a building.

Component	**Scenario**		**Area panel** [m2]	**Amount of scrap wood layers**	**Scrap wood layers** [mm]	**Total thickness scrap wood layers** [m]	**Volume of scrap wood layers in 1 panel** [m3]	**Amount of panels**	**Total volume of scrap wood layers** [m3]	**CO2 storage** [ton CO2]	**CO2 emissions of production (A1-A5)** [ton CO2]
Partition wall	2	Inner layers	31,8	3	40 **20 20 20** 40	0,06	1,91	6	11,4	8,7	0,3
Façade wall*	1	Whole panel	7,95	3	**30 40 30**	0,1	0,80	6	4,8	3,6	0,1
Internal wall	1	Whole panel	106	3	**30 40 30**	0,1	10,60	1	10,6	8,0	0,3
Stability wall	2	Inner layers	5,3	3	40 **20 20 20** 40	0,06	0,32	3	1,0	0,7	0,0
Floor	4	Middle layer	72	1	40 40 **40** 40 40	0,04	2,88	2	5,8	4,4	0,1
Roof	4	Middle layer	72	1	40 20 **40** 20 40	0,04	2,88	1	2,9	2,2	0,1
Total									36,4	**27,6**	**0,9**
									Total saved CO2:**	**26,7**	**ton CO2**
									Total saved compared to TBM:	**145,5**	**ton CO2**

Table 10_Saved CO2 calculations of the most suitable scenarios per building component (own table)

Softwood weights around 500 kg/m3 (Van der Lugt, 2021), although the weight differs per wood type and wood species. Hardwood is mostly denser and therefore heavier. For this calculation is 500 kg/m3 (=0,5 ton/m3) is used. So, yearly around 435 kton scrap wood is produced. This equals to around 217.500 m3 wood. If all scrap wood could be remanufactured into CLT in the most suitable scenarios around 217.500/36,4 = 5.975 CLT houses could be built. The amount of stored CO2 is then:
5.975 x 27,6 = 164.918 ton CO2. The total amount of CO2 emitted is only 5.378 ton CO2, and thus the amount of saved CO2 is 159.540 ton CO2 = 159,5 kton CO2. This amount would otherwise be emitted in the atmosphere. The total embodied carbon of newly constructed houses is 3,04 Mt/eyar. The scrap wood substitution can reduce 159,5 / 3040 = 5,2% of the embodied carbon by saving CO2 from being emitted into the air.

However, not all scrap wood is reusable and remanufacturable. So when only 50% of 435 kton is remanufacturable into CLT panels, the total amount of saved CO2 emissions are: 79.770 ton CO2 = 79,8 kton saved CO2 emissions. This accounts for 2,6% of the embodied carbon of newly constructed houses.

In short, the substitution of virgin wood with scrap wood can contribute to the reduction in CO2 emissions caused by the built environment, when a part of the scrap wood is substituted. If whole scrap wood panels could be manufactured from scrap wood even more CO2 emissions could be reduced.

7.7 CONCLUSION

Cross-laminated Timber, in short CLT, is a construction product suitable for (non) load bearing elements as floors, roofs and walls, made from the renewable material wood, mostly from the softwood species spruce or pine, but other wood species can also be used. CLT consists of panels of an uneven amount of layers perpendicular glued onto each other. The most commonly used layers are 3, 5 or 7. Each layer consists of lamellae laid next to each other, with varying dimensions of 20-60 mm in thickness and 40-300 mm in width. The length of lamellae can be elongated through finger jointing. The panel size itself varies, but has a maximum size of 30 m x 4,8 m, although commonly 16 x 3,5 m is manufactured. These varying dimensions make scrap wood suitable to implement in CLT panel, because of the varying consistency of scrap wood in terms of dimensions and wood species.

CLT panels have a long lifespan of buildings CLT and can be reused, so the sequestered CO2 in the wood of the CLT is sequestered for a very long time. In the meantime the trees that were needed for the CLT panels have been regrown multiple times. When the energy that is recovered during incineration at the end-of-its-life substitutes fossil fuels, CLT results in a CO2 negative impact on the environment. These aspects label CLT as a sustainable and renewable product that fits into the sustainability and circularity ideas. Together with the need for 1.000.000 houses by 2030, the demand for buildings from CLT will rise. The demand for wood will also rise, so scrap wood can partly accomodate that demand.
Some important factors of CLT are the mechanical properties. The strength class is important in the load-bearing layers, especially in the surface layers, because there the most stress occurs. In panels loaded out of plane the rolling shear strength of the transverse layers are important, which can be strengthened with a ratio of the lamellae of width = 4 * thickness and edge gluing.

To see if scrap wood can be implemented six 6 scenarios have been set up. 4 scenarios consists of substituting one or more layers in a panel with scrap wood: 1 scenario discussed the use of mixed smaller pieces in one or more layers and the last scenario discusses a certain percentage of mixed virgin and scrap wood in a panel, either in one or more layers or mixed throughout the whole panel. After the explanation of the scenarios the saved CO2 emissions for substituting virgin wood with scrap wood were calculated and compared in comparison to virgin wood and traditional building materials. Before the scenarios were discussed a few assumptions and criteria were set up. The assumptions were:

- Enough available scrap wood, but with varying dimensions
- Varying strength class where not all scrap wood meet the required strength class for load-bearing layers
- All scrap wood has the same moisture level
- The factories are located in the Netherlands
- Scrap wood is delivered to the factory has semi-finished, sorted pieces, but with varying dimensions, wood species and strength classes

The scenarios were graded on a set of a few criteria on a scale from 1-5. These criteria were:

- Importance of dimensions
- Importance of ratio
- Importance of strength class
- Impact on manufacturing process

In conclusion, the use of Cross-Laminated Timber (CLT) panels with scrap wood substitution can lead to significant reductions in CO2 emissions compared to using virgin wood, depending on the scrap wood portion in CLT. The amount of CO2 saved varies depending on the scenario, with the highest savings achieved when constructing the entire CLT panel from scrap wood.
The substitution of scrap wood not only prevents the emission of stored CO2 when incinerated but also reduces the demand for virgin wood. This reduction in demand can help preserve forests or accommodate the growing need for wooden buildings without increasing the harvesting of wood from forests.
When comparing CLT panels with scrap wood to traditional building materials, the savings in CO2 emissions are even more significant. The emissions which are normally emitted during production of TBM are not emitted and therefore extra CO2 are saved and because the saved CO2 of scrap wood are extra savings on top of the saved CO2 by using CLT from virgin wood.
The suitability of scrap wood substitution in CLT panels depends on factors such as mechanical properties and availability. Different scenarios, such as substituting specific layers or mixing scrap wood with virgin wood, offer various options for incorporating scrap wood in CLT panels. The selection of the most suitable scenario depends on the specific availability of scrap wood dimensions, wood species and mechanical properties.

Overall, the findings demonstrate the potential of using scrap wood in CLT panels as a sustainable and environmentally friendly alternative to virgin wood. By maximizing the use of scrap wood and optimizing the design and construction process, significant CO2 emissions can be saved, contributing to a more sustainable built environment. Already 5,2% of the embodied carbon of newly constructed houses can be reduced when the most suitable scenarios are applied in a terraced house when all scrap wood is remanufactured, and 2,6% can be reduced of only 50% of scrap wood is remanufactured. When looking at the substitution of TBM with CLT from scrap wood, even more CO2 emissions can be reduced.

8 CONCLUSION

8.1 DISCUSSION

In this paragraph the limitations of the research in this thesis are discussed. This helps to understand how the results were shown as well as giving insight in what still could and needs to be researched in the world of reusing waste and scrap wood.

Information about scrap wood

A big limitation of this thesis is the available information about scrap wood. Data from the amount of waste and scrap wood dates back to 2019 and 2017, with the most detailed information in 2017. There is a rough indication of how much waste wood is incinerated and recycled. The information about the amount of waste wood that is reused and how it is reused is small. About the actual consistency of scrap is also barely any information. This is due to the lack of rules to keep track of such information. The consistency of scrap wood varies widely due to the varying buildings products it consists of. Not only vary building products between each other in terms of dimensions, used wood species, mechanical properties and quality. This variation also exists within a certain building product. Figuring out all those different aspects is too time consuming for business and therefore there isn't any information. The information that is used in this thesis is from literature studie, Sloopcheck and some from interviews with different kind of people in the industry, but it is also based on assumptions of what scrap wood consists of by looking at existing building products and their properties. Because of these assumptions on the consistency the production chain and case study are also partly based on assumptions on how those varying aspects of scrap wood might impact the reuse of scrap wood. This topic is something that could benefit from more research, to really understand what scrap wood consists of and therefore what possibly could be done with it in terms of sustainability

Possible interviews

A portion of the research for this thesis was done through interviews with people from different links in the possible reuse and use chain of wood. Due to the time limit of this thesis I was able to talk to one or two people per link about the problems with the lack of reuse of scrap wood. Although they gave me a lot of information and their opinion of what should and could happen with scrap wood, one or two persons do not necessarily represent the whole chain. A research where multiple people and companies would be interviewed could bring some more information about the use and reuse of wood in the C&D industry.

8.2 CONCLUSION

In this paragraph the research questions will be answered which were stated in the introduction. First a short summary of the context is given. The world is facing a massive challenge of fighting climate change before the consequences become irreversible. The challenge is reducing the CO_2 emissions and change the material consumption from a linear economy to a circular economy where waste is eliminated and materials are mostly renewable and kept in the loop for as long as possible. Wood, due to it being renewable and having the ability to store CO_2, is going to play a big part in this challenge, especially for the built environment, which is one of the biggest contributors to climate change. But not only the use of virgin wood is going to be important, the production of waste (1,8 Mton) & scrap wood (435 kton) needs to decrease to comply with the circular (build) economy goal of eliminating waste. At the moment scrap wood is mostly incinerated and partly recycled but there might be some potential for reusing or remanufacturing scrap wood to elongate the lifespan of wood and storage of the CO2.

8.2.1 RESEARCH QUESTIONS

The main research question that was the topic of this thesis regarding the topic of reusing scrap wood was:

> *How can scrap wood be reused in the built environment and what is a suitable building product?*

In order to answer this questions some sub-questions and background questions were set up and these will be answered first before the main question is answered

8.2.2 WHAT KIND OF WOOD IS THERE?

This background question was discussed in chapter 3 Wood. Wood is renewable material that comes from trees. There are over 60.000 different kind of tree species, each with their own properties. These can be divided in softwood species, such as spruce, pine and fir or hardwood species, such as Oak, Birch, Ash or Maple or for tropical hardwood Teak, Mahogany and Meranti. The most important differences are that hardwood species are mostly harder, denser and more durable against environmental circumstances and therefore more suitable to use outside, but it grows slower. Softwood is softer and therefore easier to handle and grows quicker.

Wood has some important (mechanical) properties for the use in building products: density, thermal conductivity, linear expansion coefficient, bending strength, compressive strength, shear strength, splitting strength, and Janka hardness.

Wood has a low environmental impact because it stores CO2 (0,9 ton CO2/m3 softwood), emits low amounts of CO2 during product, and only emits the stored CO2 during energy recovery, which can be used for substitution of biofuel. Wood is the only commonly used construction material that is renewable. The use of wood in construction can therefore contribute to reducing CO2 emissions and achieving sustainable goals.

Wood identification can be a complex process, requiring expertise and specialised tools. Accurate identification is important for ensuring the proper use and recycling of wood products. While visual identification is commonly used, there is a lack of quick machine identification, but advancements in this technology could give potential for more accessible and reliable methods in the future.

8.2.3 WHAT KIND OF WOODEN PRODUCTS CONSISTS IN BUILDINGS?

Wooden building products consists of structural elements, such as HSB and CLT, beams, columns, rafters, plates, ribs & slats, window frames, doors and doorframes, stairs and planks. These products consists of solid wood pieces or wood-based materials and are used for interior and exterior applications, for the latter mostly hardwood species are used. All these building products differ between similar and different product dimensions, shape, wood species and quality. All together the properties of the wooden building products vary greatly.

8.2.4 WHAT ARE PERFORMANCE REQUIREMENTS FOR WOODEN BUILDING PRODUCTS?

For certain products the wood needs to have certain performance requirements. For load-bearing construction this is the strength class. For the ability to resist deterioration there is the durability class, which is an important requirement for wooden products that are exposed to exterior and environmental circumstances.

8.2.5 WHAT DOES SCRAP WOOD CONSIST OF?

Yearly around 435 kton scrap wood is produced, of which most is incinerated for energy recovery, a portion is recycled for OSB and chipboard and 55 kton is reused (12,6%). Scrap wood consists of building products from solid wood and wood based materials. The biggest portions are window frames, wooden walls & framework and other products. Due to the varying dimensions and wood species used in wooden building products, scrap wood consists of a wide variety of dimensions and wood species, all mixed together on a big pile. Another variation is quality, because over time and due to exposure to exterior circumstances some scrap wood is damaged or deteriorated. These aspects have a negative effect on the mechanical properties of scrap wood, resulting in less strong wood. Ageing does not have an effect on the mechanical properties. In short, scrap wood consists of a wide variety of dimensions, wood species and quality.

8.2.6 WHAT ARE EXISTING CIRCULAR METHODS FOR SCRAP WOOD?

Although most of the scrap and waste wood is incinerated, a portion is recycled and reused. Recycling consists mostly of downgrading wood by shredding the wood and manufacturing it into OSB board or chipboard. Scrap wood products are reused on a small scale, mostly by individuals. Circular demolition companies gather reusable products and sell them on their company grounds or online. Scrap wood pieces are reused by companies outside the C&D industry.

8.2.7 WHAT KIND OF SCRAP WOOD IS NOT REUSED?

Scrap wood consists of a variety of building products, dimensions, wood species and quality. Only a portion is reused. Scrap wood that is not reused is: C-wood, damaged wood, deteriorated wood, wood that is too small, wood that does not meet the performance requirements and wood that is not in demand.

8.2.8 WHAT ARE THE BARRIERS FOR REUSING SCRAP WOOD?

- The barriers for reusing scrap wood are:
- Profit & costs (money)
- Time consuming process
- Lack of mechanical processes
- Difficulty of identifying wood species
- Uncertainty of supply stream
- Varying consistency
- Legislation

These barriers are caused and impacted by each other. The lack of mechanical processes, difficulty of identifying wood species and varying consistency result in a time consuming process of figuring everything out and sorting everything, together with careful collection and processing of scrap wood products & pieces. These processes are mostly done with manual labour, which results in high labour costs and therefore high costs of reusing scrap wood. The high costs results in high product price that are competing with recycling, incineration and building products of virgin wood. This can result in reusing scrap wood not being profitable. The lack of legislation specifically for reusing scrap wood makes companies hesitant to reuse scrap and ends up more rejected scrap wood. The uncertainty of the varying supply stream results in uncertainty for companies that want to reuse scrap wood.

8.2.9 WHAT WOULD THE REUSE PROCESS OF SCRAP WOOD LOOK LIKE?

The reuse process is divided into three phases: (post-)demolition phase, remanufacturing phase and product phase. The (post-)demolition phase contains the stages circular demolition, collection and sorting. Collection needs to be carefully done to minimize damage. Sorting is done through different steps: material, circular strategies, aspects (species, dimensions, quality and/or mechanical properties) and future function. The remanufacturing phase consists of the processing stage and remanufacturing stage. Sorted scrap wood pieces are processed into standardized ribs, slats and blocks that can be remanufactured into (semi) finished building products. Some processes are removing metal, cleaning and shaving. Some remanufacturing processes are finger jointing and lamination. The product phase consists of the semi finished product and end product stages. Elements from the remanufacturing stage can either be semi finished products that still need to be manufactured into building products or already be an end product. These last stages can be done at the same location of the remanufacturing phase or by companies that produce and sell specific building products.

8.2.10 WHAT KIND OF SCRAP WOOD HAS THE MOST POTENTIAL?

The potential for reuse can again be divided into the potential for scrap wood products and scrap wood pieces. All scrap wood products that can be reused should be reused. Scrap wood pieces with the most potential for reuse in the built environment are pieces with dimensions similar to the dimensions already used in building products or consist of popular and common species, such as hardwood pieces, especially tropical hardwood, have more potential than softwood due to its resistance to environmental circumstances and other properties. The tropical hardwood species also have more potential due to its scarcity and long travel distance. In terms of mechanical properties the scrap wood pieces with a high strength class or durability class have more potential to be reused.

Products that have the most potential for implementing scrap wood are products that consist of smaller pieces of wood that are finger jointed and/or laminated. Such products are window frames, ribs & slats and CLT. Out of these three types of products CLT has the longest lifespan due to it being a construction product and reusability. CLT consists of multiple smaller wood pieces (lamellae) that are laid next to each in a layer and perpendicular glued onto other layers. The dimensions of the lamellae can vary between 20-80 mm in thickness and 60-540 mm in width. Although CLT mostly consists of the same softwood species spruce or pine, other wood species can also be used in a layer. Also some layers are load-bearing and require a certain strength class, but not all layers. So the most potential for reuse of scrap wood is CLT.

8.2.11 WHAT ARE PRODUCTION TECHNIQUES FOR THE CHOSEN WOODEN BUILDING PRODUCT?

CLT consists of an uneven amount of layers perpendicular glued onto each other. A layer consists of multiple lamellae, a rectangular shaped wood piece, next to each other that all have the same thickness. The length of the lamellae can be up to 30 m due to the lamellae being elongated with finger joints. To strengthen the rolling shear strength in the transverse layers the edges of the lamellae could also be glued. With a CNC-cutter openings can easily be custom-made created.

8.2.12 WHAT IS THE SUSTAINABLE FOOTPRINT AGAINST VIRGIN WOOD USE?

Wood is already a sustainable material due to it being renewable and the ability to sequester CO2. If wood is applied in product with a long lifespan that can be reused and recycled several times, the CO2 is possibly sequestered for centuries. In the meantime all that wood has been regrown and have absorbed more CO2. The substitution of traditional building materials, such as concrete and steel, which only produces quite a lot of CO2 emissions, with wood can reduce the overall emitted CO2, which needs to be decreased to reach the sustainability goals. When energy recovery is used as substitution for fossil fuels even more CO2 emissions can be avoided because only the stored CO2 is emitted instead of extra CO2 emissions of fossil fuels, possibly resulting in a negative impact in the environment and therefore contributing to the sustainability and circularity goals. These aspects are not yet taken into account in the MPG, but if that happens the MPG of wooden products, especially CLT scores much better than concrete and steel, even having a negative impact. Although the sequestered CO2 will be emitted during energy recovery, this aspect should somehow be taken account into the MPG, so it is more beneficial to reach the MPG value, especially when it is lowered more in the future. More wood use results in a decrease in overall CO2 emissions, which is necessary to reach the sustainability goals of 2050. The sequestered CO2 is emitted far after 2050 and maybe in the future solutions have been found to catch that CO2.

When scrap wood is used even more CO2 is saved from being emitted, because the scrap wood is kept longer in the loop, especially when it is used in CLT, because that has the highest CO2 sequestration of all products and has the longest lifespand because of it being a construction material. Scrap wood has already emitted CO2 by the harvesting process and therefore does not need to be taken into account. Scrap wood scores even better in the MPG because it is a reused material. If scrap wood products are added to the NMD, the MPG value can even be more easily reached. A stricter MPG value will result in trying to find materials that can be used to reach that goal and the use of scrap wood can contribute to that. Scrap wood can also accommodate a portion of the rise in demand for wood, ensuring either more wood can be used without more forests have to be cut down or the forests can expand more. The use of scrap wood has therefore a very low environmental footprint, although transport distances should he minised.

8.2.13 MAIN RESEARCH QUESTION: HOW CAN SCRAP WOOD BE REUSED IN THE BUILT ENVIRONMENT AND WHAT IS A SUITABLE BUILDING PRODUCT?

Although there are many barriers to the lack of reuse of scrap wood, scrap wood has potential to be reused when it is collected, sorted and processed correctly. Scrap wood consists of a wide variety of dimensions, wood species and quality, which results in some barriers when it is not correctly sorted and processed. The reuse of scrap would benefit from a processing hub, where all scrap wood can be collected and processed into semi finished products (halffabricaten) and then transported to companies that remanufacture those pieces into building products. To quicken the whole process and so reducing manual labour costs, mechanical processes have to be developed that can sort, process, identify and grade the varying scrap wood pieces. When a scrap wood piece is processed into semi finished products it can be seen as a new solid timber piece, which can be used for a variety of building products. It must also be noted that the reuse process of scrap wood could also benefit when it is already sorted during the demolition phase.

CLT is a suitable building product because of the varying dimensions of the lamellae that a CLT panel is made out of. These lamellae are now mostly from spruce but other wood species can also be used. The mechanical properties vary between the layers, depending on if a layer is load-bearing or a transverse layer. The varying consistency, in terms of wood species, dimensions and mechanical properties of scrap wood is therefore suitable to implement in scrap wood panels. The scrap wood can be substituted into one or more layers in a CLT panel or it can potentially be mixed with virgin wood in a layer. Although for the last scenario, when scrap wood consists of the same wood species and possible strength class it can be seen as the same as the virgin wood pieces. The substituting of scrap wood in the layers is possible when the necessary wood species and strength class for the load bearing layers or ratio for the transverse layers in panel loaded-out-of-plane are available. The potential unavailability combined with the uncertain supply stream can be solved by adding similar pieces of virgin wood. The CLT manufacturer should not rely on the scrap wood stream. Some research of substituting the middle (transverse) layer of a 3 layer panel shows potential for the implementation of scrap wood.

The implementation of scrap wood into CLT panels where discussed along 6 scenarios of varying scrap wood consistencies. In terms of CO_2 savings the most suitable option is construction a whole panel of scrap wood (scenario 1), because the most important layers in terms of load-bearing capacity are the surface layers. Implementing scrap wood in those layers is the most risky, except for panels that are not load-bearing such as internal walls and some façade walls. The other scenarios, 2-4, are more suitable for implementing scrap wood. The most suitable option scenario 4, where only the middle layer is substituted, but this has the lowest impact on CO_2 savings and lowest scrap wood content. The most suitable components for each scenario applies when there is not enough scrap wood of certain properties. For load bearing walls the most suitable options are scenario 2, 3 and 4, for non load bearing walls all scenarios are suitable and for floor and roof slabs the most suitable option is scenario , when a panel has 5, 9 or 11 layers. Overall the implementation of scrap depends on the availability of scrap wood with the required properties. Sometimes all components can be produced, other times on the most suitable option.

When looking at the sustainable gain of reusing scrap wood into CLT panels, the reuse of scrap wood always benefits in saving extra CO_2 emissions. The CO_2 stored in wood and CLT is much higher than it emits during production. In CLT around 0,759 ton CO_2 is stored / m^3 wood and it produces 0,026 ton CO_2 / m^3 wood for the stages of A3-A5. By substituting scrap wood into CLT elements, which are construction elements with a long lifespan and reusability the sequestered CO_2 in scrap wood is sequestered much longer.

In a CLT panel the CO_2 that is saved in scrap wood is an extra saving, because otherwise the CO_2 would be emitted during incineration and the stored CO_2 in virgin wood will stay stored, either in other building products or in forests. In terms of the scenarios: more scrap wood in a CLT panel means more extra CO_2 is saved, which is a linear relation. In scenario one there is even a rise in CO_2 savings, of 212,1%, due to the CO_2 emitted during harvesting can be left out. A substituting of 10% scrap wood in a residential building already saves 11,2% more CO_2. In comparison to the substitution of traditional building materials such as concrete and steel with wood already 0,75 ton CO_2/m^3 is saved, but with the extra substitution of scrap wood even more CO_2 emissions are saved, with an extra saving of over 100% for all scenarios.

In short, the substitution of scrap wood into CLT can elongate the sequestration of CO_2 while accomodating for the rise in demand of wood. So more wood can be used and more CO_2 can be stored. Although scrap wood can not always be implemented into whole panels of CLT, every bit of scrap wood that is reused and remanufactured results in a decrease in CO_2 emissions and waste production, which both aspects are necessary to reach the circularity goals.

9

RECOMMENDATIONS

This thesis highlights the potential of reusing scrap wood in the built environment with a case study of a suitable building product: CLT, to contribute to a more sustainable and circular construction industry. However, detailed information about the consistency of scrap wood does not exist and the scenarios for substituting virgin wood with scrap wood in CLT panels are possible scenarios that need to be tested before it can be used. This was outside the scope of this thesis, but it could further researched. Therefore is here a list of potential future research that is probably necessary to bring more information about scrap wood and to start the development of scrap wood products:

- Although there is some information about the consistency of scrap wood, mostly in percentages of products it consists of, a deeper and more thoroughly research could be done about the dimensions, wood species, shapes, quality, etc. scrap wood consists of, to bring more information of what is available for reusing scrap wood
- Evaluate the barriers of reusing scrap wood by talking to more professional throughout the wood, scrap wood and reuse chain in the built environment to understand more what the barriers are and how they can be solved, according to the professionals. For this thesis I only talked to a few experts.
- Development of automated processes that can quickly and easily
    - identify wood species
    - sort scrap wood
    - remove metal from scrap wood
- This thesis discusses some scenarios of implementing scrap wood into CLT panels, but these scenarios should be evaluated and tested to see if those scenarios could be developed or not.
- Development of legislation specifically about reusing scrap wood, especially for strength grading and who is responsible when a product with scrap wood fails. The development will help motivate companies to start reusing scrap wood and help to better understand how it can (actually needs) to happen.

10

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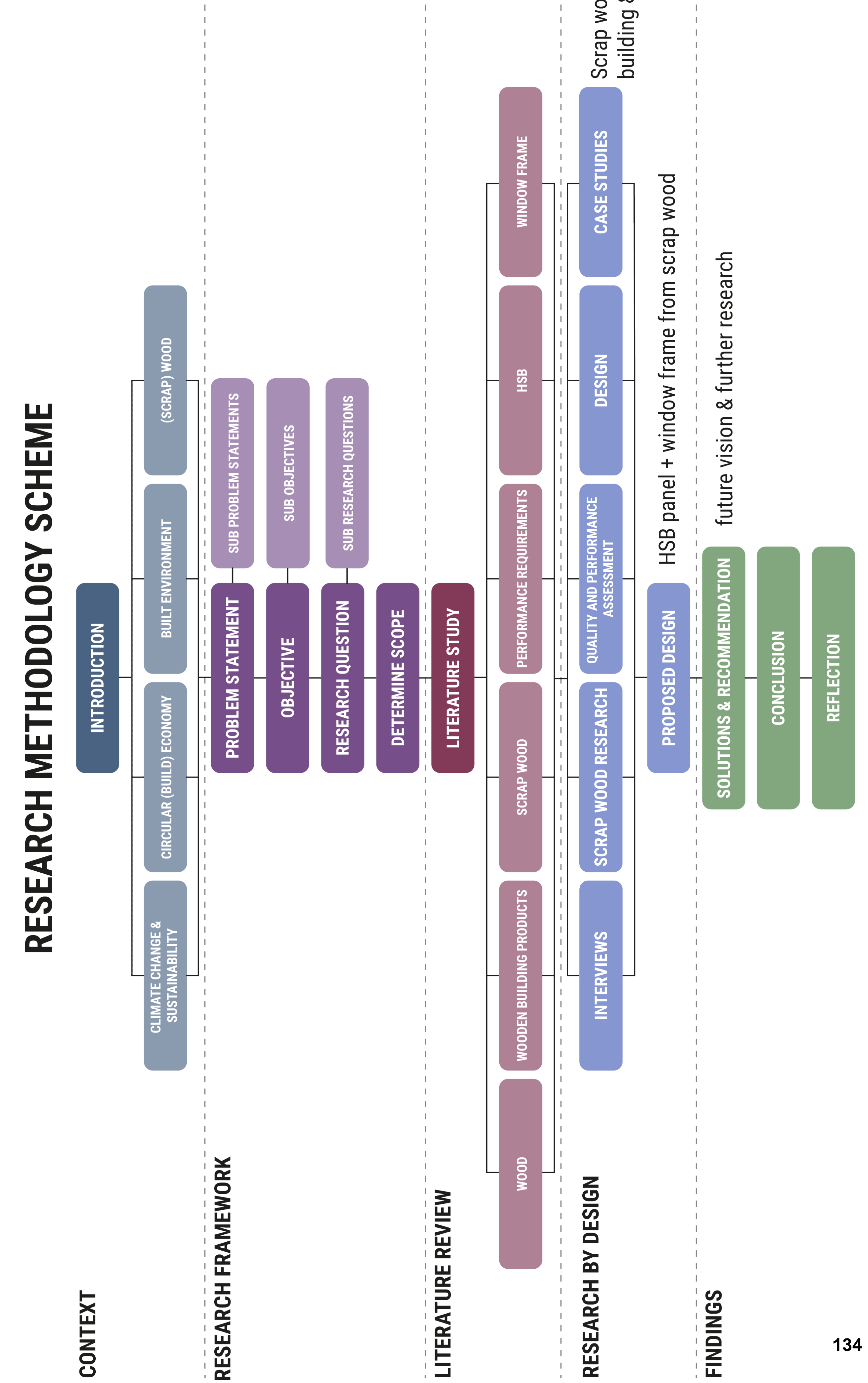
APPENDIX

APPENDIX 1 METHODOLOGY SCHEME



APPENDIX 2 R-STRATEGIES EXPLANATION

Smarter product use and manufacture	**R0**	**Refuse**	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1	**Rethink**	Make product use more intensive (e.g. through sharing products or by putting multi-functional products on market).
	R2	**Reduce**	Increase efficiency in product manufacture or use by consuming fewer natural resources
Extend lifespan of product and its parts	**R3**	**Reuse**	Re-use by another consumer of discarded product which is still in good condition and fulfils its original function
	R4	**Repair**	Repair and maintenance of defective product so it can be used with its original function
	R5	**Refurbish**	Restore an old product and bring it up to date
	R6	**Remanufacture**	Use parts of discarded product in a new product with the same function
	R7	**Repurpose**	Use discarded products or its part in a new product with a different function
Useful application of materials	**R8**	**Recycle**	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9	**Recovery**	Incineration of material with energy recovery

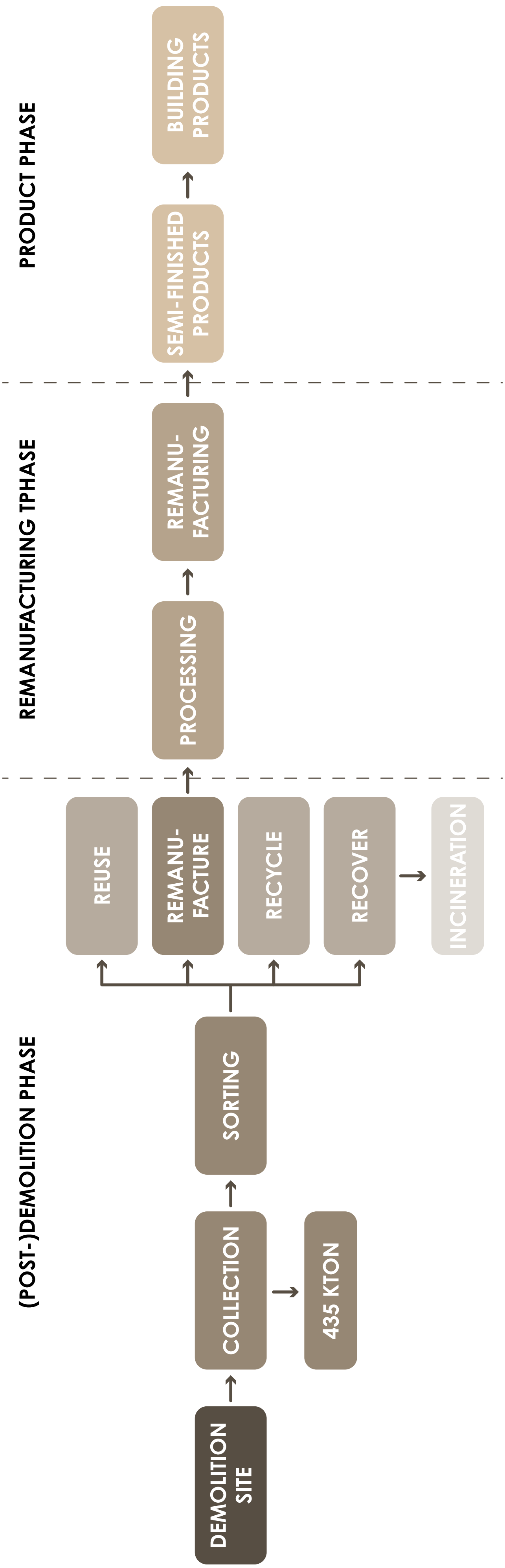
Figure X, https://www.sciencedirect.com/science/article/pii/S0921344919304598#:~:text=A framework based on 10,to scrutinise the selected targets.

APPENDIX 3 DIMENSIONS AND COMMON WOOD SPECIES OF WOODEN BUILDING PRODUCTS

Building product	Width [mm]	Height* [mm]	Length [mm]	Hardwood									Softwood					Tropical hardwood					
				Oak	Ash	Poplar	Elm	Douglas	Western cedar	Chestnut	Beech	Walnut	Spruce	Larch	Finti	Pine	Fir	Teak	mahonie	Merantie	Merbau	Iroko	Jatoba
Beams & columns	38 - 600	38 - 600	1000 - 16000																				
Planks	70 - 400	10 - 80	500 - 2500																				
Window (frames)	38 - 69	67 - 139	500 - 2500																				
Doors	530 - 1030	38 - 67	2015 - 2800													inside							
Door frames	90 - 115	45 - 66	468 - 3000																				
Ribs & Slats	12 - 50	38 - 120	100 - 3000																				

*or depth

APPENDIX 4 REUSE CHAIN OF SCRAP WOOD



APPENDIX 5 INTERVIEW SUMMARY

APPENDIX 5.1 HOUT MET HISTORIE | 28-02-2023

Hout met historie gathers used wood from across Europe and sell it processed or unprocessed for furniture, interior decoration or companies that make new products out of it. Most of the gathered wood consists of barn wood, wagon planks, log walls, beams, floor panels, bollards, railway sleepers and panelling. The processing consists of: sanding, shaving or brushed. Hout met historie does not reuse the wood als building products, so they could not give me information about that. But they gave some insight in the building industry. The industry changes slowly and works with fixed sizes and methods. Old and used wood is not in line with those methods and measurements. The old wood is "you get what you get", it can contain holes, tears, rips etc. Hout met historie does not test their wood on strength, but they do have a FSC certification for reused wood. For the strength of wood there is not yet a certification available. Because of the certain and different measurements of used wood the option for buildings are limited and the profit margins are small, in contrast to reuse wood for decorations, furniture and ornamental wood. In order to reuse wood in the building industry the pricing should be almost the same as for new wood, otherwise contractors and architects are not motivated to reuse wood. The world and the economy is a money based system, where almost everything needs to be cheap and with the most profit.

APPENDIX 5.2 HERSO - RIK RUIGROK | 16-03-2023

Rik Ruigrok is the owner of the company Herso, a circular woodworking company, where the reuse waste and scrap wood and remanufacture it into new products such as: flooring, wall panelling and furniture (mostly tables). The company does not reuse wood as a building product, but just as 'Hout met historie', Rik Ruigrok gave me some insight in the industry and why wood is not yet being reused as a building product. One of the first things he said is that reusing scrap wood as a building product is definitely possible, but the supply and consistency of scrap wood is uncertain, which makes companies and investors hesitant to use scrap wood. Accountants want to know how much profit a company will make, how wood is going in and out, etc. But for scrap wood that information is different every day, week, month, year.

The supply of wood is different every time. Demolition companies give estimations of the amount of scrap wood they will gather from a demolition site, but the numbers are always way lower due to how the wood is gathered. The scrap wood breaks or it is not stored properly. Every piece of scrap wood from a demolition project can have different measurements, which makes it hard to predict what the possibilities are. The scrap wood consistency varies for each party, demolition and delivery. Reusing scrap wood is expensive and therefore not profitable enough to start.

Within scrap wood there is:
- Material differentiation
- Size differentiation
- Quality differentiation
- Pollution degree

Between reusing scrap wood and energy recovery the gain should be considered, for example: 450 m3 wood can be turned into products or recover enough energy to provide 2,5 hours of electricity for Amsterdam.

Within the industry chain a new link has to be set up for gathering waste wood and processing it, such as drying, unnailing, planing/scraping and sanding, so it can be reused as a (semi) finished building product. This process is time consuming and expensive, due to salaries and therefore also not profitable enough.

At this moment the industry is at a tipping point from going to a circular economy from a linear economy. The industry kind of knows that it needs to change and why, but they are still trying to figure out how (and how to make it profitable). The mindset needs to change.

CLT is not really reusable but it can be made from all kind of wood, the plates consists of 8 mm multiplex.

APPENDIX 5.3 STIHO - THORBEN KWAKKENBOS | 20-03-2023

The third company I spoke with was Stiho, a company that sells building products but is also trying to become more circular and reuse building products. They work together with New Horizon, a circular demolition company, on reusing building products. They work on trying to find 1 on 1 connections between used building products and clients, building products from reused wood and at the moment they are researching how wood can be reused as a building product and semi finished products, mostly from soft wood. In their research they already found that 2x3 wooden ribs (44 x 70 mm) are very popular and commonly used, so used wood could be cut into those measurements and sold. Stiho also as found the same problem as Herso, namely that the processing of scrap wood is time consuming and expensive, which makes the use of new wood still more plausible than scrap wood. A processing production company on a big scale is still missing, only smaller companies exist that kind of reuse wood, but in order to make it more profitable it should probably be done on a bigger scale. There is also a problem with strength sorting, because there are no tests yet and due to the different placements and amount of screw holes the strength is hard to be determinant and sorted.

For the production finger jointing is a good technique, because bigger products can be created but the wood needs to be entirely nail and metal free otherwise the machines break and it is an expensive production technique.

We also talked the combining the use of new and old wood. Used wood can be implemented into the wood supply chain. The production companies are therefore not dependent on the scrap wood stream, but can add scrap wood when it IS available. The supply stream of scrap wood is uncertain. The amount of scrap wood a company has peaks. A company gets an amount of scrap wood from a demolition site (peak) and then has to process and sell that wood. During this process the amount of wood decreases and is only increased when another demolition project is finished. The time between demolition companies varies each time.

A downside to combining new and used wood is that when used wood is used it is mostly done for a certain reason, such as getting a label of being sustainable or circular. When new wood is added those labels are not applicable, which is not something clients want. But this is in my eyes a mindset thing. Reusing wood should not be done to gain a certain label, but just to decrease the amount of

CO2 and waste.

The kind of wood scrap wood consists of is mostly the most commonly used wood species, such as pine wood (vuren), oak, lariks, and for hardwood meranti (and mahonie).

Lastly, something to think about is if reusing wood has an environmental gain in terms of CO2, because all that wood is being transported from site to site, which also produces a lot of CO2.

APPENDIX 5.4 WOODJOINT - GIJS KUIPERS | 5-4-2023

The interview with Woodjoint was done with a site visit.

Woodjoint is a company that laminates and finger joints wood for the construction industry and GWW-industry from clients. I spoke to the owner Gijs Kuipers. They produce semi-finished products, for example for window frame profiles, CLT and HSB elements. Woodjoint produces, for example, a lot of window frame blocks of meranti.The wood waste that is produced during production is used as energy recovery for their own use through incineration. During the interview we walked through the factory, were he showed me how the process of finger jointing and laminating works.

For the process of finger jointing Woodjoint needs to have a minimum length of one piece that is 20 cm, the width does not matter. The thickness needs to be same when it is finger jointed to create equal strokes. The process of finger joining is cutting tooth like shape on the end and beginning of a wood slat and glueing those ends together. Then the products are shaved to shave of extra glue.

In the factory the wood is checked on its dimensions, knots and cracks and curvature. Some rejected pieces can be used for low-quality products and all other rejected material is used for biofuel.

Woodjoint is also part of the project done by BlueCity, were a CLT panel was constructed from CLT, but that panel still has to be tested.

In terms of the barriers for reusing scrap wood, Woodjoint had some suggestions. First, the removing of metal out of scrap wood is very important, especially when it is used for the manufacturing of products that have very expensive machines, because the metal can break such as machine. The company Cirqwood has a scanner that can take the metal out of the wood. Such a machine is necessary to reduce the time consuming process of removing the method, now done manually. He provided the idea of letting the sorting by building product be done by the demolition company on the demolition site. In terms of reusing scrap wood it is not suitable for reuse in exterior windows unless hardwood species are available, but it could be used for for example stairs.

An important step in the reuse chain starts at the demolition site. He suggests that the different materials in a building are removed by a demolisher that is an expert in that material, so they know how it should be removed from a building. This will ensure that more products stay whole during demounting and transport. At the moment too many demolition companies break materials and products that are hard too reach, resulting in many products that can not be reused or remanufactured. But the cleaner a products comes from a demolition site, the less processing handlings need to happen, the more profit can be produced.

At the moment the costs for reusing scrap wood in prefabricated constructions is too high to make a profitable panel. The reuse of scrap wood takes a lot of effort in terms of handling and processing. Scrap wood can better be reused in products that can ask for a higher price. The production of stairs and wooden profiles is more profitable. But the reuse process is all about costs and profit. It needs to be profitable enough. otherwise reuse won't happen. Woodjoint believes that the most profitable products for reuse are window frames, stairs, doors and ribs & slats. But he also believes it is an up-and-coming process that is at the start, but will eventually become normal.

When Woodjoint reuses scrap wood, the supply needs to consists of clean and solid wood without metal or a coating. For example, in his company a worker needs to produce 2000 m, through finger joining, a day to be able to pay the labour costs and make a profit. If the metal still needs to be removed and the coating needs to be shaved off then a worker does not have time to produce those 2000 m, especially when some scrap wood pieces also need to be laminated, which is in the width or height and does not contribute to the length of 2000 m.

In terms of strength degradation, the holes due to nails do not contribute, but knots do. The strength class depends on the latter.

Wood joints get cut out pieces from CLT panels and is able to finger joint those to make bigger panels, as long as the overall thickness is the same. For the GWW it combines hardwood and softwood for poles that are stuck in the ground and in water. The softwood part is used in the ground and the hardwood part in the water. This is done because hardwood is more valuable, so you want to use a minimum amount and when softwood is used in the ground, oxygen can't reach it so the softwood does not deteriorate. Scrap wood can be used for this.

APPENDIX 5.5 RENEWI | 20-4-23
The interview with Woodjoint was done with a site visit.

For the interview with Renewi I went to their location in Nieuwegein. While is was walking to the office I could already see massive piles of all kinds of scrap wood. The pile looked like it was a few meters high, around a 50-80 meters long and 20-40 meters wide. This pile was brought to Renewi in the last couple of days. The scrap wood seemed to consists of different products, dimensions, quality and of solid wood but also wood-based materials. After a talk in the office, they showed me around.

Renewi gathers all kinds of waste materials. They try to recycle the gathered products and materials that have become waste as much as possible, and otherwise it is used for energy recovery. They try to have the waste-to-product mindset, instead of contributing to the waste production. In terms of waste wood they gather A- and B-wood on big piles, which are then shredded and stored in a big container, that is later shipped to Belgium for the production of OSB- or chipboard. C-wood is just incinerated. At Renewi they try to become more sustainable and so they try to find other ways to reuse the waste wood better. On site were a few smaller containers that contained a portion of the scrap wood pile that was going to be researched about its consistency and what could possibly be done with it. They also see the potential of reuse, but the process chain is difficult.

Then they showed be how the other waste processing worked. They try to sort the waste as much as possible according to their material, to be able to recycled more materials. For certain sorting processes a machine shook so the smaller or heavier components fell down.

APPENDIX 5.6 VERMEULEN SLOOPWERKEN & ZN - PATRICK VERMEULEN | 25-4-23

Vermeulen & Zn Sloopwerken is a circular demolition company located in Breda. Instead of demolishing the whole building they take everything out of building, before demolishing the structure. The owner of the company, Patrick, showed be around his barn where he sold used products that he took or demounted from buildings and deemed reusable. The products consisted of wooden beams, ribs & slats, windows, doors, insulation, wooden plates, toilets, kitchen cupboards and appliances, furniture, metal structural elements, bricks, roof tiles, etc.

Patrick tried to put everything on Marktplaat.nl but the whole processing of photographing the products, measuring its dimensions and writing a description was too time consuming, which resulting in labour costs that were higher than the price a customer wanted to pay for a product. So on his website he has pictures with the categories that he has in is barn. Through google maps on that page you can also “walk” digitally through the barn: https://gebruiktesloopmaterialen.nl/. The products he sells the most are plates, beams, and ribs & slats, because of their cheap price. Some products from a building are taken by companies that produce new products of it.

An important factor of circular demolition is time. Removing all the materials and products by hand is a time consuming process. This results in a longer demolition time and therefore higher costs. Some client do not want that and therefore do not choose for circular demolition.

A hard product to remove are wooden plinths and are barely profitable, so those products are not really worth it to remove and sell. Another product that is hard to remove are window frames. A lot of window frames break. They sent their waste wood to Renewi, where it is recycled.

APPENDIX 6 WOOD PRICE INDEX

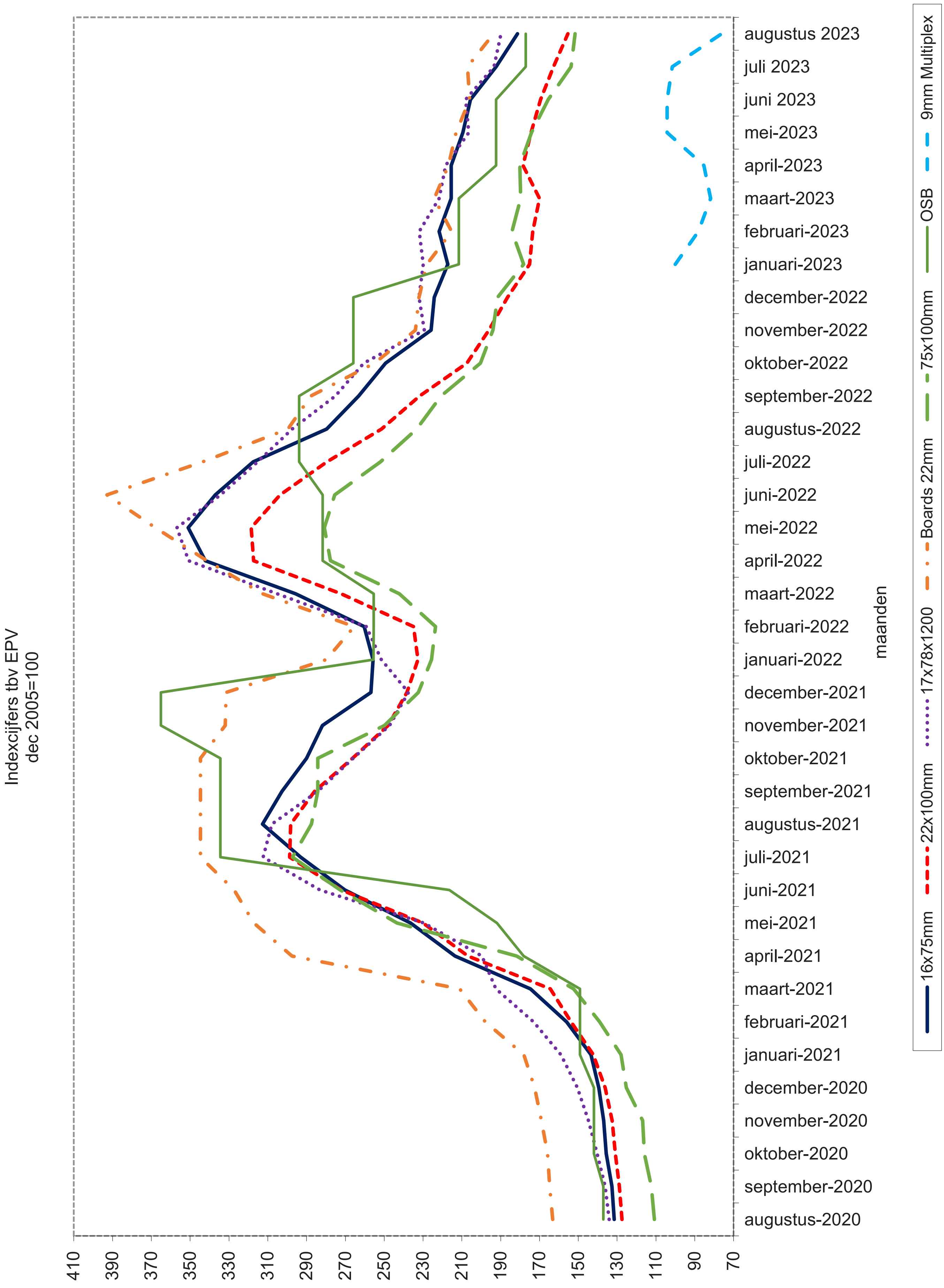
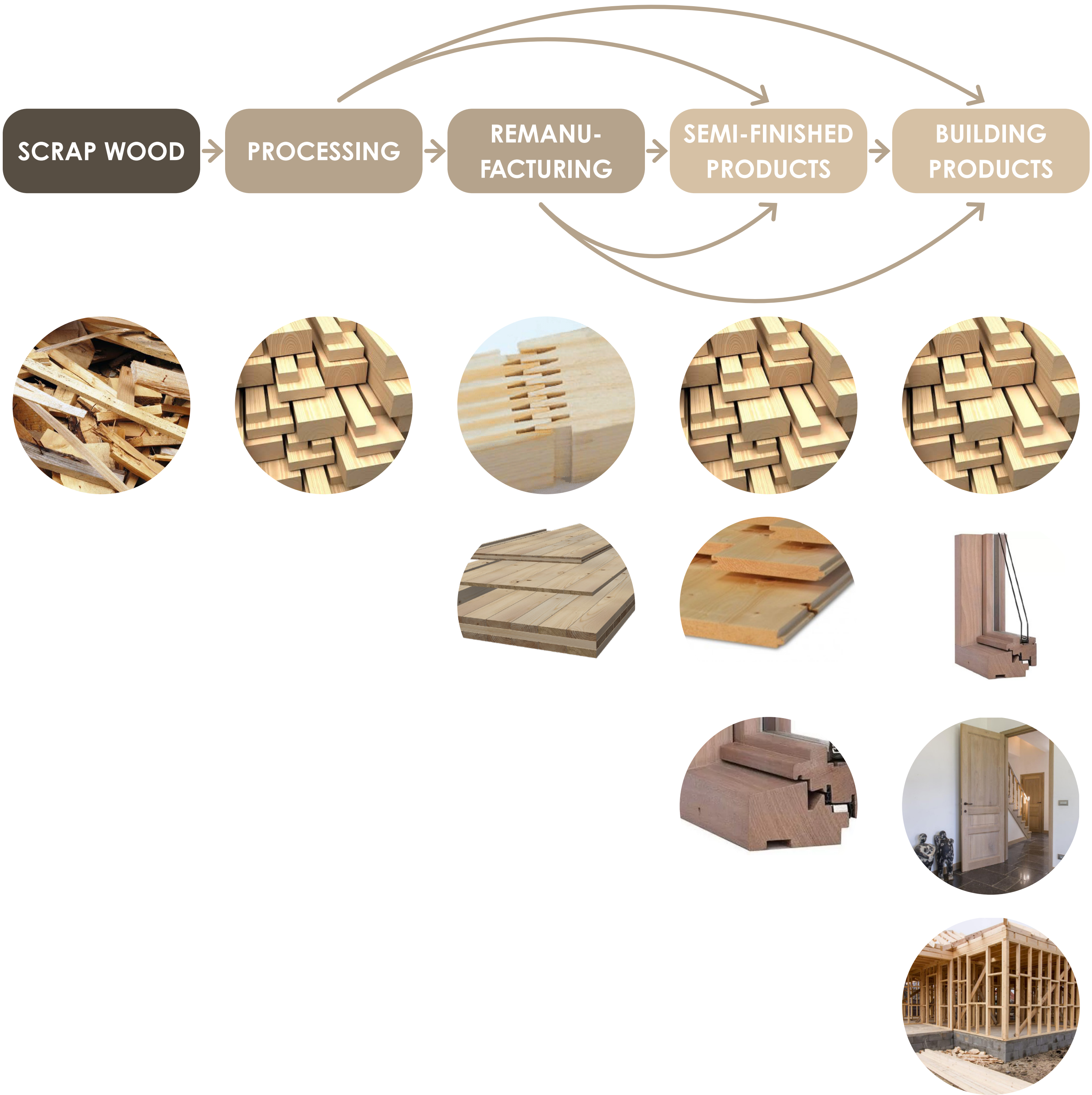
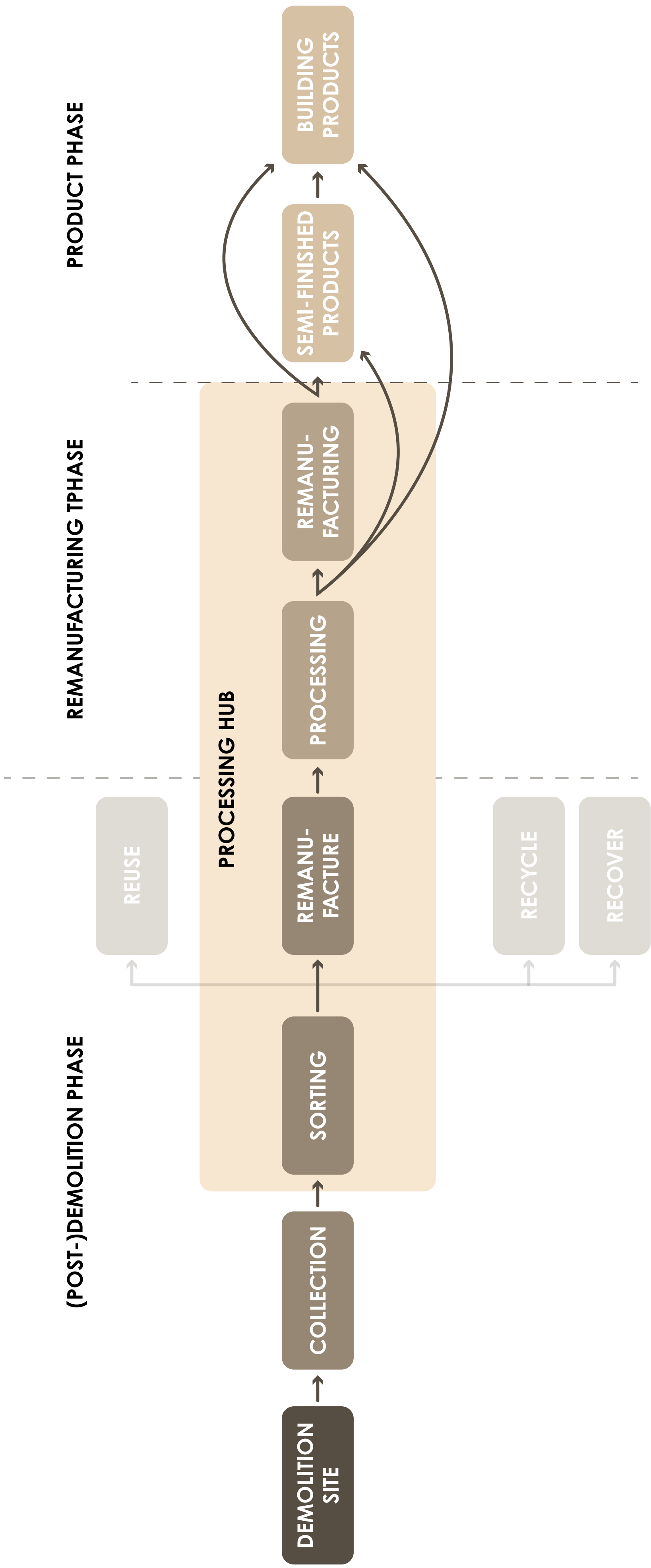


Figure X Wood price index (EPV, 2023)

APPENDIX 7 PROCESSING DIAGRAM EXPANDED



APPENDIX8 PROCESSING HUB DIAGRAM



APPENDIX 9 CLT PANEL OF 3 AND 5 LAYER PROPERTIES

Table 3.11 Cross-section properties for 3-layer CLT panels as in *figure 3.6*.
Conditions: k_{tor} = 0.65 (slits between boards), widths b_x and b_y = 1.0 m

Dimension (mm)	Thickness per layer (mm)			Cross-section (mm)			Surfaces (cm²)			Bending along y-axis (cm⁴, cm³)			Bending along x-axis (cm⁴, cm³)		
h_{CLT}	t_1	t_2	t_3	h_x	h_y	z_s	$A_{x,net}$	$A_{y,net}$	A_{CLT}	$I_{x,net}$	$W_{x,net}$	$S_{R,x,net}$	$I_{y,net}$	$W_{y,net}$	$S_{R,y,net}$
60	20	20	20	40	20	30	400	200	600	1,733	578	400	67	22	0
70	20	30	20	40	30	35	400	300	700	2,633	752	500	225	64	0
80	20	40	20	40	40	40	400	400	800	3,733	933	600	533	133	0
80	30	20	30	60	20	40	600	200	800	4,200	1,050	750	67	17	0
90	30	30	30	60	30	45	600	300	900	5,850	1,300	900	225	50	0
100	30	40	30	60	40	50	600	400	1,000	7,800	1,560	1,050	533	107	0
100	40	20	40	80	20	50	800	200	1,000	8,267	1,653	1,200	67	13	0
110	40	30	40	80	30	55	800	300	1,100	10,867	1,976	1,400	225	41	0
120	40	40	40	80	40	60	800	400	1,200	13,867	2,311	1,600	533	89	0

(Gustafsson et al., p. 45, 2019a)

Table 3.12 Input data for 5-layer CLT panels as in *figure 3.7*.
Conditions: k_{tor} = 0.65 (slits between boards), widths b_x and b_y = 1.0 m.

No.	Dimension (mm)	Thickness per layer (mm)					Cross-section (mm)			Weight and area (kg/m², cm²)				
	h_{CLT}	t_1	t_2	t_3	t_4	t_5	h_x	h_y	z_s	g_{mean}	g_k	$A_{x,net}$	$A_{y,net}$	A_{CLT}
1	**100**	20	20	20	20	20	60	40	50	42	39	600	400	1,000
2	**120**	20	30	20	30	20	60	60	60	50	46	600	600	1,200
3	**140**	20	40	20	40	20	60	80	70	59	54	600	800	1,400
4	**110**	20	20	30	20	20	70	40	55	46	42	700	400	1,100
5	**130**	20	30	30	30	20	70	60	65	55	50	700	600	1,300
6	**150**	20	40	30	40	20	70	80	75	63	58	700	800	1,500
7	**120**	20	20	40	20	20	80	40	60	50	46	800	400	1,200
8	**140**	20	30	40	30	20	80	60	70	59	54	800	600	1,400
9	**160**	20	40	40	40	20	80	80	80	67	62	800	800	1,600
10	**120**	30	20	20	20	30	80	40	60	50	46	800	400	1,200
11	**140**	30	30	20	30	30	80	60	70	59	54	800	600	1,400
12	**160**	30	40	20	40	30	80	80	80	67	62	800	800	1,600
13	**130**	30	20	30	20	30	90	40	65	55	50	900	400	1,300
14	**150**	30	30	30	30	30	90	60	75	63	58	900	600	1,500
15	**170**	30	40	30	40	30	90	80	85	71	66	900	800	1,700
16	**140**	30	20	40	20	30	100	40	70	59	54	1,000	400	1,400
17	**160**	30	30	40	30	30	100	60	80	67	62	1,000	600	1,600
18	**180**	30	40	40	40	30	100	80	90	76	70	1,000	800	1,800
19	**140**	40	20	20	20	40	100	40	70	59	54	1,000	400	1,400
20	**160**	40	30	20	30	40	100	60	80	67	62	1,000	600	1,600
21	**180**	40	40	20	40	40	100	80	90	76	70	1,000	800	1,800
22	**150**	40	20	30	20	40	110	40	75	63	58	1,100	400	1,500
23	**170**	40	30	30	30	40	110	60	85	71	66	1,100	600	1,700
24	**190**	40	40	30	40	40	110	80	95	80	73	1,100	800	1,900
25	**160**	40	20	40	20	40	120	40	80	67	62	1,200	400	1,600
26	**180**	40	30	40	30	40	120	60	90	76	70	1,200	600	1,800
27	**200**	40	40	40	40	40	120	80	100	84	77	1,200	800	2,000

(Gustafsson et al., p. 46, 2019b)

APPENDIX 10 MANUFACTURING PROCESS CLT

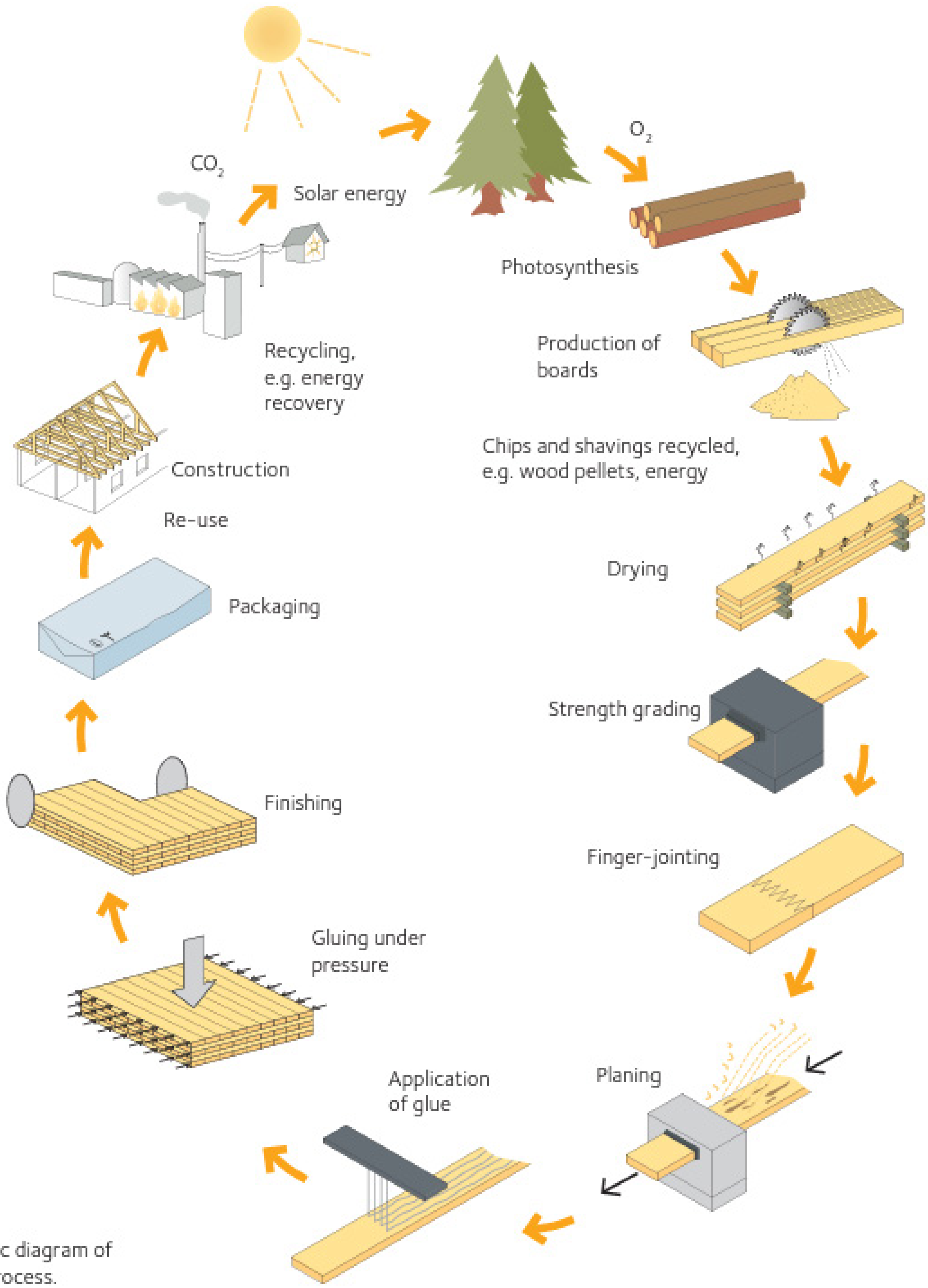


Figure 1.6 Schematic diagram of the CLT production process.

SOURCE: (Gustafsson et al., 2019)

APPENDIX 11 REFLECTION

Below a reflection on the research, design, method and planning is discussed.

Methodology & Approach

This graduation thesis began with a research by design approach. The research by design starts with literature research about wood, wooden building products and scrap wood. This research functioned as a foundation for the, then still in mind, design. The literature research showed that quite some information about scrap wood was hard to find. I wanted to better understand why scrap wood was not reused and where those problems applied, so I wanted to figure out the chain of reusing scrap wood, from collecting wood to the manufacturing of end products. The best method to figure out this chain was besides literature research, talk to professionals from each link in the chain. The professionals have the most experience with what the chain consists of, how it works and why certain things do and do not happen. These interviews were done through email, phone and video calls and visits to the companies. The interviews, together with the release of the rapport "De herfabricage van sloophout in Zuid-Holland", resulted in a shift of the focus of this graduation thesis. The research by design approach changed to design by research approach, where the design functioned as a case study for a method of how scrap wood could be reused in the built environment. This case study consisted of a building from CLT. The design functions as an example of possibilities for reusing scrap wood, and what the hurdles are in reusing scrap wood, and therefore what needs to change. This thesis transformed into an overview of possibilities for CLT from scrap wood, to possibly contribute to the change from a linear (build) economy to a circular (build) economy and maybe bring possible ideas to other people.

The feedback from my mentors helped me choose the direction. I want to know everything before I feel like I can make a decision, but for a graduation thesis the time is short and the research needs to become more focussed on a smaller topic. I really had to learn that I can't fix and know everything for this thesis. Therefore throughout the weeks my focus shifted from figuring everything out about scrap wood and the production chain to choosing a building product, a CLT panel, and testing my findings through that product. They also helped me bring me into contact with good professionals in the different industries related to the topic. During the feedback sessions they came with different and multiple ideas where my focus could go. Those ideas were not what I needed to do, but they helped me get me out of tunnel vision and helped me see what else was possible. And lastly, and for me the most important one, is they helped me see that what I was doing was valuable and interesting.

Relation to Building Technology and the master programme (MSc AUBS)

Building Technology consists of different topics: façade design, product design, climate design, structural design and lastly computational design. All topics relate to designing innovative and sustainable building components. These components contribute to a more sustainable and comfortable built environment. Developing a method for reusing scrap wood as a building product, in this thesis a CLT panel, touches the topics façade design and product design and a little bit structural design. In terms of climate design it relates to designing a sustainable product that can contribute to the decrease in CO_2 emissions and waste production. Reusing material is part of the 10R strategies and is an important aspect of the circular (build) economy strategy to make the world more sustainable. So, this graduation thesis relates to multiple Building Technology topics. Building Technology consists of engineering skills and architectural design skills. The engineering part of the graduation thesis is developing a product that functions well and is of high quality. The design of a building product relates to the architectural part. In order for architects to reuse wood, the products need to be designed well and be available in the desires of the architect (quantity and quality).

Value

The literature research was necessary to understand the basics of wood. By diving into the molecular level of wood, I could understand the difference between the wood types (hardwood vs. softwood) and wood species and where those are used in a building and why. This not only helps me know how to use wood in building products but also what types of wood are released during demolition. The literature research of scrap wood helped me understand what scrap wood consists of but also showed me there is almost no research about scrap wood and the reuse and recycling of scrap wood. But in order to understand the wood production chain in the built environment and the chain of reusing wooden products, literature research is not enough. Professionals in those chains know how those chains work and why certain things do and do not happen and therefore professionals need to be contacted. I acknowledge that I should have reached out to professionals earlier in the process in order to have meetings earlier and maybe more often. I also realised, through feedback from one of the professionals, that my email that I sent to the professionals was due to the massive amount of questions, a bit overwhelming. This could have discouraged some professionals to react to my email. Although I specified that I did not expect them to answer each question, but rather that they could maybe help me with answering some questions. Due to my lack of choosing a more specific topic within the general topic of reusing scrap wood in the earlier stages of the research process, the end product is less worked out than I expected in the beginning. On the other hand, I wanted to know everything before choosing a more specific topic. I have gathered a lot of general information on the overall topic. This is partly why the topic shifted from a more design based approach to a more research approach with a design as an example. I believe that this resulted in a more suitable approach for the topic of how scrap wood can be reused as a building product. This production method is a new and still a developing method and to give an overview of the necessary chain that needs to be developed contributes to changing the build environment production chain. This research helps to summarise the information on reusing scrap wood and making a cohesive story out of the existing, scattered information available.

Social & academic value and ethics

The climate around the world is changing and the temperature on earth is rising which could have catastrophic results. Besides climate change, we live in a linear economy, where products are made from exhaustive materials and after its user life the products are thrown away and turned into waste. So, in order to fight climate and handle our material use better, the world has to shift to a circular economy, where there is no waste, products are mostly made from renewable materials and/or reused, repaired, remanufactured or recycled (10 R strategies). Reusing scrap wood as a CLT panel relates to a circular economy. The scrap wood, that is now mostly turned into waste and incinerated, is reused. This takes waste out of the equation.The CO_2 that is stored in scrap wood stays stored for a longer period of time due to the long lifespan of CLT, decreasing the CO_2 emissions. This thesis focuses on reusing and remanufacturing scrap wood. Lastly, wood is also a renewable material, which is also part of the circular economy ideology. So, this thesis contributes to making the build environment more sustainable and circular.

There is already a lot of research on why and how the built environment needs to change to a circular build economy and to become more sustainable, but the research on how waste & scrap wood can be reused and remanufactured is still lacking. There are some reports that note that it would be useful and necessary, but they only state that it is not yet possible due to the time consuming process and the high costs. This research dives deeper into how scrap wood can be reused as a building product (CLT). So it contributes to further development and provides information on reusing waste wood as a building product, supported by literature research, research about the market and interviews with professionals.

I did not really encounter moral or ethical issues. Reusing scrap wood is not a hazardous approach. C-wood is the only wood that can be hazardous, but it is not allowed to be reused or recycled and already sorted. So, C-wood is not included in this reuse chain of scrap wood. On the other hand, companies are also interested in this topic and have started their own research. The research is not based on testing on people or asking for their opinion. The only potential issue is testing the strength of scrap wood. There are not yet regulations for testing the strength of scrap wood. Therefore a testing method needs to be developed in order to make safe structural building products. In theory, it is possible, but before it can happen it should be able to test its strength. You don’t want structural building products to collapse.

Transferability
The results of this graduation project is an overview of the possible consistency of scrap wood and the existing and the to be developed chain for reusing scrap wood as building products, with examples of how scrap wood could be implemented in a CLT panel. It also gives insight where in the production chains links are missing and what needs to be researched, developed and/or changed. Overall, this report gives a summary of the problem in society for reusing scrap wood and some food for thought on what the possibilities are and what needs to happen. Even if the scrap wood CLT ideas result in “not usable” after research about different configurations of scrap wood into CLT panels, this report could also bring some ideas on how scrap wood could be used in other building products or other products. This report is not only about reusing scrap wood into a CLT panel, but also shows how complex the scrap wood industry is and helps people understand that it is possible to reuse scrap wood, but that it just needs to be further researched.

Own questions
Lastly, for the reflection I had to come up with two own reflection questions related to the content of my work:

Own question 1: Does the research contribute to society in the way you had in mind?

When I started this graduation topic, a few weeks into graduation, I had in mind to design something new from scrap wood. After reading multiple reports and papers about sustainability and reusing waste and scrap wood, I got quite frustrated. Almost every report had the same conclusions, that “reusing scrap wood is possible, but that further research needs to be done”. I did not want to finish with the same conclusion, that after reading my whole report the conclusion would be that further research is needed. But after researching myself through reading more papers and reports and talking to multiple people from different branches of the industry, I also came to the same conclusions. More research needs to be done, and the research that needs to be done is probably going to be a process of a couple years and outside the scope of a graduation thesis at the TU Delft.

Most importantly, is the amount of scrap wood and what it consists of needs to be researched, which is a difficult task because the supply and consistency differs every time and that will keep happening in the future because new building methods and materials are used, so new materials will come free when newer buildings get demolished. Two other important aspects are the need for changing and/or adding legislation that simplifies reusing scrap wood and the development of easier, quicker and cheaper tests methods for determining the wood species and the mechanical properties and easier, quicker and cheaper production methods to remove metal. All aspects are outside the scope of my graduation thesis. One or two aspects could probably be a whole graduation topic of its own. So, I kind of have the same conclusions as all the other reports, but mine is more focussed on CLT and the production chain of reusing scrap wood. So, to answer the question: no, this research does not contribute to society in the way that I had in mind, but I do believe it contributes something. The contribution is more in the way of summary of the consistency of scrap wood and its problems summarised in this thesis and give some possible ideas in how scrap wood could be reused as CLT, or give inspiration for other wooden (building) products.

Own question 2: Do you believe that reusing scrap wood into building products is possible?

At the moment, still a lot needs to change before reusing scrap wood will become “normal” in society. I believe most of the world is led by money. So, reusing scrap wood should become a profitable method, which isn’t the case at the moment. The process of removing the wood from buildings, removing metal and preparing the scrap wood for remanufacturing is a time consuming and costly process, where labour is done by people with a distance from the labour market in order to make some profit. A processing hub that can reduce the time and labour costs could possibly help the development of reusing scrap wood. Legislation is also in the way of encouraging companies to start reusing scrap wood, due to lack of available tests and warranty. Therefore legislation needs to be changed. But I do believe that reusing scrap wood will become more normal in a couple of years. Some people or companies need to start and invest in it, creating easier, quicker and cheaper methods, and it will probably be tough, but someone needs to start and eventually all/most companies will probably follow. The benefits of reusing scrap wood due to the CO2 storage compared to the need for a reduction in CO2 emissions will result in the development of processes that can ensure reusing scrap wood is possible.