CLT based opportunities for a resilient housing sector in Zuid-Holland

a scenario analysis of a CLT industry in Zuid-Holland

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Abstract

This research focused on the role of cross-laminated timber (CLT) in the transition to a circular and bio-based housing sector in the province of Zuid-Holland (PZH). A scenario-model framework was used to assess the socio-economic and environmental impacts on the construction sector, as a result of CLT construction in general and as a result of different timber material origins. The central research question is: “What are the impacts of a transition to a housing sector in PZH that is for 20% based on CLT? and could regional CLT production offer socio-economically and environmentally sustainable solutions?”. The outcomes from the scenario analysis show that regional production of CLT is beneficial from a socio-economic perspective, while simultaneously being environmentally sustainable. The CLT required to reach the CLT implementation aim in PZH is sufficient to operate a price-competitive CLT industry. On paper, national timber flows are sufficient to produce this CLT and if national timber flows are not adequately available sawn timber should be imported from other European countries. The most important action points are related to increasing the domestic timber stock, ensuring high-grade application of timber, standardizing and bundling of demand for CLT construction, and ensuring adequate carbon policies to create a financially level playing field.

Keywords: CLT, Bio-Based Construction, Timber Construction, Circular Economy

Executive Summary

The aim of the research was to quantify the impacts of fulfilling 20% of the 2025 to 2035 PZH housing demand with CLT houses and to quantify how these impacts are affected by alternative methods of CLT panel and timber supply. First, the general drive to bio-based construction, and the associated uncertainties, were described in the context chapter. Thereafter, a baseline scenario was made that compared the impact of a 100% conventional scenario with the 20% CLT aim. Finally, a scenario-planning framework was used to create 4 scenarios, ranging from import-focused to largely focused on regional CLT production. The scenario analysis aimed to quantify the socio-economic benefits of regional CLT production, quantify the transport emissions of imported timber materials, and to finally formulate an optimal scenario. Information on the various stages was acquired through extensive literature research, expert interviews, quantitative assessment, and open access governmental reports.

The context chapter described the dilemma between the housing shortage and the climate pressures. As a result, conventional construction is in many cases no longer a suitable solution since it is conflicting with climate adaptation goals such as CO2, NOX and PM emissions. On the other hand, bio-based alternatives, such as CLT, become increasingly favourable. CLT is a construction method that addresses multiple of these issues simultaneously, being sustainable, quick, scalable and under the right circumstances even price competitive. The shift to a circular and bio-based housing sector does induce uncertainties, which are mainly related to the job market and the material supply. The transition disturbs the current construction regime since a CLT construction regime requires different companies, jobs, skills and infrastructure. The material demand will also change, which creates uncertainties related to material availability, material origin, and the associated market dynamics.

A key finding from the baseline chapter is that CLT implementation can greatly reduce the material demand and carbon emissions of the housing sector. When accounting for the carbon embedded in the timber, CLT houses have negative carbon emissions. Therefore, constructing 20% of the housing demand with CLT can reduce carbon emissions of the housing sector by 26%. Another key finding is that a regional, self-sufficient and financially competitive CLT industry is possible. The estimated CLT demand needed to reach the aim is approximately 120.000m3 of CLT per year. These quantities are sufficient for a financially competitive national CLT industry since, on the scale of at least 50.000m3 per year, production can be financially competitive with large-scale EU producers. Self-sufficiency is also not entirely unrealistic; if national timber flows are optimized, on paper about 130.000 to 200.000m3 of CLT could be produced from Dutch timber annually. The last key finding from the baseline chapter is that CLT construction and CLT production require fewer jobs and different types of jobs compared to conventional construction, thereby putting existing jobs at risk. The skills required for CLT construction are mainly higher-skilled jobs such as IT-related skills like 3D-rendering. However, at the start of the time frame, there is an estimated shortage of available labour in the Dutch construction sector. CLT construction could help alleviate some of the impacts caused by this labour shortage and reduce the outflow of workers from the construction sector.

The main finding from the scenario analysis chapter is that regional CLT production, even from imported sawn timber, is beneficial from both a socio-economic and environmental perspective. Ideally imported timber materials should be minimized and local production needs to be

maximized. However, if national timber proves to be insufficiently available any remaining demand can be imported as sawn timber. However, only dried and sawn timber materials should be imported since the added mass of unsawn timber will greatly increase transport emissions. Compared to the import of CLT panels, the import of sawn timber does not increase transport emissions, while adding an extra domestic production stage. Relative to the other CLT-production stages, the CLT-panel-production stage adds the most revenue and jobs.

Action points:
The recommended steps that are needed to move towards a CLT based housing sector and a national CLT production industry are addressed by the following action points.

1: Increasing timber availability

- Reforestation programs need to be implemented on large scales well in advance of the estimated increase in demand. Timber is most likely becoming an ever more important sustainable resource. Therefore, to prevent deforestation it is important that the standing stock is expanded before the increase in demand. Since it takes decades to grow trees, this means large-scale reforestation should happen now. Reforestation could be included as a standard demand for new construction projects.
- Policies should target low-grade applications of timber streams and ensure these are used for high-grade applications, such as construction. A substantial share of the current annual timber flows is exported or is used for low-grade applications, such as firewood and biomass. Examples could be to prohibit solid timber to be sold as firewood and to regulate the shredding of timber wastes for energy generation and composting.
- Governmental agencies should consider embedding rules and regulations associated with wealth distribution from natural resource extraction. Instigation of a regional CLT industry will allow for the government to set the rules of the game, manage the value distribution from natural resources and assure value reflow into society. These monetary flows could be used to counteract the socio-economic impacts resulting from automation.
- Increasing regional timber production is preferable over import since this will increase resilience and reduce market uncertainties. Dependency on EU timber markets introduces a risk especially since price dynamics are influenced by international production dynamics and international politics.
- To prevent burden-shifting there need to be regulations that prohibit unsustainably harvested timber and that enforce the use of sustainably harvested domestic timber or sustainably harvested timber from within the EU.
- For all EU member states the future demand for timber needs to be mapped. Such a mapping will also give insight into possible issues regarding overexploitation and burden shifting. Based on this mapping policy needs to be created that ensures the availability and affordability of timber construction materials. Such policy needs to prevent international trade dynamics from affecting the financial feasibility of bio-based housing.

2: Sharing of knowledge and bundling demand

- Steady and reliable demand for CLT housing is needed to kick start the transition. This will allow for larger investments from CLT producers and allow for a price reduction (economy of scale). The increased turnover rate also allows for a reduction of margins and increases the overall affordability of housing.
- A reliable demand should be created by structurally embedding sustainability-related demands in tenders. This will ensure no democratic processes are bypassed. It is important that municipalities are stimulated, or enforced, to incorporate these sustainability

guidelines in a fixed share of their housing tenders.

- Not all municipalities have adequate skills and sufficient knowledge to implement this in practice. In order to create more uniformity; guidelines for bio-based and circular housing tenders need to be made on a national level.
- The standardization of tender guidelines also needs to enforce integrated design, combining CO_2 reduction goals, with greening, ecology, water, and energy generation goals. The national government or province could play a role in facilitating such detailed guidelines in cooperation with consultancy firms.
- This integrated design is especially relevant for timber construction. Although modular CLT construction offers some flexibility, in general, it is more difficult to alter a CLT building after the design phase. Therefore, it is beneficial to force cooperation between various companies and already implement multiple essential design aspects early on in the design phase.
- Modular CLT construction is very well suited for standardized, sustainable, and flexible construction. There are possibilities for semi-portable production facilities; such facilities could be very promising for the development of new areas or neighbourhoods. These modular CLT assembly facilities will create opportunities for industrial symbiosis in the field of electricity and heat.
- If such a bio-based and CLT-based future is desired, it is important that these wishes are clearly propagated and conversations with the industry are initiated. The province and the municipalities could also adapt regional development plans to include designated areas for integrated bio-based material production initiatives.
- Think about regulations that currently limit entrepreneurs to instigate CLT-production projects in industrial areas in PZH, such as the Rotterdam harbour area. Certain exceptions or changes in these regulations might help to attract project developers to instigate a CLT industry.

3: Shaping the markets

- A level playing field is required since CLT construction is in some cases still marginally more expensive. Therefore, environmental shadow costs need to be incorporated in material prices. Examples of such measures are the pricing of embedded CO_2 or tax benefits for bio-based materials. Another option is increasing the tax on mineral construction materials and reducing the tax on labour simultaneously. This will benefit more sustainable materials while also stimulating the implementation of labour.
- In the context of the transition, there is no use in increasing the availability of regional timber if it remains financially uncompetitive with imported timber from other EU member states. Therefore, it should be considered to regulate the prices of Dutch timber for national producers of timber construction materials. Whenever the EU timber prices are lower than the domestic timber prices, the prices could be matched by means of subsidies.
- Re-evaluate the building codes to assess if there are aspects that hamper CLT construction and bio-based construction in general. Building codes are identified to often hamper the growth of the CLT industry (Larasatie et al., 2020). An example of this is the maximum allowable height of a building; since CLT floors are generally thicker than concrete floors a comparable CLT building will be slightly higher. In certain cases, a CLT building might be conflicting with the building code, while a comparable conventional building would not be (Commu et al., 2021).
- Adapt existing education programs in the construction sector to industrialized construction and timber construction. This will help to reduce a future mismatch in available and required skills. The most important skills are ICT skills (such as structural 3D-rendering),

structural calculations for timber buildings, integrated design, woodworking skills, and knowledge of timber construction in general.

- Promotional campaigns that show the benefits of timber could prove beneficial in changing the public's attitude towards timber as a construction material and showcase the role timber plays in a circular economy. The civil attitude towards wood as a construction material could hamper the demand for timber construction and the support for timber harvesting.

Samenvatting voor Beleidsmakers

Het doel van dit onderzoek was om de impact van CLT implementatie t.o.v. conventionele bouw te kwantificeren, en met name te kwantificeren hoe materiaal oorsprong deze impacts beïnvloed. Eerst zijn de drijfveren achter de transitie naar een circulaire en biobased woningsector beschreven (de context). Vervolgens is er een nulmeting beschreven, waarin de impact van CLT woningen is vergeleken met conventionele woningen en waarin is beschreven hoe de materiaal vraag verandert als er voor een vast aandeel met CLT gebouwd zal worden. Het CLT implementatie doel was 20% van de woningvraag van PZH tussen 2025 en 2035. Vervolgens zijn er met behulp van een scenario-planning methode 4 verschillende scenario's gecreëerd, van volledig import afhankelijk tot voornamelijk afhankelijk van Nederlands hout. Het doel van de scenario analyse was het in kaart brengen van; de sociaal-economische voordelen van nationale productie, de extra transport emissies door materiaal import en het formuleren van een optimaal scenario. De informatie voor dit onderzoek is verkregen uit uitgebreid literatuur onderzoek, beleids rapporten, interviews met experts en kwantitatieve analyse.

Het context hoofdstuk beschrijft het dilemma tussen de klimaatdoelen en het woningtekort. Aangezien conventionele bouw afhankelijk is van minerale materialen is het veelal in strijd met de klimaatdoelen en is het steeds minder vaak een geschikte oplossing. Met name hierdoor stijgt de vraag naar biobased alternatieven, zoals CLT. CLT is met name geschikt aangezien het niet alleen een duurzaam materiaal is maar ook snel, schaalbaar, flexibel en in sommige gevallen ook al prijs competitief is. De overgang naar een industriële bouw methode creëert onzekerheden en veroorzaakt een verschuiving binnen de bouwsector. Zo zijn er voor het bouwen met CLT andere bedrijven, banen en skills nodig en is er andere infrastructuur nodig. Ook verandert de materiaal vraag, dit brengt opnieuw onzekerheden en afhankelijkheden (van de Europese houtmarkt) met zich mee .

Een belangrijke uitkomst van de nulmeting is dat CLT zowel de materiaal vraag als de CO2 impact sterk terug kan dringen. Doordat er koolstof zit opgeslagen in het hout heeft een CLT woning negatieve CO2 emissies. Het voorzien van 20% van de woningvraag in CLT kan daardoor de CO2 voetafdruk van de woningsector met 26% reduceren. Een andere belangrijke uitkomst is dat een volledig zelfvoorzienende en prijs competitieve Nederlandse CLT industrie niet onhaalbaar is. Om het 20% CLT implementatie doel te bereiken is naar schatting gemiddeld 120.000m3 CLT per jaar nodig. Deze vraag is voldoende om een competitieve CLT industry op te zetten, aangezien een fabriek van minimaal 50.000m3 per jaar al prijs competitief kan opereren. Het herverdeling van de huidige houtstromen kan op papier genoeg hout vrijmaken om ongeveer 130.000 tot 200.000m3 CLT produceren.

Een andere uitkomst van de nulmeting is dat er minder banen nodig zijn voor het bouwen met CLT. Er zijn niet alleen minder banen nodig maar er zijn ook andere vaardigheden vereist. Dit kan ervoor zorgen dat huidige werknemers slecht aansluiting kunnen vinden bij de houtbouw industrie. Voor industriële houtbouw zijn met name banen voor hoger opgeleiden nodig, relevante vaardigheden zijn bijvoorbeeld structurele berekeningen van houtconstructies, ICT kennis en gedetailleerde 3D tekeningen maken. Aan het begin van het tijdsvak is er echter een geschat tekort aan arbeiders in de bouw sector. CLT productie kan in theorie de weerslag van dit tekort reduceren, zo kan het vertragingen door personeelstekorten voorkomen en kan het door betere arbeidsomstandigheden de uitstroom uit de sector beperken.

De belangrijkste uitkomst van de scenario analyse is dat regionale CLT productie gewenst is, zowel uit een sociaal-economisch als uit een klimaat perspectief. Het ideale scenario is een geheel zelfvoorzienend scenario, met minimale materiaal import en maximale lokale productie. Mocht de lokale houtstroom echter beperkend blijken dan is het importeren van gezaagd hout een duurzaam alternatief. Doordat de massa van gezaagd hout vergelijkbaar is met die van CLT panelen is de transport impact ook vergelijkbaar. Het importeren van gezaagd hout vergroot dus niet de klimaatimpact maar geeft wel de mogelijkheid voor extra binnenlandse productie. In vergelijking met de andere CLT productiestappen voegt de productie van CLT panelen (uit gezaagd hout) de meeste waarde toe en creëert het de meeste banen. Het importeren nat en ongezaagd hout is niet voordelig aangezien dit de transport emissies met een factor 3 vergroot.

Actiepunten:

1.Beschikbaarheid van Nederlands hout vergroten

- Het is van belang dat er direct op grote schaal nieuwe bossen worden aangeplant. Nog voordat de vraag naar hout drastisch zal toenemen. Het belang van hout als duurzame grondstof voor de bouwsector zal steeds groter worden. Aangezien het jaren duurt voordat de bomen volgroeid zijn is het nodig om direct aan te planten, om zo de staande houtvoorraad te vergroten en ongewenste ontbossing te voorkomen. Het aanplanten van bos kan ook als een standaard vereiste worden geimplemteerd bij nieuwbouw projecten.
- Laagwaardige implementatie van houtstromen moet gereguleerd worden. Een aanzienlijk deel van de Nederlandse houtstromen wordt gebruikt als haardhout of biomassa (48%). Het reguleren of verbieden van zulke laagwaardige toepassingen kan veel hout vrijmaken voor de bouw industrie, en ervoor zorgen dat de CO2 langdurig blijft opgeslagen in de infrastructuur.
- Er is duidelijke regelgeving nodig omtrent houtgebruik in de bouwsector. Uitsluitend duurzaam geoogst Europees hout dient gebruikt te worden, om zo verschuiving van impact te voorkomen.
- Overheidsinstanties zullen moeten overwegen om regelgeving te implementeren die de gecreëerde waarde, door het winnen van natuurlijk grondstoffen (zoals hout), her-verdeeld. Automatisering zal in vele sectoren voor baanverlies gaan zorgen. Bij het initiëren van een nieuwe houtindustrie heeft de overheid de mogelijkheid om de regels binnen de sector vorm te geven. Deze financiële herverdeling kan ervoor zorgen dat de sociaal-economische impact wordt verzacht.
- Voor alle EU-landen zal de verwachte toekomstige houtvraag in kaart gebracht moeten

worden. Dit zal inzicht geven in de vraag-aanbod balans en zal mogelijke toekomstige overexploitatie inzichtelijk maken. Op basis van deze analyse kan beleid gemaakt worden dat de beschikbaarheid en betaalbaarheid van houten bouwmaterialen waarborgt. Dit beleid dient te voorkomen dat internationale handelsrelaties biobased bouwen onrendabel maken.

- Het vergroten van de Nederlandse houtproductie zal helpen om markt onzekerheden te reduceren. De Europese houtmarkt is momenteel gevoelig voor internationale dynamieken in politiek en productie. Nationale productie is essentieel voor een stabiele biobased toekomst, in ieder geval zolang er geen Europese regelgeving is omtrent het exporteren van hout uit de EU.

2: Kennis deling en het bundelen van vraag

- Om de transitie op gang te helpen is er een vaste en gestandaardiseerde vraag naar CLT nodig. Dit geeft financiële zekerheid voor investeerders en stelt producenten in staat om door schaalvergroting prijzen te reduceren. Daarnaast stelt een snellere kapitaal doorstroom de keten in staat om marges te reduceren, en zo woningen betaalbaarder te maken.
- Duurzaamheidseisen dienen structureel in aanbestedingen verwerkt te worden, om zo zekerheid te bieden aan de markt. Ook is het belangrijk dat gemeenten gestimuleerd, of verplicht, worden om een vast deel van de aanbestedingen circulair uit te schrijven.
- Niet alle gemeenten hebben de juiste kennis en vaardigheden om dit in praktijk uit te voeren. Het is daarom aan te raden om op nationaal niveau richtlijnen te formuleren omtrent circulaire en duurzame aanbestedingen. Met name omdat de wijze waarop een aanbesteding wordt uitgeschreven de toepasselijkheid van biobased oplossing beïnvloedt.
- Geïntegreerd ontwerp dient ook opgenomen te worden in deze gestandaardiseerde richtlijnen. Zo kunnen verschillende kwesties, zoals, CO2 reductie, groen, ecologie, water en duurzame energie, tegelijkertijd worden aangepakt. Dit is met name belangrijk voor CLT, aangezien de industriële productie methode de flexibiliteit inperkt. Het is voor geïntegreerde duurzame oplossingen van belang dat de samenwerkingen tussen bedrijven en sectoren al in de ontwerpfase worden afgedwongen.
- Modulaire CLT constructie is uitermate geschikt voor gestandaardiseerde, duurzame en flexibele woning bouw. Deze bouwmethode biedt mogelijkheden voor mobiele productie locaties. Dit kan een rol spelen in het ontwikkelen van nieuwe wijken. Zulke productie locaties kunnen mogelijkheden creëren voor industriële symbiose, bijvoorbeeld op het gebied van energie en warmte.
- Indien een CLT industrie gewenst geacht wordt, is het belangrijk dat deze ambities expliciet uitgedragen worden om investeerders aan te trekken en te inspireren. De provincies of gemeenten kunnen daarnaast bestemmingsplannen aanpassen om specifiek initiators van geïntegreerde bio-based productie aan te trekken.
- De bouwnormen dienen geherevalueerd te worden m.b.t. bio-based bouwen. Bouwnormen zijn in veel gevallen ongewild beperkend voor CLT constructie. Een voorbeeld hiervan is de maximale hoogte van een woning in stedelijk gebied. Aangezien CLT vloeren

dikker zijn dan betonnen vloeren, kan een CLT woning in conflict zijn met de bouwnorm terwijl een vergelijkbaar betonnen gebouw dit niet zal zijn. Mogelijke beperkende regelgeving worden aangepast om investeerders en ondernemers voor een CLT industrie aan te trekken.

3: Het vormen van de markten

- Een gelijk speelveld is essentieel, met name omdat hout vaak nog duurder is dan minerale bouwmaterialen. Verborgen kosten en CO2 emissies dienen meegenomen te worden in de materiaal prijs. Voorbeelden zijn; het beprijzen van ingebedde CO2 en belastingvoordeel voor duurzame bouwmaterialen. Dit kan in combinatie met het verlagen van belasting op arbeid, de kosten verhogingen van minerale bouwmaterialen wordt dan tegengegaan door een reductie in arbeidskosten. Op de lange termijn zal dit banenverlies tegengaan en duurzame materiaalkeuze stimuleren.
- Naast het vergroten van de nationale houtstromen is het belangrijk dat Nederlands hout prijs competitief is met de Europese houtmarkt. Het is daarom belangrijk dat er gekeken wordt of prijs regulatie van Nederlands hout vereist is voor een succesvolle productie industrie van bouwmaterialen.
- Bestaande educatie programma's moeten worden aangepast aan de geïndustrialiseerde bouw. Dit zal de kans op een slechte aansluiting tussen het vraag en aanbod op de arbeidsmarkt verkleinen. Met name structurele berekeningen, kennis over hout als materiaal, geïntegreerd ontwerp en ICT vaardigheden zoals 3D rendering zijn belangrijk.
- De houding van de burger tegenover hout als bouwmateriaal is essentieel. Campagnes die de voordelen van bouwen met hout laten zien zijn nodig om de blik van de bevolking op hout te veranderen, met name aangezien er in Nederland van oorsprong voornamelijk met minerale grondstoffen wordt gebouwd. Een negatieve opvatting tegenover hout kan de vraag naar CLT en het toekomstige draagvlak voor het oogsten van hout belemmeren.

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1.Introduction

A transition in the functioning of the Dutch housing sector is needed to fulfil the increasing housing demand, while also reaching national climate targets. It was estimated that by 2030 one million additional houses need to be built in the Netherlands (StudioMarcoVermeulen, 2020; Manshanden & Koops, 2019). This means that the current building rate of 70.000 houses per year has to be increased (StudioMarcoVermeulen, 2020) while simultaneously reducing the environmental impacts of the sector. Currently, the Dutch housing sector is mainly dependent on non-renewable materials, such as concrete, steel and brick (EIB #1, 2020). Therefore, a shift in material usage and construction practices is needed to achieve a circular and sustainable housing sector.

Previous studies have shown that it is not feasible to fulfil the entire future material demand through Urban Mining, both at the national and at the municipal level (Verhagen et al. 2020; EIB #1, 2020). Therefore, bio-based materials are key to supply the remainder of the material demand in a sustainable way (Sathre & González-García, 2013; Ellen MacArthur Foundation, 2013). The environmental impacts of timber construction have been extensively researched; cross-laminated timber (CLT) in particular shows to be a promising construction method (Nakano et al., 2020; Sathre & González-García, 2013; Darby et al., 2013; Peñaloza, 2017).

On the other hand, various reports have shown that the transition to a circular economy brings about socio-economic disturbances and causes inter-sectoral job shifts, which could result in a mismatch between required skills and available labour (EC, 2018; TNO, 2019; ECORYS, 2019). Moving to a circular economy will require a shift along the supply chain, reducing virgin material production and maximizing material re-usage (European Commission, 2018). Since a CLT industry is currently lacking in the Netherlands, increasing implementation of CLT will result in the outsourcing of material production to other European countries. This creates a dilemma where choices have to be made between environmental, social and economic sustainability.

While timber construction and CLT in particular offer clear advantages for reducing the impact of the construction sector, the socio-economic impacts related to the transition to a circular housing sector have not been explicitly researched. It is unclear to what extent the large-scale implementation of CLT can be sustainable when considering a possible increase in material imports and whether there are opportunities for sustainable regional CLT production (Lucassen, 2020). It is also unclear how this will affect the housing sector, how many jobs and what type of skills are needed for CLT production and construction.

The aim of this research is to identify the relations between regional CLT production opportunities and the import of CLT and to quantify the socio-economic and environmental impacts associated with these dynamics. These dynamics were scrutinized using a scenario-planning framework. The scenarios were modelled in a simple logic model, which was used to quantify the impacts of various possible future scenarios; the province of Zuid-Holland (PZH) is used as a case study. The various scenarios were then compared and the outcomes were used to formulate policy recommendations and to facilitate well-informed decision making.

2.Concepts and Theory

This section gives an overview of important definitions and concepts. These include sustainability concepts that are often used in literature and policy documents, such as the transitional agenda of PZH. Also, concepts such as technical transitions, niche innovation, and scenario analysis are reviewed. These concepts are the theoretical foundation of this research and help to clarify the framing of the topic.

2.1 Circular Economy

The province of Zuid-Holland wants the construction sector to become fully circular and bio-based by 2050 (PZH, 2019). Circular economy (CE) is a widely used concept with an even wider variety of definitions (Kirchherr, Reike, & Hekkert, 2017). According to Ghisellini, Ripa, & Ulgiati CE refers to a model of economic development that aims to maximise the re-use of materials and minimize waste generation (Ghisellini, Ripa, & Ulgiati, 2018). A CE needs to be lean and designed around the efficient use of materials. As described in the 9R-framework, recycling and recovery should only be a last resort, after various steps of downcycling (Kirchherr, Reike, & Hekkert, 2017).
One of the most well-known examples of a CE model is the butterfly diagram from the Ellen Macarthur Foundation (Ellen MacArthur Foundation, 2013). This diagram makes a division between technical and biological material loops. This shows the thrive for circularity but also the need to shift towards natural resources, or bio-based materials, in order to be able to fully close material loops.
Besides the physical domain of sustainability, there is also a need for economic and social sustainability. The doughnut economics model from Raworth, 2017 describes the balance between these three domains. Sustainability is described as a doughnut-shaped zone where a balance is struck between environmental burdens and the social foundations (Raworth, 2017). This reasoning is especially important in scenario creation since the proposed future should not only consider the environmental impact but also consider living and working conditions.

2.2 Urban Mining

Besides changing the material inputs into the construction sector it is important to optimize the re-usage of the materials currently stored in the building stock. The current construction sector is still rather linear and mainly focuses on recycling (Lucassen, 2020), rather than more circular options such as re-usage or refurbishing (Kirchherr, Reike, & Hekkert, 2017). From a quantitative perspective, the performance of resource recovery is already at its maximum (Koutamanis, van Reijn, & van Bueren, 2018), but this does not take into account the application or value of the materials. Reportedly 94% of the construction and demolition waste (C&DW) in the Netherlands is recycled (Mulder, de Jong, & Feenstra, 2007; Royal Haskoning, 2017). For a large part, this is due to the stony fraction that is used as road filler; a rather low-grade application. Metal recycling already reached its maximum and improvements in this sector are not expected to affect the overall C&DW recycling performance (Koutamanis et al., 2018). This shows there are still major opportunities for efficiency improvements, such as designing for re-usage.

The concept of urban mining (UM) could be a partial solution to this issue. Brunner, 2011 refers to the concept of UM as; “the systematic reuse of anthropogenic materials from urban areas”. However, circularity goals cannot be reached with UM alone; it is estimated that the city of Leiden UM could facilitate 40% of the material demand from 2020 until 2030 (Verhagen et al. 2020). This share could increase since the difference between material in and outflows is expected to become smaller (EIB #1, 2020). This difference is declining, from a factor of 2,4 in 2014 to an estimated 1,7 in 2030 (EIB #1, 2020). It is estimated that in 2030 59% of the material demand could be facilitated from material outflows. However, the material demand will still outway the available material streams from demolition (EIB #1, 2020).

2.2 Bio-based materials

Bio-based materials are key in this transition since they do not require an energy-intensive industry but utilize biological processes to grow (Sathre & González-García, 2013). Since they are organic they can, in theory, be brought back into the environment to close material loops (Ellen MacArthur Foundation, 2013). Bio-based materials have a low impact on climate change since they store biogenic carbon (Peñaloza, 2017). Increasing the lifespan of wooden structures in the built environment, therefore, extends their carbon sequestration potential and environmental performance (Nakano, Koike, Yamagishi, & Hattori, 2020).

When properly managed this dependency on natural ecosystems can induce many positive externalities, such as social and ecological ecosystem services (Sathre & González-García, 2013). This is however also the biggest risk of the dependency on natural ecosystems. If demand surpasses the annual production capacity of sustainably produced timber this can lead to overexploitation and clear-cutting of virgin forests. Various European countries have agendas and goals for a biobased economy, based on timber as a primary material (Nabuurs et al., 2016). There is still potential to increase the production of sustainable timber in Europe, but globally there are limited regions where production can be sustainably increased (Nabuurs et al., 2016). This highlights the importance of proper scenario analysis to assess a wide range of future outcomes.

2.3 Social technical systems and the multi-level perspective

A technical transition is described by Geels, 2002 as; a large-scale and long-term change in the way certain societal functions are fulfilled. Such a technology change also brings about change in other domains, such as infrastructure, policy, user practices, culture, and industrial networks (Geels, 2002). This interrelation between technology and its function in society is often described as a socio-technical system (STS).

The functioning of this STS is dependent on the set rules and the involved stakeholders. These three dynamically influence each other and together create a technological regime (Geels, 2004). It can be hard to initiate change in such a regime since relations between these three dimensions reinforce each other. It can be seen as a self-reinforcing stable state that needs sufficient disruption to change states.

The change towards a bio-based construction sector, and the use of CLT, can be seen as a technological transition. For CLT to infiltrate the regime and become the norm, sufficient pressure on the current construction regime is needed. This is described by Geels, 2004 as the multi-level perspective (MLP); where sufficient landscape pressures are needed to allow a new niche innovation to disrupt the status-quo and infiltrate the regime (Geels, 2004). In this report, the landscape pressures will be referred to as the drivers of the transition.

So far CLT has still failed to push out conventional non-renewable materials and infiltrate the socio-technical regime. Change in practices involves uncertainties and risks that stakeholders might not be willing to take. Currently, the construction sector is under great pressure to comply with environmental norms and goals, such as nitrogen and carbon emissions. Changes in regulations, transitional agendas, and the perception of the stakeholders create opportunities for CLT to disrupt the current regime.

2.4 Transition pathways

There are many routes, or transition pathways, towards a predominantly CLT-based construction sector. The new regime will evolve differently, depending on the development of the pressures and the adaptability of the current regime actors. A different transitional pathway means that the new regime evolves in a different way, which results in different power structures and stakeholder relations (Geels & Schot, 2007).

Transition pathways are descriptive since they describe the likelihood of future developments based on an analysis of the current situation. Backcasting is a more prospective method that describes an ideal envisioned future scenario based on a pre-defined sustainability framework (Holmberg, 1998). Thereafter, strategies are formed to move from the current system to the envisioned goal. These envisioned futures are much like the target set by PZH, to become fully circular and largely bio-based by 2050.

However, radically different future scenarios might be hard to envision since these visions are inherently based on current knowledge and understanding. To diversify future visions a scenario analysis can be helpful. In scenario analysis, the analytical focus is not put on estimating probable outcomes, but rather on assessing the consequences of various possible outcomes (Duinker & Greig, 2007). To cope with these uncertainties various scenarios are created and analysed.

The method of scenario planning was initially developed for companies to understand external change (Kelly, Sirr, & Ratcliffe, 2004). However, it can also be used in other transitional situations where decision-making involves significant uncertainties (Duinker & Greig, 2007). By the creation of various diverging future scenarios, the scenario-planning method aims to compensate for both under and overprediction of change (Paul, 1995). The creation of these opposing scenarios allows for a wider vision of the possible future outcomes and thereafter a middle ground pathway can be charted (Paul, 1995).

2.5 The benefits and properties of CLT

The main bio-based solution researched in this study is cross-laminated timber (CLT). CLT is a wood composite made by bonding multiple layers of wood laminate sheets. The resulting CLT panels are a lighter construction material than concrete, yet they are strong enough to function as a load-bearing structure for multi-storey buildings (Lehmann, 2012; Di Bella, 2020).

A CLT building is practically a huge carbon sink, storing carbon throughout its lifecycle. Half of the mass of wood is carbon. Wood contains about 1.8kg of CO_2-eq per kg of dried wood, which is captured as CO_2 from the atmosphere (Robertson, Lam, & Cole, 2012). Increasing the lifespan of wood products extends its carbon sequestration potential and thereby the environmental performance (Nakano, Koike, Yamagishi, & Hattori, 2020).

The life cycle energy inputs of a CLT building are significantly lower than those of buildings based on concrete, steel and bricks (Sathre & González-García, 2013). Total cradle-to-gate GHG emissions are reported 60-70% lower compared to cast-in-place concrete construction (Robertson, Lam, & Cole, 2012; Darby et al., 2013). This difference is for a large part caused by carbon stored inside the timber, although even when this carbon is not accounted for CLT still outperforms conventional construction methods (Robertson et al., 2012). The carbon emissions of fabricating CLT equals about half of the carbon stored in the wood (Nakano et al., 2020). This shows that transitioning to timber construction will reduce production-related emissions and sequester carbon from the atmosphere.

Incineration of products releases the embedded carbon back into the atmosphere. Therefore, re-usage of high-grade materials is preferred over recycling and incineration. This is another advantage of CLT since it is a high-grade material with many options for material cascading (Sathre & González-García, 2013). When incineration is eventually required the EoL primary energy benefit of CLT is 8-24% higher than other wooden materials (Dodoo et al., 2014).

The majority of the life cycle energy use of a building is related to the usage phase (Guggemos & Horvath, 2016), an estimated 80% of the total energy is needed for heating, cooling and lighting (EIB #1, 2020). Alternate construction methods should yield equal or better insulation performance to reduce future energy demand. The industrialized construction methods allow for smaller tolerances and better airtightness; as a result, CLT has a 10% lower energy need for space heating than alternate wood construction methods, (Dodoo, Gustavsson, & Sathre, 2014; Lawson, Ogden, & Bergin, 2012; Guo et al., 2020).

Besides the above-mentioned advantages, there are many more advantages associated with industrialized construction methods. CLT construction requires no on-site construction and panels or modules can be easily installed on-site. This reduces construction-related energy usage and emissions by a factor of 2, compared to concrete construction (Robertson, Lam, & Cole, 2012). On-site deliveries are reduced by 70%, which in turn reduces the impacts on climate change, acidification, eutrophication (nitrogen emissions), and air quality (PM emissions)(Lawson, Ogden, & Bergin, 2012). Building times are shortened and less heavy machinery is needed; resulting in fewer emissions and fewer nuisances. Shorter construction times also yield financial benefits due to faster start-up times and reduced interest charges. These benefits can be up to 5,5% of the entire building's costs (Lawson, Ogden, & Bergin, 2012). Construction waste is reduced from 10-15% for conventional construction to less than 5% (Lawson, Ogden, & Bergin, 2012). Factory construction also offers a safer work environment; compared to on-site construction-work-related accidents are estimated to be reduced by 80% (Lawson, Ogden, & Bergin, 2012).

A frequently raised concern about timber construction is the fire hazard. However, CLT offers great potential for fire resistance since the solid structure reduces propagation via cavities, charring of the timber counteracts fire propagation and most importantly timber retains its structural rigidity better under heat as opposed to steel (Di Bella, 2020; Barber, 2015).

3. Research Focus

3.1 Problem Definition

During the transition to a circular economy, the material inputs into the construction sector will decline while more emphasis is put on the processing of material outflows. Different materials are required in a circular housing sector, which requires different job skills, supply chains and infrastructure. A primarily CLT-based housing sector will affect the construction sector in three ways. Firstly, it reduces the material demand and changes the type and quantity of required materials. Secondly, bio-based alternatives, such as CLT, utilize more automated and industrialized production and construction methods. This automation creates a further reduction in labour demand and a change in the types of required jobs. Lastly, CLT construction materials need to be imported, since a CLT industry is still lacking in the Netherlands. This dependency brings about material supply uncertainties. The CLT market is growing rapidly, but so is the demand for CLT. Whether future production will be of sufficient size to fulfil this increase in demand is uncertain.

The dynamics described above cause shifts in the construction regimes. These shifts change power dynamics and affect the available jobs, the predominant production methods, the material demand and market relations. Many of these aspects are currently lacking in the Dutch construction regime. Therefore, moving to bio-based materials will in the short term lead to outsourcing and regional labour loss. In the longer term, regional production of CLT could be desirable to counteract these losses in labour and economic activity.

Whether it is feasible to facilitate the material demand of PZH entirely with locally produced materials and products is unclear. It is also unclear if a regional industry based on imported materials is environmentally sustainable. However, most likely a balance needs to be struck between local production and the import of raw materials and pre-fabricated components. Charting a new direction for the future construction sector should therefore be carefully considered, to avert unexpected lock-ins, path dependencies and negative externalities.

3.2 Goal and Scope

The general aim of this study is to quantify the socio-economic and environmental impacts as a result of the transition to a bio-based housing sector based on CLT as a front runner. These impacts are put into context with the circular economy vision of PZH. The central question revolves around the import of CLT panels and of timber from other European countries and the possibilities for regional CLT production.

The main goal of this study is to identify and quantify the differences in socio-economic and environmental sustainability, between varying timber material flow scenarios. Insights into the relations between these variables and their impacts will be used to identify critical problems and limitations. These insights are used to create policy guidelines that can help steer the bio-based transition to the most favourable and resilient future, and to take the right actions at the right time.

For all scenarios, the impacts and solutions are scaled to the housing demand of the Province of Zuid-Holland. The scenarios will be put into context with the PZH transitional agenda, which aims to have a 50% circular economy by 2030 and a 100% circular economy by 2050 (MIXM, 2019; PZH, 2019). This is also in line with the Dutch policy aims for reducing carbon emissions with 49% by 2030 and 95% by 2050 (Rijksoverheid, 2019).

The spatial boundary is not restricted to PZH, since the material flows are not limited by the provincial boundaries. Also, acquiring substantial timber flows from PZH might not be realistic, since PZH is a densely populated and urbanized province. The true spatial boundary is the European Union since intercontinental transport of timber is not considered to be a sustainable solution.

The temporal timeframe of the various scenarios is from 2025 to 2035. This starting year is chosen to omit the variability and uncertainty related to the growth phase of Dutch CLT production. The assumption is made that the current investment in CLT infrastructure and the demand for CLT keeps increasing until 2025. Dutch CLT production is assumed to be in a juvenile stage at the starting point of all scenarios. This will allow for the scenarios to specifically focus on the trade-off between material flows of raw materials and fabricated components. The endpoint of 2035 is chosen since forecasting further into the future will greatly increase uncertainty. This will reduce both the applicability and the legitimacy of the outcomes.

The proportion of the PZH housing demand that will be fulfilled with CLT is highly relevant for the PZH policy goals, but will not differ between the scenarios, since it does not affect the above-formulated aim of this study. The percentage of the housing demand fulfilled with CLT is chosen at 20%. The effect of this CLT implementation is quantified and related to the material usage of the current construction practices. This quantification will serve as a baseline for all scenarios. This baseline can easily be extrapolated if the assessment of a larger share of CLT implementation is desired.

3.3 Research questions

What are the impacts of a transition to a housing sector in PZH that is for 20% based on CLT? and could regional CLT production offer socio-economically and environmentally sustainable solutions?

- Context: What are the essential problems and conflicts regarding the transition towards a circular housing sector in PZH?
- Baseline: What are the socio-economic and environmental impacts associated with constructing 20% of the housing demand of Zuid-Holland with CLT housing, as opposed to conventional construction?
- Assessment: What are the environmental and socio-economic trade-offs between regionally produced and imported timber construction materials?
- Scenarios: What scenario for fulfilling 20% of the future housing demand with CLT is most desirable in the context of the PZH circular economy and climate goals
- Recommendations: What policy actions need to be implemented to facilitate the transition towards this most desirable future scenario?

4. Research Approach and Method

A mixed-method research approach is used, based on scenario-planning frameworks (Kelly et al., 2004 and Duinker & Greig, 2007), and the sustainability framework by Taelman et al., 2018. These frameworks where adapted served as a methodological guideline for this research (figure 1). The outputs of the various scenario-planning steps were used to identify and legitimize the focus for this research. An overview of the resulting research steps, the used methods, and the input of data is shown in the figure below (figure 1). Figure 2 gives an overview of the scenario-planning framework. The research approach diagram shows where the outputs of these steps are incorporated in the final research framework.

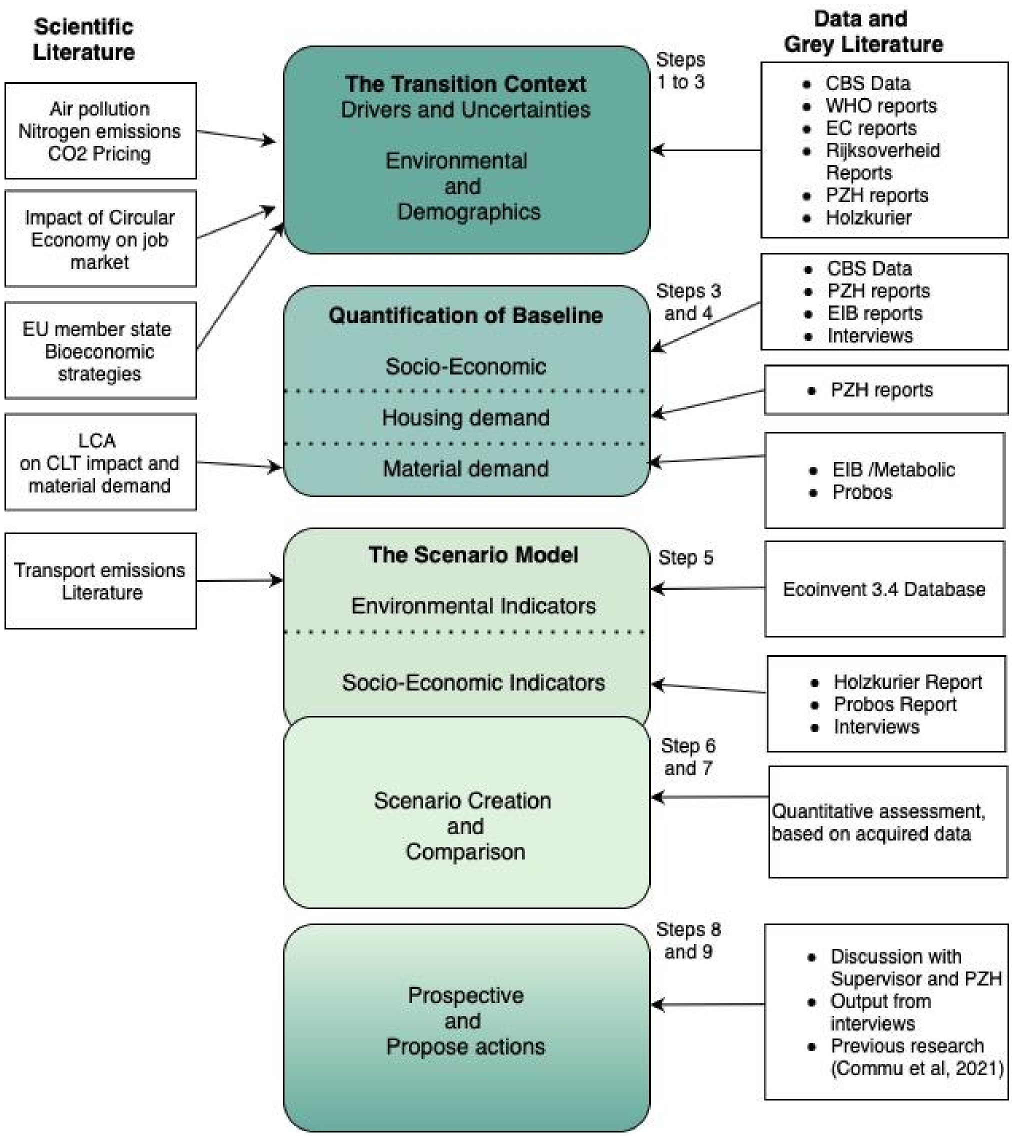


Figure 1: Overview of research approach, each coloured box represents a research stage. Next to each colouredbox, the corresponding steps from the scenario planning framework are shown. All boxes feeding into the research stages show what sources and methods are used in the specific stage.

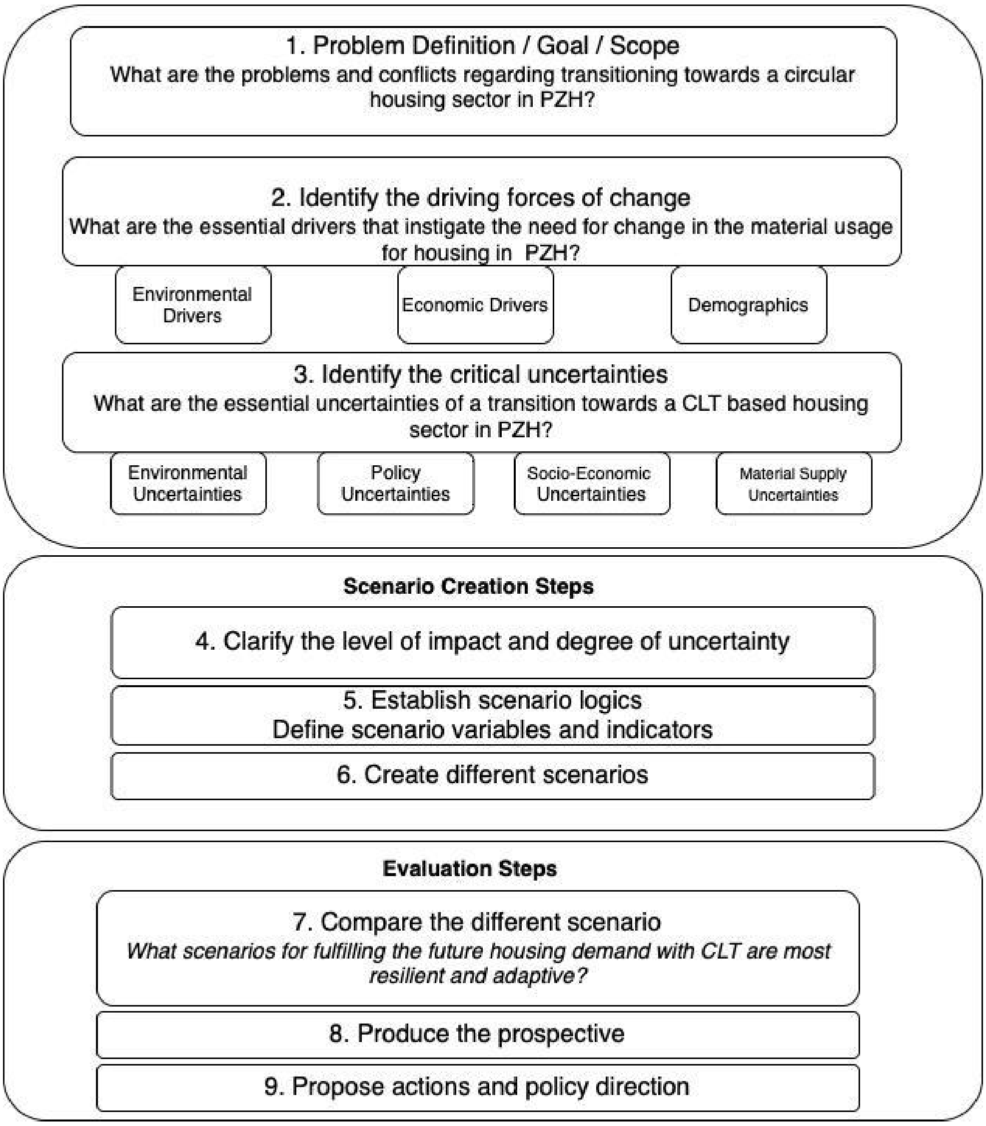


Figure 2: The structural representation of the scenario framework steps, based on Kelly et al., 2004 and Duinker & Greig, 2007.

4.1 The Bio-Based transition context

This section described the general context and the drivers behind the transition to bio-based construction, which represents the first three steps of the scenario framework (figure 2). These steps were used to identify the main aim of this research and they served as a foundation for the remainder of the research. This section also served as a guide for the final policy recommendations.

First, the specific bio-based material transition problems were formulated based on policy documents from PZH and a general scan of relevant literature. This problem definition was used to formulate the goal and to define the scope of this research. Next, the drivers were structured by adapting the sustainability framework from Taelman et al., 2018. The drivers were divided into three categories; demographics, environment, and economy & policy. Further literature searches and data from governmental organizations were used to describe and quantify the primary drivers. Thereafter, the bio-based transition uncertainties were described and related to these drivers. Finally, both the drivers and the uncertainties were systematically structured in a matrix to identify the critical uncertainties. Critical uncertainties were assumed to both have a high impact and high uncertainty. These critical uncertainties were used to eventually formulate and define the input and output variables for the scenario model. The uncertainty diagram and the literature search terms can be found in the appendix (figure 25, appendix section 8.2).

4.2 Baseline Quantification

The baseline chapter compared impacts of CLT construction to conventional construction, in the context of the goal and scope of this study. This baseline can be seen as a benchmark for the improvements associated with CLT construction. The non-scenario-specific baseline assumptions were formulated using the previously defined quantitative, spatial and temporal scope. These baseline assumptions were then quantified and related to a BAU scenario; based on the social, economic and environmental impacts.

The data on employment in the construction sector was acquired from government datasets (CBS) and reports (EIB). This data was compared to qualitative information on CLT assembly acquired from interviews. Documents published by PZH were used to quantify the housing demand dynamics. These housing demand dynamics were used to estimate the annual CLT demand needed to reach the 20% CLT aim. The variables used in this calculation can be found in section 8.3.1. For all analyses, the average housing demand over the scenario timeframe was used. This demand and the timber needed to produce this CLT was related to the annual Dutch timber flows from 2012 (Nabuurs et al., 2016). All further data sources and search terms can be found in the appendix section 8.1.

Literature was reviewed to estimate and quantify the material-related impact of 20% CLT implementation versus a BAU scenario. Numbers acquired from the literature were extracted and used in the quantitative assessment. When possible, multiple sources were used and data was cross-referenced and averaged (see appendix 8.3.1).

First, the baseline material demand and the baseline embedded carbon were quantified on a per apartment basis (8.3.1, table 14). These baseline impacts were based on the average of all houses built in 2014 (EIB #1, 2020). Data on the type of materials, the mass of these materials, and the embedded carbon in these materials were divided by the total number of constructed houses in 2014. It was assumed that the data from 2014 was still representative of the current material demand in the conventional construction sector. These numbers represent the mix of various types of houses built in the Netherlands in 2014, about 50% apartment buildings and 50% single-family homes (EIB #1, 2020). Detailed assessment based on specific building types and the corresponding living area was beyond the scope of this study.

Secondly, the CLT construction material demand, material composition, and the embedded carbon in these materials were quantified (8.3.1, table 13). This data was acquired by extrapolating data from an LCA on a CLT apartment building. The total impact of the apartment building was devised by the number of apartments within the building. All the referenced comparative LCAs in this report applied to multi-story apartment buildings since this is the most beneficial building type for CLT construction. The relative share of materials was assumed to stay similar for smaller and larger CLT larger apartments.

Thirdly, the impacts of the baseline apartments were compared to CLT apartments. To ensure an equal comparison, the emissions per m2 of living area for CLT buildings were multiplied by the average area of all conventionally constructed buildings in 2014. The average living area of the 45 thousand houses constructed in 2014 was 146m2 (for apartment buildings specifically it was 86m2). Fourthly, the apartment level comparison was used to quantify the annual change in material demand and the change in embedded carbon emissions as a result of the 20% CLT implementation aim. The impact of the 100% conventional baseline was compared to the 20% CLT (2200 CLT houses annually) and 80% conventional (80% of the 2014 impact).

Finally, the total avoided emissions and the monetary value of these saved emissions as a result of the 20% CLT aim were determined. The embedded carbon data only represented the emissions embodied in the material, these did include production emissions but excluded construction emissions. Therefore, the construction-related emissions were estimated based on literature and were added to the material embedded carbon emissions. Thereafter, the saved emissions were multiplied by the estimated monetary value of a ton of CO2-eq.

4.3 The Scenario Model

A scenario model was created to assure clear causal relations between scenario variables and thereby allowing direct comparison between scenarios. This systematic overview of the scenario model is shown in figure 3. The model consists of four input variables, three intermediate production steps, and the socio-economic and environmental output indicators. In the following sections, both the model and the methods for quantification are described.

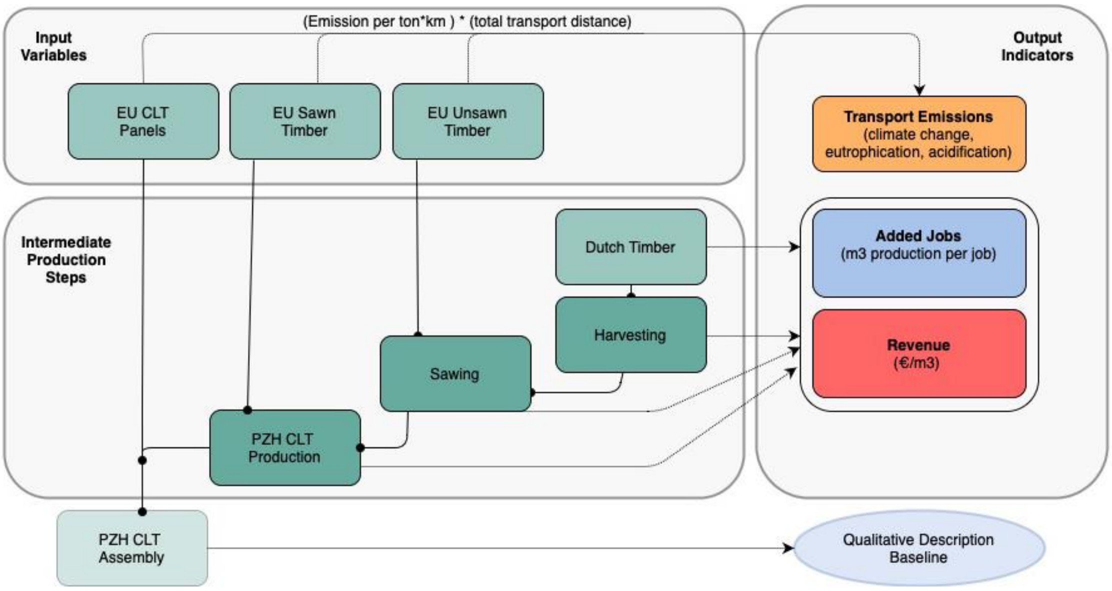


Figure 3: Scenario model, imported timber PZH CLT assembly is not included in the scenario assessment but is qualitatively described in the baseline section.

4.3.1 Input Variable Description

The Dutch unsawn timber, EU unsawn timber, EU sawn timber, and EU CLT-panel material flows served as scenario variables. Altering these variables allowed for an impact comparison between a future construction sector based on regionally CLT produced or imported CLT panels, and whether this regional CLT production industry is dependent on imported timber resources or not. The transport emissions were only quantified for the imported timber streams. Transport emissions from the forest to the CLT factory are assumed to be similar for CLT produced domestically or in other EU countries. Thereby, these transport emissions are generally already included in LCAs on CLT production.

4.3.2 Output Indicator description

Socio-Economic indicators
Two socio-economic impacts are used as assessment indicators for the various scenarios, the number of added jobs and added revenue. Firstly, the production efficiency was quantified; the m3 of production per full-time job. For this quantification information on existing production facilities was used. For various production facilities, the annual production capacity was divided by the total number of employees. The result is an overview of m3 of annual production per full-time job for each production stage (8.3.2, table 16). Preferably factory sizes applicable to the PZH case were used and otherwise, the data were averaged. Secondly, for the estimation of the added revenue of each intermediate production step, the value per m3 of each timber material stream was quantified. Interviews and literature were used to estimate the current market prices of unsawn timber, sawn timber and pre-cut CLT panels (8.3.2, table 17).

Environmental indicator
The environmental impact is based on the added transport emissions resulting from material imports. First, the emissions of the various means of transport were quantified based on data from the EcoInvent 3.4 database. All unit processes were imported into CMLCA and for four transport unit processes, the emissions resulting from 1 ton/km were extracted. The specific unit processes and the various categorized outputs can be found in the appendix (8.3.3, table 18). The following three impact categories were used for further assessment; global warming, acidification and eutrophication.

These categorized outcomes were cross-referenced with literature (8.3.3, table 19). Extrapolation of emission data of lorry transport found in literature yields 0,093 kg CO2-eq per ton-km (Lindholm et al., 2005). These lorry climate change emissions are in line with Ecoinvent data. The CO2 emissions of barge transport are reported to be approximately 30-40 grams CO2 / ton-km (Mckinnon, 2007.) This is in proximity to the 48 grams CO2-eq / ton-km resulting from the ecoinvent data.

Thereafter, the optimal transport method was determined. In the interviews, rail transport was identified to be unpreferable for CLT transport and was therefore not modelled. For barge and lorry transport the emissions per ton*km were multiplied by the distance of the transport routes. Austria is chosen as the material origin since it is the largest CLT-producing country in the world and many CLT Dutch assembly companies import from Austria. Distances were estimated based on the shipping route from Rotterdam (Netherlands) to Linz (Austria) (1335km), plus the distance from the production facility in Austria to the port in Linz (190km). The direct route from the production facility to Rotterdam by road was 1150 km.

An overview of the assumed transport means and distances per material input is shown in figure 4. In all further assessment for all imported timber materials only transport by lorry was assumed since this showed to be most beneficial.

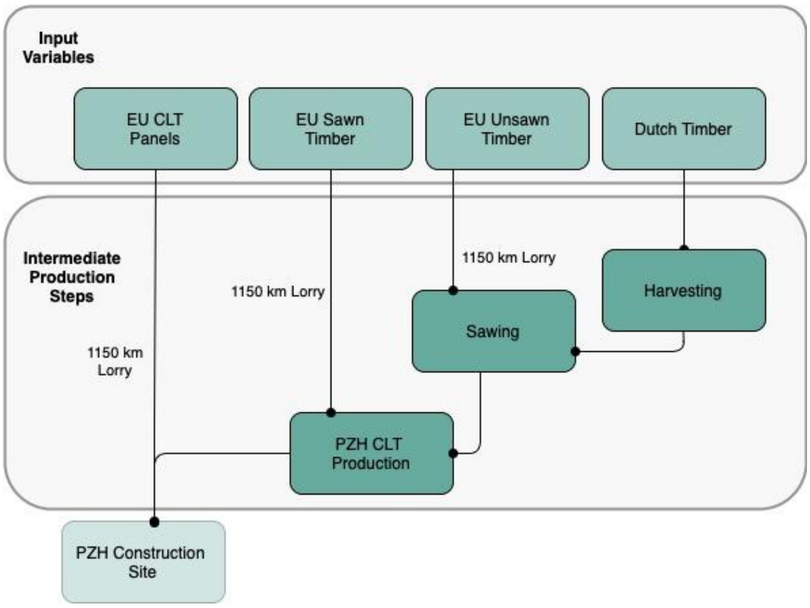


Figure 4: Overview of modelled transport distances and means of transport for all input variables.

4.4 Scenario Creation

First, a simple matrix was created where the y-axis reflected CLT panel origin and the x-axis timber origin (imported versus domestic) (appendix 8.2, figure 27). Then, two opposing scenarios were plotted in the matrix to serve as extremities. These extremities were used to demarcate desirable and realistic future outcomes. The four scenarios were plotted within the matrix and chosen to cover a wide range within these defined extremities. Lastly, these four plotted scenarios were described and the input variables were arbitrarily quantified. Yielding the material flows shown in the table below (Table 1). Volumetric material requirements were based on estimated production losses found in the literature. These volumes were extrapolated from the CLT demand by means of production losses found in the literature (Nakano et al., 2020; Commu et al., 2021), see (appendix 8.3.1, table 12).

	EU CLT (m3)	**Dutch CLT (m3)**	Dutch Unsawn Timber (m3)	Imported EU Sawn Timber (m3)	Imported EU Wet Timber (m3)
Scenario 1	104.025 (95%)	5475 (5%)	16.425	0	0
Scenario 2	54.750 (50%)	54.750 (50%)	82.125	27.375	0
Scenario 3	21.900 (20%)	87.600 (80%)	131.400	43.800	0
Scenario 4	21.900 (20%)	87.600 (80%)	131.400	0	131.400

Table 1: Quantitative overview of material streams for each scenario. Note that the Dutch timber flows are represented as +/- 3 times larger than the European flows since it concerns unsawn wet timber)

4.5 Scenario Comparison

For the socio-economic impact assessment, the values of the previously defined output indicators are multiplied by the volumetric material streams. This is done for each production stage and for each scenario. The results were plotted and assessed on both the total contribution and the relative contribution of each production stage.

Added Jobs (Jobs/year)= Production efficiency (m3/job) * Volume (m3/year)

Added Revenue (€/year) = Value (€/m3) * Volume (m3/year)

For the environmental impact assessment the volumetric material streams (m3/year) were converted to mass flows (tons/year) by means of the average density of the various timber materials. The density of undried timber was assumed to be 0.87 tons per m3 (Lindholm et al., 2005), the average density of sawn timber was assumed to be 0.46 tons/m3 and the density of CLT panels was assumed to be 0.47 tons per m3 (Chen et al., 2019).

Mass flows (tons/year) = Volumetric flow (m3/year) * Density (tons/m3)

Thereafter, the total amount of required ton*km of transport per scenario was determined. For each material stream, the mass flows were multiplied by the previously defined transport distances. Finally, the total amount of required transport was multiplied by the impact per ton*km. The following three impact categories were used: climate change, eutrophication, and acidification. This resulted in the total scenario impacts associated with the import of timber materials. The formula for the climate change impact is shown below, the calculation for the other two impact categories is identical. All data can be found in the appendix section 8.3.3.2.

Annual Climate Impact (kg CO2-eq / year) = Mass flow (tons/year) * Transport Distance (km) * Transport Impact (kg CO2-eq / ton*km)

4.6 Evaluation

The outcomes of the scenario analysis were used to describe the most desirable future CLT construction sector. Thereafter, these outcomes were related to the baseline quantification to give context to positive and/or negative impacts, and to determine if regional production was feasible and desirable. Thereafter, the general transition context chapter was used as a structure to formulate policy recommendations. Finally, these recommendations were discussed with PZH to ensure the applicability of recommendations. Hereafter, based on the input from PZH the recommendations were expanded upon.

5.Results

5.1 The bio-based transition context

This section describes the broader context and the underlying drivers (landscape pressures) of the transition to a circular and bio-based housing sector. These concepts describe the foundation, complexity, and intricacies of the transition. This context is relevant for understanding the development of pressures on the construction sector over time; both before, during, and after the scenario timeframe. An overview of the drivers and the resulting uncertainties is shown in figure 5. The following question is central for this section: *What are the essential problems and conflicts regarding the transition to a circular and bio-based housing sector in PZH?*

The figure shows how environmental and demographic pressures shape the demand for more sustainable and affordable materials and construction methods. The environmental drivers put indirect pressure on the industry and society via climate policy and economic sanctions. These policy measures are the essence where in practice the distinction between sustainable and conventional construction is made. These sanctions either favour or require more sustainable and low emission solutions.

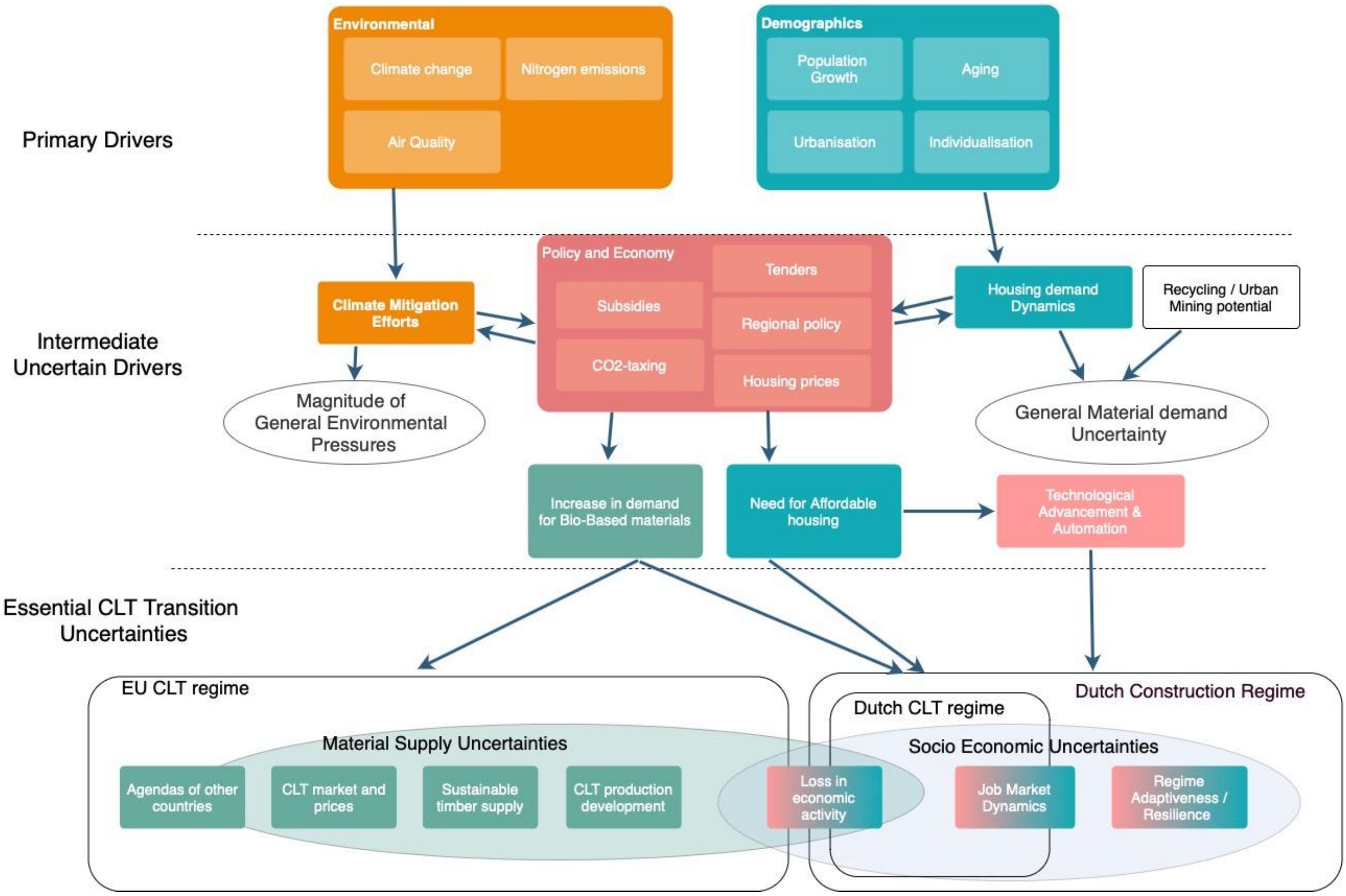


Figure 5: Overview of the drivers, how these affect policy and the economy, and how these result in the corresponding CLT transition uncertainties.

Besides these environmental pressures on the construction sector, there is also the pressure of increasing demand for housing. These two pressures create a conflict that cannot be solved with conventional construction practices but requires a change in materials and methods. Initially, this will lead to an increased demand for affordable housing that is preferably a low-carbon alternative. In the long-term when CO2 pricing increases the latter two will become analogous, where low carbon will equate to more affordable.

CLT is a promising material since it is sustainable and in certain cases already price competitive with conventional construction. This highlights that CLT is outgrowing its niche and moving towards the status-quo. The corresponding change in material demand brings about a change in the supply chains and construction companies. This change leads to a shift from the conventional construction regime to the CLT construction regime. However, since a domestic CLT regime is currently still developing and production is non-existent, this shift results in the outsourcing of economic activity and labour to other European countries. These regime shifts will serve as the foundation of the further scenario analysis.

5.1.1 The Primary drivers

5.1.1.1 Environmental Drivers and Climate Policy

The development of the climate crisis will greatly impact the pressure on the current construction regime. The longer it takes to take significant actions towards a carbon-neutral economy, the more severe these actions have to be and therefore the stronger the pressures on the current regime will become. The European green deal aims to decouple economic growth from carbon emissions and become the first carbon-neutral continent by 2050 (EC, 2019). To achieve this, it is necessary to reduce virgin materials, shift to lower impact materials and put more emphasis on end-of-life solutions. Or in other words transition to a more circular economy.

Although timber construction has a lower impact on all environmental impact categories (Robertson et al., 2012), currently the financial measures on emissions are either not in place or not of significant severity to make timber materials price competitive with mineral-based materials (Interview 4). The development of these financial measures is crucial in the further development of the timber construction niche.

An example of financial implications resulting from climate change is subsidies and CO2 emissions taxes. Currently, the EU emission trading system (ETS) carbon price is about 38€/ton-CO2eq, a 60% increase from January 2020. To reach the Paris Agreement targets, the price of a ton of CO2 should rise to US$50-100 by 2030 (Klenert et al., 2018). On top of the ETS, the Dutch government has introduced an additional levy for industry (NE, 2021). The current Dutch levy on a ton of CO2 emissions is 30 euros, this is meant to increase by 10 euros yearly and reach 125 euros by 2030. This amount is chosen to reach the envisioned reduction with 75% certainty (NE, 2021).

Another substantial driver for change is nitrogen emissions. The Dutch aim is to restore 50% of the Natura-2000 natural areas to healthy nitrogen levels by 2030 (LNV, 2020). To achieve this, it is advised to reduce NOx and NH3 emissions to 50% of the 2019 amount by 2030 (J.W. Remkes, 2020). To adequately reduce the nitrogen emission of the construction sector by 2030 the Dutch government reserved 500 million euros (LNV, 2020). The construction is hampered by NOx emission limitations; more than one-third of all construction companies experience hindrance caused by nitrogen emissions, mainly due to delays in acquiring permits (EIB, 2020 #3). This impacts mainly larger companies with more than 50 employees.

Another example of an environmental driver is air quality. The Dutch government and PZH have signed an accord, the “schone lucht akkoord” (SLA), to reduce air pollution by 50% by 2030 (IenW, 2020). This policy is in accordance with the ambitions of the WHO, for example in aiming to reduce annual average concentrations of PM2.5 below 10μg/m3 (WHO, 2005). Currently, the average PM2.5 content in the Netherlands is between 15 to 18 ug/m3 depending if you are in a rural area or city (IIASA, 2014). As of 2016, the entire population is exposed to PM2.5 levels above the WHO norm (World Bank, 2021). Industrial and construction activities significantly contribute to all of them, but also other activities related to construction, such as transport, non-road mobile machinery, and energy production.

5.1.1.2 Demographics

The current population growth is the largest since 1975, about 85% is related to immigration (CBS, 2021). The immigration-driven growth mainly applies to cities in the middle and west of the country (Groenemeijer et al., 2020). The migration balance is at a record high while the birth surplus is rather low. It is expected that the birth surplus will decline and may become negative, after 2040 (CBS, 2021). Based on this forecast from the CBS the deficit between immigration and emigration will be reduced, mainly due to the expected increase in emigration. In the coming decades, the national population growth is not expected to become net zero.

The CBS forecasted a population growth for PZH from 3.7 million in 2020 to 4,2 million by 2050. These dynamics are also being affected by the current covid pandemic, which results in less migration and more mortality (CBS, 2020). Due to pandemic-related excess mortality, the population growth in PZH was briefly negative in April 2020. The amount of birth is also expected to be lower in the coming year, this is related to economic uncertainty caused by the pandemic (PZH, 2021 #1).

As described above the majority of the population expansion will be immigration driven and in cities in the middle-western parts of the Netherlands (CBS,2020). The two largest cities in PZH, Rotterdam and The-Hague, are the second and third fastest-growing cities in the Netherlands, by absolute numbers, as of 2019. Inequality in these regions is high, having both a large proportion of people in high and low-income groups (CBS, 2020). In Rotterdam and The-Hague 50% of the population falls in the lowest 40% income group (CBS, 2020). This works two ways since living in cities is overall more expensive as opposed to rural areas (CBS, 2020).

This inequality is amplified by the trends in the housing market. It is expected that the share of social housing will decline, and the real estate sector will grow, with an emphasis on more expensive properties (Groenemeijer, et al., 2020). Highlighting the need for policy regarding affordable housing and the need for lower construction costs. This is especially relevant since 48% of the national housing demand is for more affordable housing, both rental and real estate (PZH, 2017).

During the years 2019-2030 the growth in the number of households (+7.4%) is estimated to be higher than the population growth (+4.3%) (Groenemeijer et al., 2020). Nationally an increase of 585 thousand households by 2030 is forecasted (with an uncertainty of about 20%) (Groenemeijer et al., 2020). The majority of the growth in housing demand can be attributed to individualisation. The number of single-person households increased by 16% in 2019 (Groenemeijer et al., 2020), of which the majority applies to the 65+ age category (PZH, 2017).

5.1.2 Circular economy transition uncertainties

The identified areas of critical uncertainty are related to the national regime shift, from conventional to bio-based, and the international regime shift, see figure 5. These shifts cause material demand uncertainties and socio-economic uncertainties. These two uncertain areas are expanded upon in the following sections and will serve as the context for the specific choice of the scenario variables and indicators.

5.1.2.1 Socio-Economic Uncertainties

The transition to a circular economy will likely positively affect employment, creating jobs for various skill levels (European Commission, 2018; ECORYS, 2019). The transition to a circular economy can increase GDP by 0,5% by 2030 as well as increase jobs by approximately 700.000 (EC, 2018 #2). This increase in jobs is spread over a variety of skill types but does greatly differ per sector. Especially small to medium-sized enterprises will benefit from these opportunities (EC, 2018 #2).

Benefits do not only differ per sector but also per region and member state. This shift will benefit GDP and employment in Central and Eastern European countries more than in Western European countries (EC, 2018 #2). CE performance of member states is also affected by differences in GDP, corruption indices, government efficiency indices, and education (Škrinjarí, 2020). Especially lower economic growth resulting from corruption is a common factor in low-performing countries. The top-performing countries generally have higher GDP, more adequate policy, better infrastructure, more consumer awareness, and higher R&D investments (Škrinjarí, 2020; Busu & Trica 2019).

On a European level, the transition to a circular economy is found to have a net negative impact on employment in the construction sector (European Commission, 2018). These reductions are mainly caused by reduced material demand, changes in construction methods, and innovations that increase efficiency (TNO, 2019). For PZH specifically, the effect of a circular economy on employment in the construction sector is reported to be net-zero (TNO, 2019). However, it is uncertain whether this assumption applies to a more automated bio-based construction sector.

The transition to a circular economy in PZH is estimated to facilitate 6.8 to 13.7 thousand extra jobs by 2040, which is a 0,24% to 0,5% increase from a regular scenario (TNO, 2019). This will bring an extra 450 to 2.450 million euros of additional production to PZH (TNO, 2019). Currently, there are already 15 thousand companies in PZH that are affiliated with circular economy practices. These jobs are mainly related to repair and recycling activities, and employ about 91 thousand people, which represents 5% of all jobs in PZH (TNO, 2019).

The emphasis in a circular construction sector will shift from primary production towards more labour-intensive jobs related to the closing of material loops (European Commission, 2018). A reduction in material use in combination with technological innovation will lead to employment reduction in production-related jobs, while new job opportunities arise in remanufacturing, recycling, and repair (European Commission, 2018). These changes will result in an inter-sectoral job shift, requiring people to find new jobs, re-educate and maybe temporarily accept a lower salary (ECORYS, 2019; TNO, 2019). In a circular economy, the type of job and the level of required education greatly differ per sector. Newly created CE jobs mostly require more specialized skills, therefore reskilling strategies are likely needed (European Commission, 2018).

During the transition, the availability of employees could become a potential risk that could hamper the expansion of a CLT industry. This can both be caused by a lack of specific high-knowledge jobs but also by a lack of experienced and skilled construction workers. The CLT industry already reports shortages of people with 3D rendering skills and a shortage of constructors with timber construction knowledge (Interview 1; Interview 2). Therefore, financial security and re-education programs are necessary to guide the transition.

The Covid-19 pandemic causes a short to mid-term change in labour demand, which requires re-education of workers and may cause future mismatches in the job market (CP, 2020). This disruption in the job market can either be amplified by a transition towards a circular economy or serve as an opportunity. Since there is already movement in the job market, these dynamics can be steered towards a more beneficial future state. Timing is essential in this since disturbing the job market when it is already recovering will further damage the economy.

5.1.2.2 Material Supply Uncertainties

In the ideal circular economy the dependency on material imports should be minimized (Škrinjarí, 2020). However, whether complete self-sufficiency is realistic for the Netherlands is unclear. Therefore, the future development of a bio-based material supply is essential. Both the future growth of the European bio-based material markets and the development of national timber production are important.

It is likely that the bio-economic strategies of other European countries also include timber as an important material in their transitional agenda. An understanding of the future development of the supply and demand sides of the European CLT market is needed, to assess the uncertainties related to future EU timber flows. All EU countries share the same overarching sustainability goals, but still have rather diverging strategies and pathways. Therefore, the future development of the demand for timber materials is rather uncertain. Dynamics in the EU policy, such as carbon taxing, could speed up the CE transition in lower-performing countries, causing a more simultaneous increase in demand for bio-based alternatives. Benefits from transitioning to a circular economy also differ per country, the impact on GDP and employment being favourable for central and Eastern-European countries (EC, 2018 #2).

However, it is unsure if production can keep up with this growing demand. European CLT production has been growing exponentially over the past decade, reaching 2 million tons annually last year (Holzkurier, 2020). Still, in 2019 the demand for CLT in the DACH region surpassed the annual production (Holzkurier, 2020). This shows there is huge supply uncertainty especially when the CLT market is expanded to other countries in the future. Building a new factory only takes approximately 2 to 3 years, so CLT producers can rather quickly react to increasing demands (Interview, 1). In the next 5 years, the CLT market is forecasted to grow by 15% annually, and reach a 1.4 billion USD market size by 2025 (IMARC group, 2019). This would mean EU production could reach 3 million m3 in 2025. Half of the current EU production is concentrated in Austria, where there are eight large CLT producers within a 150km radius with an estimated combined capacity of 900.000m3 (Holzkurier, 2020).

European timber supply is unlikely to be limiting, about 0,05% of the EU production would be needed to facilitate 20% of the PZH housing demand with CLT (Commu et al., 2021). If the demand for timber in Europe would surpass the sustainable production capacity, this would induce unwanted externalities. Especially since globally the opportunities for expansion of sustainable forestry are rather limited (Nabuurs et al., 2016) and long transport distances are undesirable (Nakano et al., 2020). In the worst case, a material lock-in could arise, where the sector is dependent on imports of unsustainably harvested timber to supply the increasing demand.

Timber market dynamics do significantly influence the CLT market. Future fluctuations of prices on international markets could hamper the availability and affordability of CLT construction. For example, in early 2021 there was an extremely high demand for saw timber in the U.S., caused by the covid pandemic, international politics, and a shortage of sawmill capacity. This resulted in price inflation on the European markets; sales of sawn timber in the US made more profit than selling CLT on the European market (Holzkurier, 2020). This made it difficult for European CLT producers without their own sawmill. Timber prices were reported to be 10-20% higher than in 2019 and were growing each month, at the time of writing. This price increase made it difficult for CLT to remain price competitive (Interview, 1). Such a price increase is rather decisive since in many cases CLT is already more expensive than other timber construction alternatives and especially more expensive than conventional construction (Interview, 1). This shows the difficulty of the market situation, where European demand surpasses supply, and still, both timber and CLT are exported to foreign markets.

5.2 Baseline Quantification

In this chapter the scenario-common impacts, as a result of the 20% CLT implementation aim, will be determined and quantified. First, the socio-economic baseline is quantified; this includes a description of the current construction sector and employment dynamics. Thereafter, the housing demand for the scenario timeframe is quantified. This quantification is then used to determine the change in material demand and the impacts associated with this change in material demand. The central question for this section is the following: “What are the socio-economic and environmental impacts associated with constructing 20% of the housing demand of Zuid-Holland with CLT housing, as opposed to conventional construction?”

5.2.1 Socio-Economic Baseline

As of 2019, there were about 180.000 Dutch construction companies, of which 24% were based in Zuid-Holland (CBS, 2021 #1). These 44.240 construction companies in PZH accounted for 9% of all companies within the province (CBS, 2021 #2). The construction sector is divided into three categories; general construction, specialised construction, and infrastructure. An overview of the various sizes of these subsectors is shown in table 2. The specialized construction sub-sectors include companies such as carpentry, painting, plumbing, electricity, heating and roofing, etc.

PZH 2019	no. of Companies	% of total
Entire Construction Sector	44.240	100%
● 41.General Construction and project development	20.050	45%
● 42.Infrastructure	2.155	5%
● 43.Specialized Construction	22.035	50%
○ 431.Demolition and groundwork	● 2145	● 5%
○ 432.Building Installation	● 5915	● 13%
○ 433.Finishing	● 9555	● 22%
○ 439.Other specialized	● 4420	● 10%

Table 2: Size of PZH construction sector, data sourced from: CBS, 2021 #1, CBS, 2021 #3

In the year 2019, the national growth in the number of construction companies was the largest to date (8%), from all provinces PZH showed the largest growth with 11% (CBS, 2021 #3). Growth was especially large in the city of The-Hague and Rotterdam. This growth can almost be entirely attributed to an increase of one-man companies in the specialized construction sector (CBS, 2021 #3). Some of these companies are specific to conventional construction practices, such as bricklaying companies, and will likely suffer from the transition to timber construction. However, the majority of the specialized construction companies, such as plumbing, electricity, painting, carpentry and glazing companies, could also apply to timber construction. The general construction sector remains the largest sub-sector in the cities of The Hague and Rotterdam. In Rotterdam, this is followed by carpentry and in The-Hague by concrete weavers (CBS, 2021 #3). This indicates that it is more likely that these cities in particular will be affected more by the transition towards timber, and for The-Hague even more so than Rotterdam.

The employment opportunities in the construction sector and the available labour fluctuate along with the economy. After the previous financial crisis, there has been a shortage of employees in the construction sector. In 2019 it reached a record height of 59 job offerings per 1000 employees (see figure 7) (EIB, 2020 #2). During this time approximately 25% of the construction companies experienced employment-related production impediments (EIB, 2020 #2).

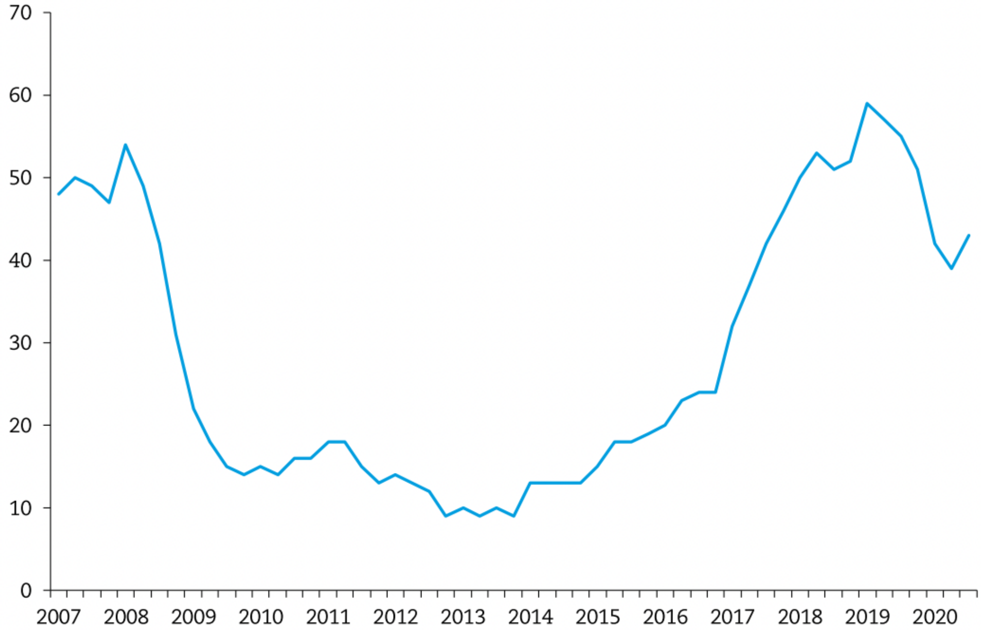


Figure 7: The development of job vacancies per 1000 employees overtime, source (EIB, 2020 #2).

During the current pandemic, along with a reduction in production, employment in the sector also decreased. At the end of 2020, the shortage in employees declined to 43 vacancies per 1000 employees (EIB, 2020 #2). In 2020 employment opportunities declined with 6.000 employment years, in 2021 a decrease of 18.000 employment years is expected. Therefore, the sector-wide loss in jobs is larger than the outflow of jobs due to retirement, so no net inflow of employees is needed. However, in the period from 2021 to 2024, the employment opportunities in the sector are expected to increase again with 34.000 employment years (EIB, 2020 #2). It is expected that about 75.000 additional employees are needed in the years 2022 to 2024 (EIB, 2020 #2). To be able to fill these positions, there have to be sufficient newly trained workers (EIB, 2020 #2).

The main employment inflow into the sector comes from schools. Trends in the annual number of students follow the economic cycles of the construction sector; if employment opportunities are low, fewer people choose for education in construction. This results in a temporary shortage of schooled workers when employment demand increases. Foreign workers are generally used to flexibly fill these gaps (EIB, 2020 #2). However, to fulfil the future employment demand, from 2022 onwards it is estimated that workers from other domestic sectors need to be attracted (EIB, 2020 #2). This requires effort from the sector and results in increased wages and investment in education programs. The costs for employment are already rather high and it is estimated that conventional construction employment accounts for 40 to 50% of the total costs of a building (Interview 4).

Besides increasing the inflow of new employees, also reducing the outflow is important to keep employees within the sector. These outflows consist of retirements, injured workers, and resignations. The main reasons for resignations in the construction sector are; too physically heavy work (25%), bad organization (23%), and the lack of implementation of knowledge and skills (23%) (EIB, 2021). About 50% of the construction workers experience a high physical workload, the same applies to the perceived mental workload (EIB, 2021). This perceived mental stress is mainly caused by time pressures, especially on the construction site (EIB, 2021).

The instigation of a regional CLT industry could help reduce foreseen labour shortages and keep employment within the sector, even though CLT construction requires less labour than conventional construction. Thereby, a more organized working environment and safer working conditions will reduce physical and mental stress on workers, thereby also reducing injuries. This may reduce resignations from the sector and attract more workers from other sectors.

5.2.2 Qualitative description of CLT construction and assembly

The production of CLT is by nature more industrialized than conventional construction practices. The industry is striving for optimization through automation; which is highlighted by the huge variety in innovations such as wireless light switches, joinery techniques, and glueless lamination (Holzkurier, 2020). Although this automation is beneficial for the reduction in resource use, cost and construction times; it will greatly affect the type and amount of jobs in the sector. The result of this automation is the reduction of labour demand and a shift in the required jobs. Compared to the current construction sector, jobs will likely shift from physical labour oriented to jobs requiring ICT skills and knowledge. This shift from more general jobs towards more high-skilled and ICT jobs is a result of increased automation and is a general trend seen in multiple industries (Bonekamp et al., 2015; Oschinski et al., 2018).

Scale and efficiency increases are a necessity to achieve a price competitive CLT building; especially since shadow costs and embedded carbon emissions are not yet adequately taxed. Currently, a cubic meter of CLT is still about 3 to 4 times more expensive than concrete (Interview 4). Reductions in labour costs are one of the primary ways to reduce the construction cost of a CLT building. In conventional construction, the share of labour costs is estimated to be 40-50% of the total building costs (Interview 4). In the CLT-construction industry, the aim is to move this share towards 18%, as seen in other more automated production industries (Interview 4). This reduction of labour is not solely a financial drive but also a response to the shortage of skilled labour (Interview 4; Interview 2).

In CLT construction there are two main types of construction methods; flatpack and modular construction (Interview 4). Both methods start with detailed 3D renderings of the building. These detailed renders include all openings for windows, doors, and plumbing. These renders are then sent to the CLT producers where all the holes are automatically routed in the factory.

In flatpack construction, these pre-cut panels are shipped to the construction site where they are directly assembled. Reportedly 4 people can assemble a 3 story building in just 3 days, while for conventional concrete construction this would require more people and would take significantly longer (Interview, 2). This way of construction still requires various subcontractors to finish building. However, there is a mismatch between CLT construction and the way traditional construction workers operate. In general, traditional construction workers are not used to working with 3D renders. Therefore, commissioners generally need to specifically clarify the required tasks using 2D images taken from the original model (Interview, 2). Another interesting aspect is the difference in the required woodworking skills, flatpack CLT companies rather hire furniture makers instead of conventional carpenters (Interview, 2). Since the attention to detail and the required working margins require higher-skilled woodworking (Interview 2).

The modular construction methods assemble the pre-cut CLT panels in a designated assembly factory. Such a factory is a semi-automated production line, the structure is assembled and entire modules are inserted along the production line. This way of construction does not require individual subcontractors but requires cooperation with other producers of modules, such as glazing, facades, kitchens, and bathrooms (Interview 4). Designing a standard building, constructed from pre-designed modular components, requires approximately one full working week of labour (Interview 4).

These production facilities require relatively low capital investments, in the order of a few million euros, and are rather portable (Interview 4). This opens up opportunities for temporary production facilities that can be altered to fulfil other functions afterwards. A single production facility can produce about 8 modules per day, which comes down to about 4 apartments of about 60-80m2 (Interview 4). This would mean that 2 of these facilities could produce the 20% CLT goal for PZH (2200 annual CLT houses). After production the modules have to be installed, about 10 of these modules can generally be installed per day. This comes down to about 5 apartments per day, depending on the size of the apartment.

5.2.3 Quantification of the housing demand

There is an acute need for 150.000 additional houses by 2030, of which the majority needs to be fulfilled in the coming 5 years (PZH, 2017). Until 2025 it is expected there will be the need for 85 thousand new houses. The total housing demand within the scenario timeframe, 2025 to 2035, is estimated to be 110 thousand. Of which the majority (60%) needs to be realised in the first half of the timeframe. This means 67.7 thousand between 2025 and 2030 (PZH, 2021 #3) and another 42.5 thousand from 2030 to 2035 (PZH, 2021 #2). For all further assessments, the average yearly housing demand during the scenario timeframe will be used. The figure below gives an overview of the increase in housing demand in PZH.

	Housing demand	Housing demand/year
2025-2030	67.780	13.556
2030-2035	42.500	8.500
Average over the entire time frame	**110.280**	**11.028**

Table 3: The housing demand and annual housing demand during the scenario timeframe.

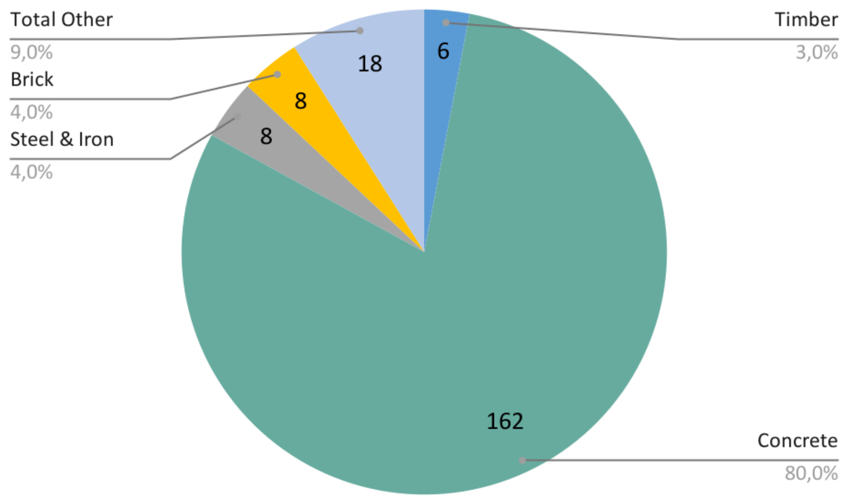
In 2019 the growth in the housing demand still surpassed the construction rate, at 18.300 versus 17.400 (PZH, 2021 #2). If the current housing shortage is adequately tackled in the coming years, the pressure on the construction sector will likely decrease since after 2030 the population will be growing at a slower pace. Therefore, the largest part of the current housing deficit has to be tackled in the coming 4 years (PZH, 2017). If in the coming years the envisioned reduction of the housing shortage is not achieved, the pressure on fast and affordable housing will further increase. Until 2025 there are sufficient planned projects, but these are not all legally founded, only 21% is approved by the municipal council. In the period from 2025 to 2030, there is still a need for additional planned projects, which highlights the opportunity for CLT projects in this timeframe (PZH, 2020).

5.2.4 Material demand baseline

5.2.4.1 Material demand conventional construction

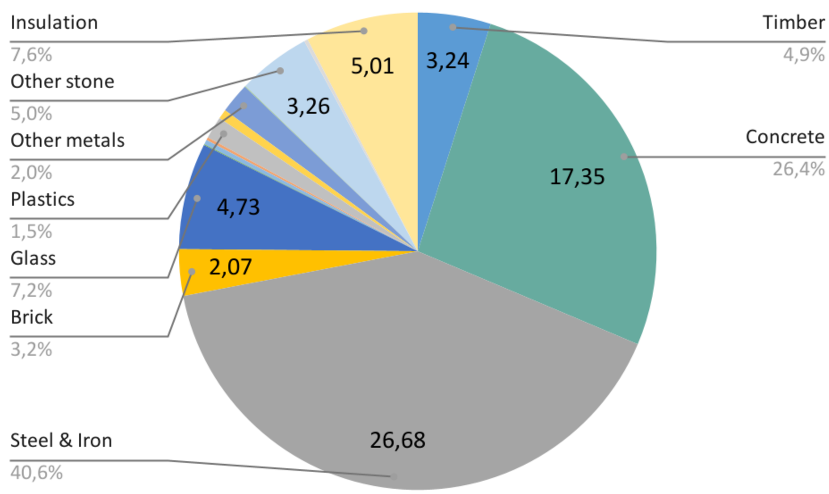
In 2014 about 80% of the mass flow of the conventional construction sector was concrete (75-85%), other major streams were brick (4%), timber (3%), and steel (4%) (EIB #1, 2020). Figure 8 gives an overview of the material demand for an average single house. Approximately 20% of buildings' embedded CO2 emissions are associated with material usage, the majority (80%) is associated with energy consumption in the usage phases (EIB #1, 2020).

Figure 8: Material demand of the average house constructed in 2014, in tons per house. Data acquired from (EIB #1, 2020).



The relative contribution of all materials to the carbon footprint of the average building constructed in 2014 is shown in figure 9. Although 80% of the material mass is concrete, the contribution to the carbon footprint is just 25%. While only 4% of the building's mass consists of steel and iron, these materials have a very high impact on the carbon footprint. Based on the data presented below, the average material-related carbon emissions of a conventionally constructed house in 2014 is approximately 66 tons CO2-eq. This number increases to 77 to 88 tons CO2-eq when assuming that construction accounts for 15-25% of the total embodied carbon emissions (Robertson et al., 2012).

Figure 9: Embedded CO2 in the materials, the extraction and the component production. Emissions are in tons CO2-eq/house and do not include transport and assembly emissions. Data acquired from EIB, 2020 #1



The negative environmental externalities (Milieu Prestatie Gebouwen, MPG) of the housing sector were on average 0,61€/m2/year in 2014 (EIB #1, 2020). In 2014 the financial impact of negative environmental externalities of the construction of new houses is estimated to be 214.5 million Euros (EIB #1, 2020). The majority of these impacts, 58%, are associated with the foundation and construction of the general structure, also 25% with finalization. In a BAU scenario, these externalities are estimated to grow by 37% (EIB #1, 2020). Under a BAU scenario, the material-related shadow costs (MKI) are expected to increase to 797 million euros in 2030, a 57% increase from 2014 (EIB #1, 2020).

5.2.4.2 Material demand CLT construction

The estimated material demand for a single 58m2 CLT apartment is shown in figure 10. The majority of the mass of the building is caused by concrete and crushed stone for the foundations. For smaller buildings with fewer stories, the share of these materials is likely lower.

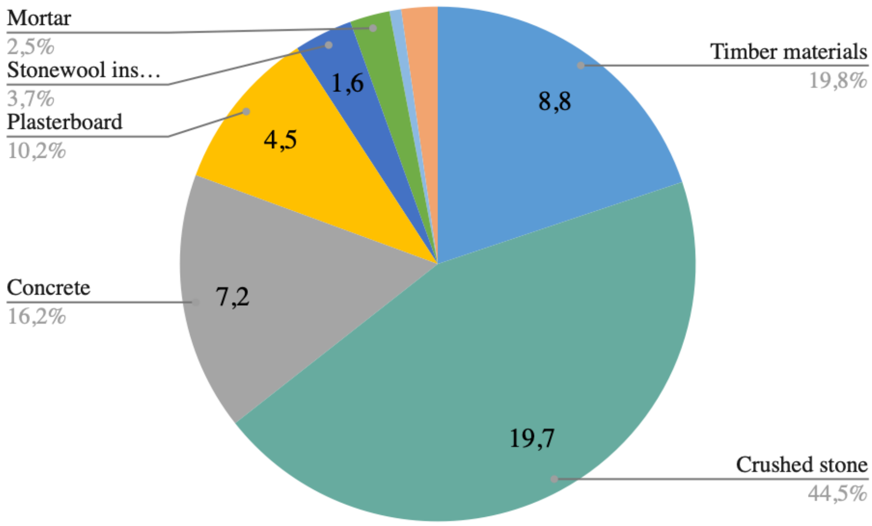


Figure 10: Material use in tons per CLT apartment (58m2). Other includes; PVC, Polyurethane, EPS, Aluminium, Zinc and copper, Glass, Paint, Putty and fillers; data from Dodoo et al 2014

Figure 11 shows the material production-related carbon emissions per m2 of living area. This shows once again that a mass-oriented approach to material demand can be rather deceiving since the majority of the carbon emissions is needed for other materials such as insulation and various non-structural components. The material related carbon emissions of a CLT building are around 114 to 127 kg CO2-eq per m2 of living area (Dodoo et al., 2014). Construction-related emissions add another 5%, increasing the impact to 120-133 kg CO2-eq per m2 of a living area (Dodoo et al., 2014).

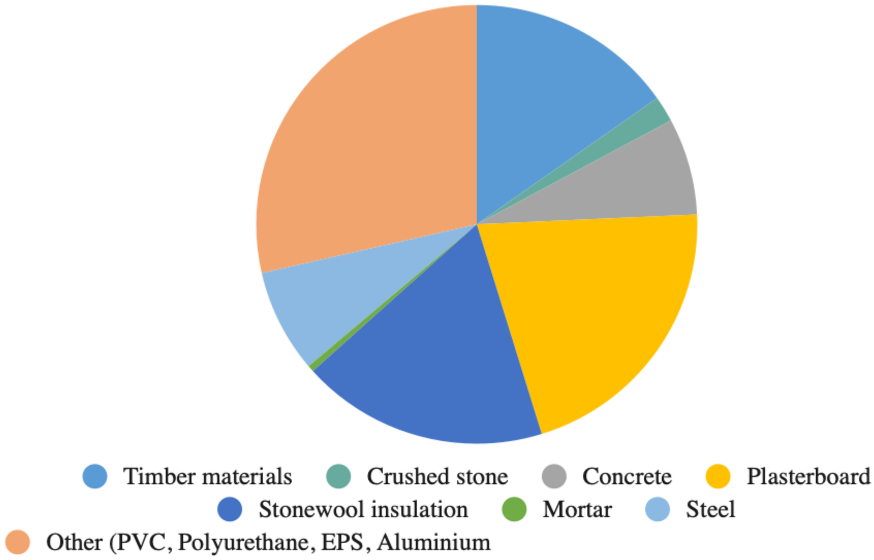


Figure 11: Approximation of the relative contribution of material production-related carbon emissions of a CLT building. These numbers do not include biogenic carbon storage. Data acquired from (Dodoo et al., 2014). Percentages are not shown since values are estimated from a figure.

If the CLT-building carbon emissions per m2 are extrapolated to the average floor area of the conventional construction analysis (146 m2), the embedded carbon emissions of such a CLT apartment is approximately 18 tons CO2-eq (16.6 to 18.5). These carbon emissions are about 63% lower than the embedded material emissions of the average (conventionally) constructed house (Note that these values are solely for comparison since the average area of apartment buildings in 2014 was only 86m2 (EIB #1, 2020)). The total emissions, including construction-related emissions, are 77% lower than conventional construction since CLT construction is less energy-intensive. These numbers are in line with other comparative LCA's on CLT construction versus cast-in-place concrete construction for multi-story buildings. These show CLT to have 60% to 70% lower production and material-related GHG emissions (Darby et al., 2013; Robertson et al. 2012).

In all cases, CLT has lower cradle-to-gate emissions than conventional alternatives. How much lower these emissions greatly depend on the way biogenic carbon is modelled and on the assumptions made for EoL. The carbon content stored in CLT is approximately twice as much as the amount of emissions needed for the production of the material (Nakano et al., 2020; Dodoo et al., 2014). LCA's on multi-story CLT buildings show that, if biogenic carbon flows are accounted for, the production-related carbon emissions can be -213 to -233 kg CO2-eq/m2 of living area (Dodoo et al., 2014). If energy contents of biomass waste streams are also accounted for this can increase to -510 kg CO2-eq/m2 of living area (Dodoo et al., 2014).

5.2.4.3 Emissions reductions resulting from 20% CLT implementation

Figure 12 shows the change in the annual material demand and the change in the material-related carbon emissions, as a result of the CLT implementation aim. The material demand and emission data described in the previous sections (5.2.4.1 and 5.2.4.2) are extrapolated to represent the average annual housing demand.

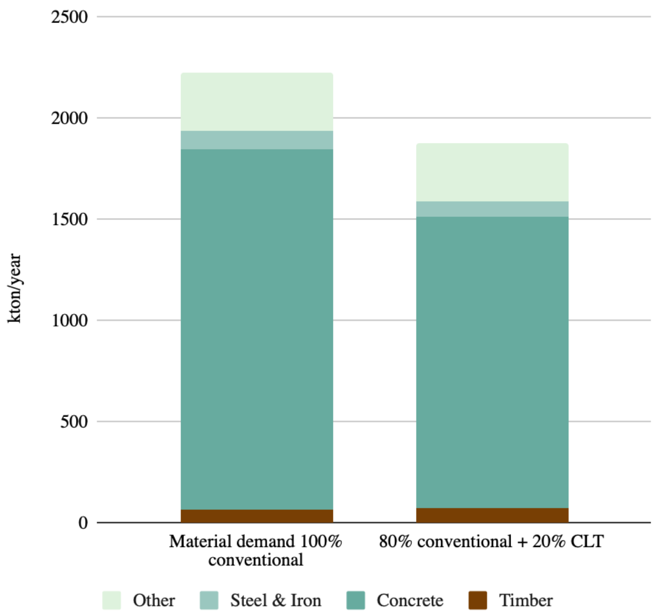


Figure 12a: Change in the PZH material demand, in ktons per year, as a result of 20% CLT implementation.

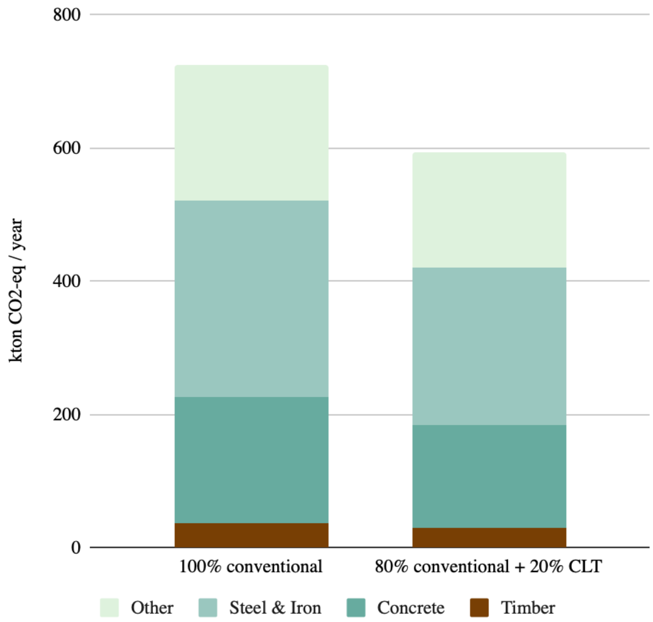


Figure 12b: The corresponding reduction in CO2 emissions embodied in the materials. Construction-related emissions and embedded carbon in the timber are not included.

Table 4 shows the actual reductions in carbon emissions for each half of the timeframe, including construction emissions and carbon sequestration. These estimates show that facilitating 20% of the housing demand with CLT can reduce the impact of the entire housing sector with 13% when not accounting for biogenic carbon storage and with 26% when biogenic carbon storage is accounted for. Thereafter, table 5 shows an estimation of the saved emissions and the estimated value thereof.

Timeframe	Housing demand	Housing demand/ year	Emissions 100 % conventional (tons CO2-eq / year) (1*)	80% conventional + 20% CLT (no biogenic carbon) (tons CO2-eq / year) *2	80% conventional + 20% CLT (with biogenic carbon storage) (tons CO2-eq / year)
2025-2030	67.000	13.400	1.1E6 (100%)	9.7E5 (87%)	8.2E5 (74%)
2030-2035	42.500	8.500	7.0E5 (100%)	6.1E5 (87%)	5.1E5 (74%)

Table 4: 1)For conventional houses 65,67 tons CO2-eq per house in materials (EIB #1, 2020), and assumed 20% of embodied emissions are construction emissions, and 80% are material related emissions (Robertson et al., 2012). Totals 82 tons CO2-eq per house*
2) Biogenic carbon stored is assumed to be 1,9 times the production emissions (1,8 to 2) (Dodoo et al.,2014; Nakano et al., 2020)*

Timeframe	Emissions saved (ton CO2-eq/ year)	€ of emissions saved / year
2025-2030	2.9E5	29 million
2030-2035	1.8E5	23 million

Table 5: emissions saved based on the estimated 26% reduction, price of CO2 based on expected Dutch emission prices. The average CO2 price in the period 2025-2030 is assumed to be 99 €/ton CO2 and 125 €/ton CO2 thereafter (NE, 2021).

5.2.4.4 Baseline CLT and timber demand

The amount of CLT required per house is very much dependent on the building type and design. However, it is assumed that on average a single CLT house requires approximately 50m3 of CLT panels (Commu et al., 2021). If 20% of the required houses were to be built with CLT about 135.000m3 of CLT would be needed per year between 2025 and 2030. In the years 2030 to 2035, this demand will decline to 85.000 m3 per year. This means that approximately 6% of the current total EU CLT production would be needed on average over the entire time frame. In 2025 the EU production is forecasted to reach 3 million, so this figure reduces to 4%. However, the majority of the housing demand is in the first half of the 10-year time frame. An overview of CLT demand and the corresponding timber demand is given in table 6.

Timeframe	Housing demand	Housing demand/year	20% CLT (m3 CLT / year)	Timber demand (m3/year)
2025-2030	67.780	13.556	1.4E5	4.2E5
2030-2035	42.500	8.500	8.5E4	2.6E5
Average over the entire time period	**110.280**	**11.028**	**1.1E5**	**3.4E5**

Table 6: Housing demand and corresponding estimated CLT demand. Approximately 3m3 of unsawn timber is needed for each m3 of CLT (Commu et al., 2021; Nakano et al., 2020).

On paper, there is enough harvest from Dutch forest to supply the 20% CLT goal entirely from Dutch timber. To produce enough CLT to supply 20% of the average annual PZH housing demand (2200 houses) with CLT, about 330.00m3 of timber is needed. This is about 27% of the annual timber harvested from Dutch forests or 15% of the total Dutch timber production (see figure 13). The timber harvest from forests accounts for 51% of the annual Dutch timber flows. About 34-46% of this share is exported to Belgium and Germany since there are no Dutch factories producing construction materials (Nabuurs et al., 2016).

The remaining 49% of the Dutch timber flows (33% from the built environment and 15% from rural areas) are used for low-grade applications such as; energy generation, composting and firewood (Nabuurs et al., 2016). Utilizing these streams for higher grade applications would allow for more timber availability for CLT production. So in theory there is enough quantity available, but whether it is feasible to implement it in CLT production is unsure.

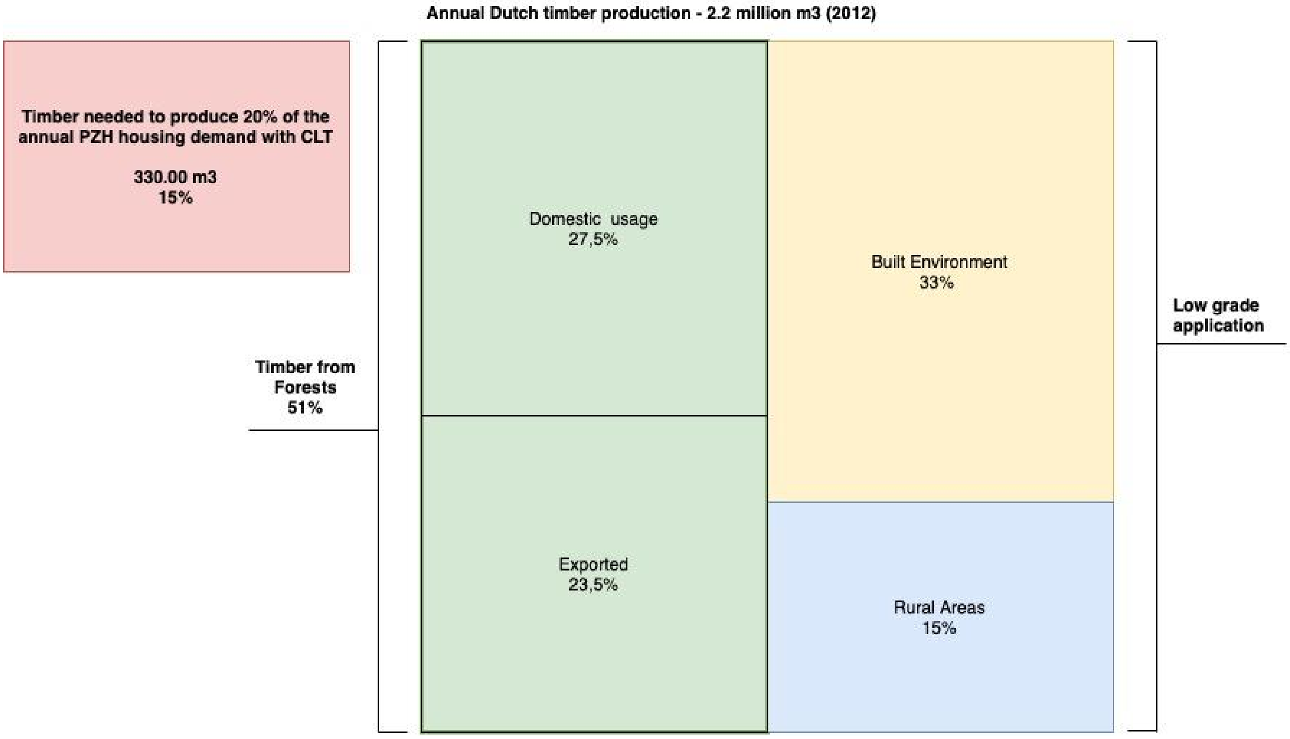


Figure 13: Overview of Dutch timber flows, the red square represents the timber demand needed to produce 20% of the average housing demand in CLT. Data taken from Nabuurs et al., 2016.

In the Dutch production forests, on average only 63% of the annual growth is harvested (Oldenburger et al., 2020). Theoretically, there is a surplus stock of 13.2 million m3 of timber available from Dutch forests (Commu et al., 2021). This would be sufficient for 3.7 million m3 of CLT or 74.000 houses (Commu et al., 2021). This shows that there are opportunities for a temporary increased timber harvest. It is unrealistic to assume that all these maximizations will be implemented. However, the CLT implementation goal seems achievable (15-22% of the maximum annual Dutch production); especially if reforestation projects are successfully implemented.

5.3 Scenario Modelling

In this chapter, the input variables are quantified and described. The scenario model contains four timber material inputs; EU CLT-panels, EU sawn-timber, EU unsawn-timber, and Dutch timber. For all the imported timber streams the transport emissions are quantified. These four inputs feed into various intermediate production steps, for which the socio-economic impacts are determined (jobs and revenue). The added revenue and labour resulting from the CLT-assembly step are assessed in the baseline quantification section since this step does not differ between scenarios.

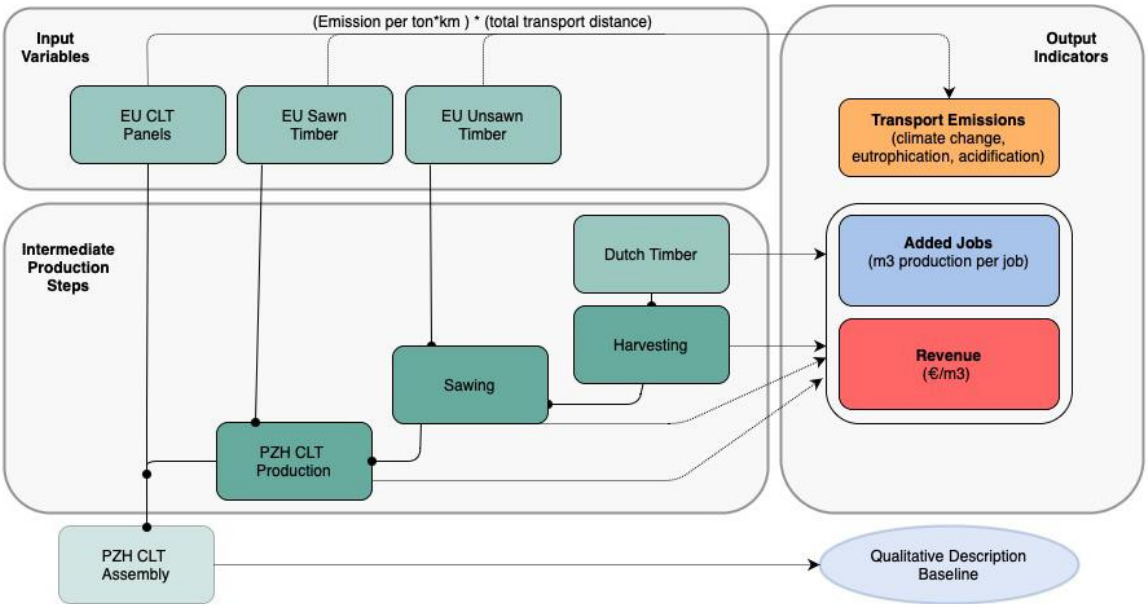


Figure 14: The overview of the Scenario-model, and how the input variables relate to the final scenario assessment indicators.

5.3.1 Transport Emissions

An overview of three transport methods and their impact on the acidification, eutrophication, and climate change impact categories is shown in figure 15. On a per ton*km basis there is a trade-off in impacts for each transport method. Barge transport and rail transport have a 45% to 53% lower impact on climate change but do have a substantially higher impact on both acidification and eutrophication. In the acidification impact category, train transport (electric) and lorry transport perform similarly, while barge transport has a 45% higher acidification impact. Lorry transport has the lowest eutrophication impact; compared to lorry transport the impact of barge transport is 78% higher and the impact of electric rail transport is 120% higher. The reason for this is unclear since no contribution analysis was performed (absolute values are shown in table 7).

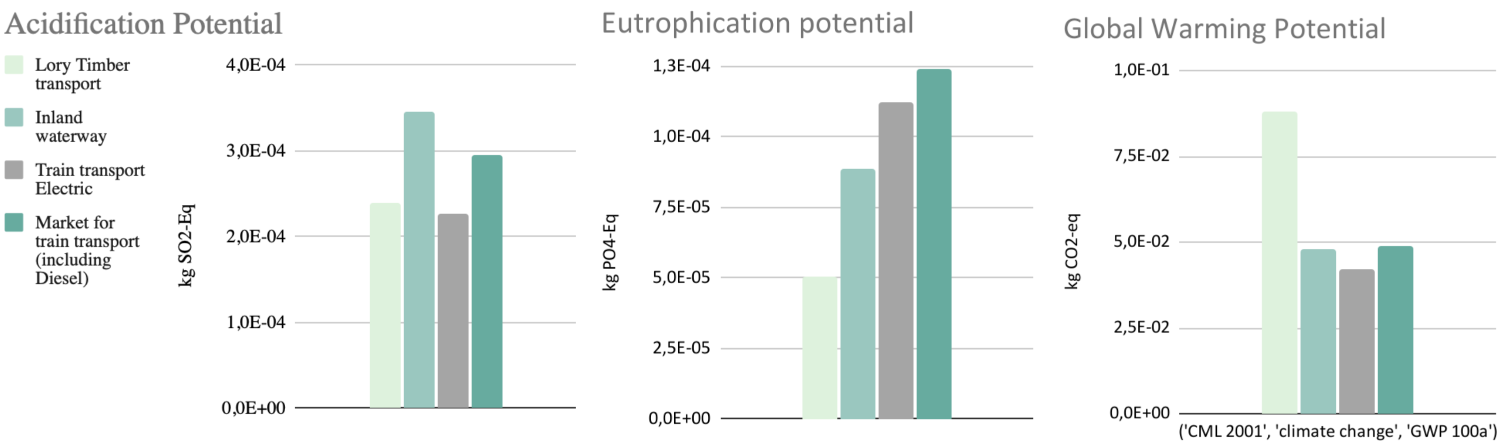


*Figure 15: Visual representation of the various impacts for 1 ton*km of transport per transport type. Source data from Ecoinvent 3.4 database.*

Impact Category	Lorry transport	Inland waterway	Train transport Electric	Train transport (including Diesel)	Unit
CML 2001, Acidification potential	2,4E-04	3,5E-04	2,3E-04	2,9E-04	kg SO2-Eq
CML 2001, Climate change	8,8E-02	4,8E-02	4,2E-02	4,9E-02	kg CO2-Eq
CML 2001, Eutrophication potential	5,0E-05	8,9E-05	1,1E-04	1,2E-04	kg PO4-Eq

Table 7: Characterization outputs from ecoinvent background processes, the functional unit is 1 ton-km.

In further analysis, only two types of transport are considered, road transport by lorry and inland waterway transport. Transporting CLT and timber by rail is not desirable, since additional packing is required due to iron deposition from braking, and rail transport requires additional loading and unloading that could damage the material (Interview 1). Rail transport could prove a viable option for unsawn timber transport since this material is not yet processed.

For the scenario analysis, the transport routes from Austria to Rotterdam are modelled, and this route is substantially longer by river than by road. This added distance reduces the advantage of barge transport in the climate change impact category from 45% to only 20%, while simultaneously increasing the eutrophication and acidification impacts (see figure 16). For this specific material origin, it seems that lorry transport is beneficial over transport via barge. For other material origins, this might be different, in these cases barge transport might reduce the carbon emissions at the cost of increased eutrophication and acidification impacts.

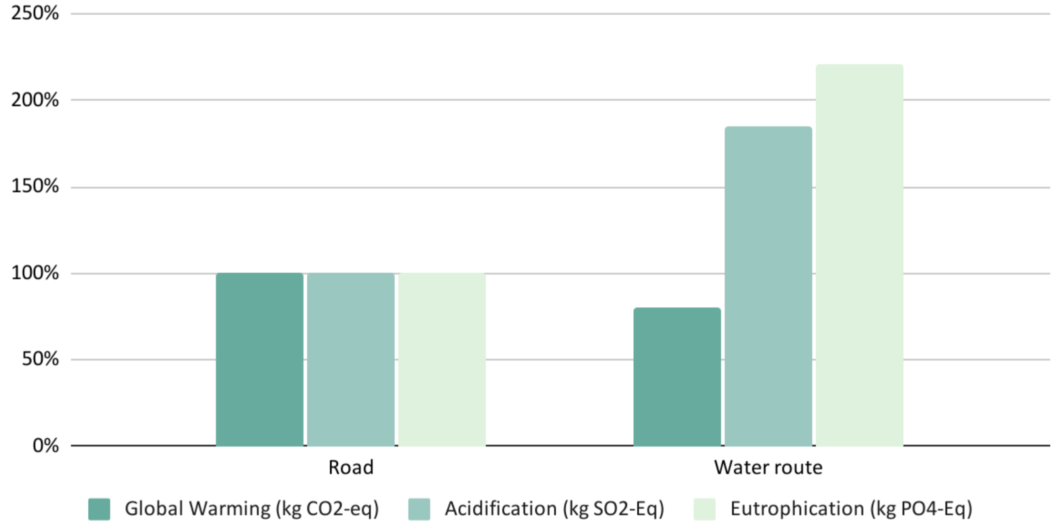


Figure 16: The scaled values for three impact categories of a transport route from Austria to Rotterdam. The route by water includes 190km lorry transport to the harbour and 1335km of barge transport. This route is scaled to the direct route by road, which is only 1150 km.

5.3.2 Jobs and Revenue

Based on surveys on employment in the CLT industry in Central Europe it is assumed that, on average, one employee is needed for each 1000m3 of CLT produced (Larasatie et al., 2020). This number is confirmed by information on employment in CLT production facilities in Austria (Pfeifer Group, 2021). The jobs types include production workers, engineers, designers but also sales and marketing (Larasatie et al., 2020). Since CLT production is such an automated process the required job skills revolve around machine maintenance, IT skills such as 3D rendering and, the feeding and loading of materials (Interview 1).

These labour estimations may vary widely and are greatly dependent on the production capacity, co-production, and whether the plants are running at full capacity (3 shifts per day). The particular CLT factory used for this assessment only produces CLT and has sawn timber as a feedstock. However, many CLT producers co-produce other timber products, either because CLT production was added to an existing plant, or to utilize waste streams (Larasatie et al., 2020). For these facilities, it is rather convoluted to estimate the labour needed solely for CLT production (Larasatie et al., 2020).

The number of jobs required in timber processing is approximately 1 to 0.4 times the number of jobs required for CLT production, depending on the scale of operation. Labour in the sawing stage is mainly dependent on the size of the production facility. Ranging from 1 job per 1000m3 for a facility with a 50.000m3 annual production capacity, to 1 job per 2600m3 for a facility with a 310.000 to 500.000m3 annual production capacity (Pfeifer Group, 2021). These large facilities generally also co-produce other byproducts from waste streams, such as pellets and electricity. For further assessment, an average value of 1 job per 1900m3 of sawn timber is used.

The number of jobs related to the forestry practices is estimated based on forecasted harvest and the forecasted labour during the timeframe (Nabuurs, et al., 2016). It is estimated that on average one full-time job is needed to harvest 9000 to 9200 m3 of timber annually.

Table 8 shows the estimated number of full-time jobs per 1000m3 of production for each of the three intermediate production steps.

	Timber harvest	Sawing of timber	CLT production
FT Jobs / 1000 m3 produced	0.1	0.5	1.0

Table 8: Estimated jobs for intermediate production steps.

To estimate the added revenue for each stage, the scenario quantities are multiplied by the current market value of the various materials. The value of timber, sawn timber, and CLT are shown in table 9.

	Unit	**Logs**	**Sawn Timber**	**CLT panel**	**CLT-pre cut**
Average value	€/m3	75	178	600	1000

Table 9: the value of various timber streams in €/m3. Data sources; sawn timber (Timber-Online, 2021), CLT-panel prices Brandt et al., 2019, log prices Nabuurs, 2016, and the value of pre-cut CLT is based on an interview with a Dutch CLT assembly company.

5.3.4 Scenario Description

The scenarios are chosen to reflect a wide range within the realm that is assumed to be both realistic and desirable. A complete self-sufficient scenario is desirable but most likely not feasible and an entirely import-dependent scenario the opposite. A visual representation is shown in figure 17, where the x-axis represents timber origin and the y-axis the CLT-panel origin.

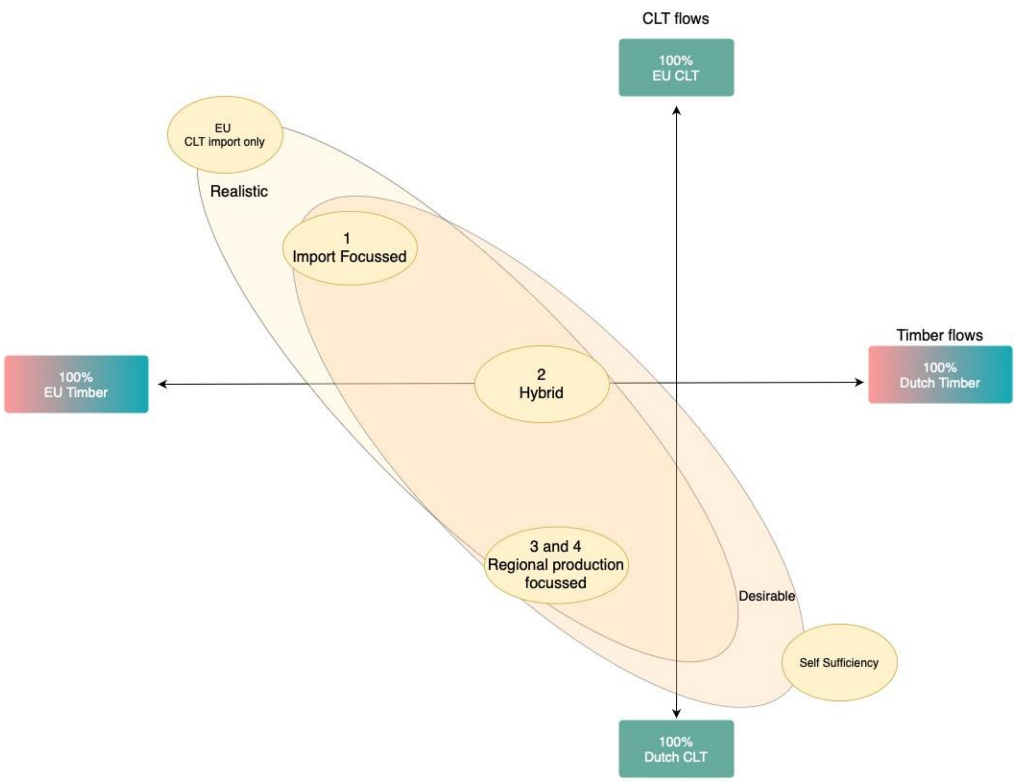


Figure 17: Figure showing the various scenarios, the x-axis represents the timber origin and the y-axis the CLT origin. The top left represents 100% import of EU-CLT and no use of Dutch timber. The bottom right corner represents a scenario that is completely self-sufficient. The three chosen scenarios are in the area that is considered to be both realistic and desirable.

Scenario 1: Import Focussed
Mainly based on the import of CLT panels from the EU, 95% of the described CLT demand. The remaining 5% of CLT is regionally produced from Dutch timber flows.

Scenario 2: Hybrid
A hybrid scenario where 50% of the CLT is imported and 50% is produced in PZH. Half of the Dutch CLT is produced from Dutch timber and the other half from imported sawn timber. So 25% of the CLT supply for this scenario is entirely produced from regional timber flows, 25% is regionally produced from imported sawn timber and 50% is imported as CLT panels.

Scenario 3: Regional Production Focussed (sawn timber import)
The regional industry is the main CLT source (80%) and 20% of the CLT is imported. Dutch timber flows have increased, but still only supply 50% of the timber needed for the regional CLT production, the other 50% is imported as sawn timber. This means that 40% of the CLT demand is entirely from regional timber flows, 40% is locally produced from imported sawn timber and 20% is directly imported as CLT panels.

Scenario 4: Regional Production Focussed (unsawn timber imports)
Identical to scenario 3 but with the import of unsawn logs instead of sawn timber. Therefore, there is an almost 3 fold increase in timber imports. This scenario is added to assess how the added socio-economic benefits from increased regional production relate to the increase in transport emissions.

	EU CLT (m3)	**Dutch CLT (m3)**	Dutch Unsawn Timber (m3)	Imported EU Sawn Timber (m3)	Imported EU Wet Timber (m3)
Scenario 1	104.025 (95%)	5475 (5%)	16.425	0	0
Scenario 2	54.750 (50%)	54.750 (50%)	82.125	27.375	0
Scenario 3	21.900 (20%)	87.600 (80%)	131.400	43.800	0
Scenario 4	21.900 (20%)	87.600 (80%)	131.400	0	131.400

Table 10: Quantitative overview of material streams for each scenario. Note that the Dutch timber flows are represented as +/- 3 times larger than the European flows since it concerns unsawn wet timber)

Figure 18 is a visual representation of table 10. The red bars show the imported timber flows; these are used to assess the difference in transport emissions for each scenario. The green bars show the domestic timber streams and the grey bars show the upstream sawn timber and unsawn timber flows in the country of origin. The transport impacts of the latter two flows are not modelled since these are included in the CLT-production emissions and do not differ for regionally produced or imported CLT.

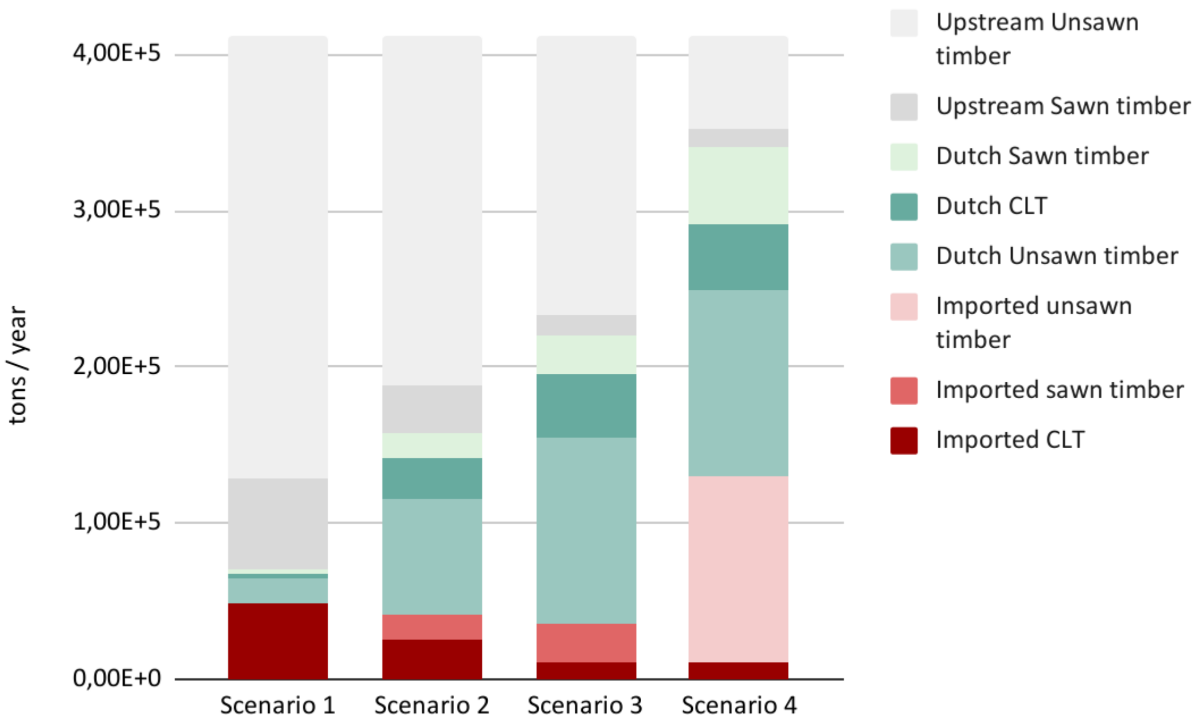


Figure 18: Visual representation of all timber mass flows for each scenario. These include the composition of the domestic timber flows, the imported timber materials, and the associated upstream timber flows in the country of origin.

5.4 Scenario Comparison

The various scenarios will be compared based on the quantification of the output variables. The corresponding research questions are: *"What are the environmental and socio-economic trade-offs between regionally produced and imported timber construction materials?" and "What scenarios for fulfilling the future housing demand with CLT are most resilient and adaptive?"*

5.4.1 Transport Emissions

The mass flows of each type of imported timber material per scenario are shown in figure 19. Scenario 1 represents a scenario where there is almost no domestic CLT production. Scenarios 2 and 3 show a reduction in imported timber, due to an increase in national CLT production. Scenario 3 requires the least timber mass to be imported since this scenario mainly depends on domestic timber flows. The fourth scenario is the least favourable from an environmental perspective since it mostly depends on the import of unsawn timber, which is still wet and unprocessed.

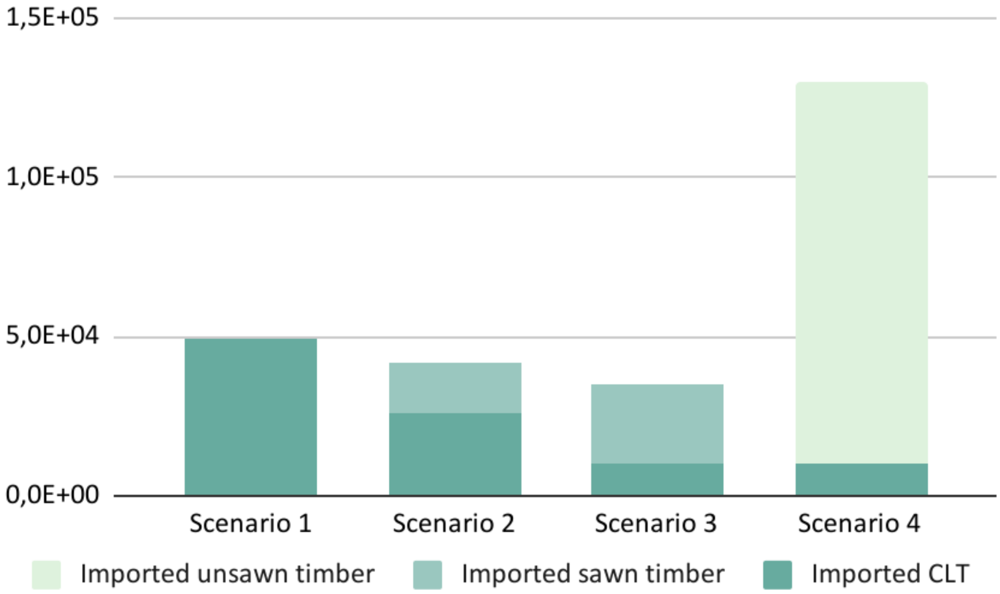
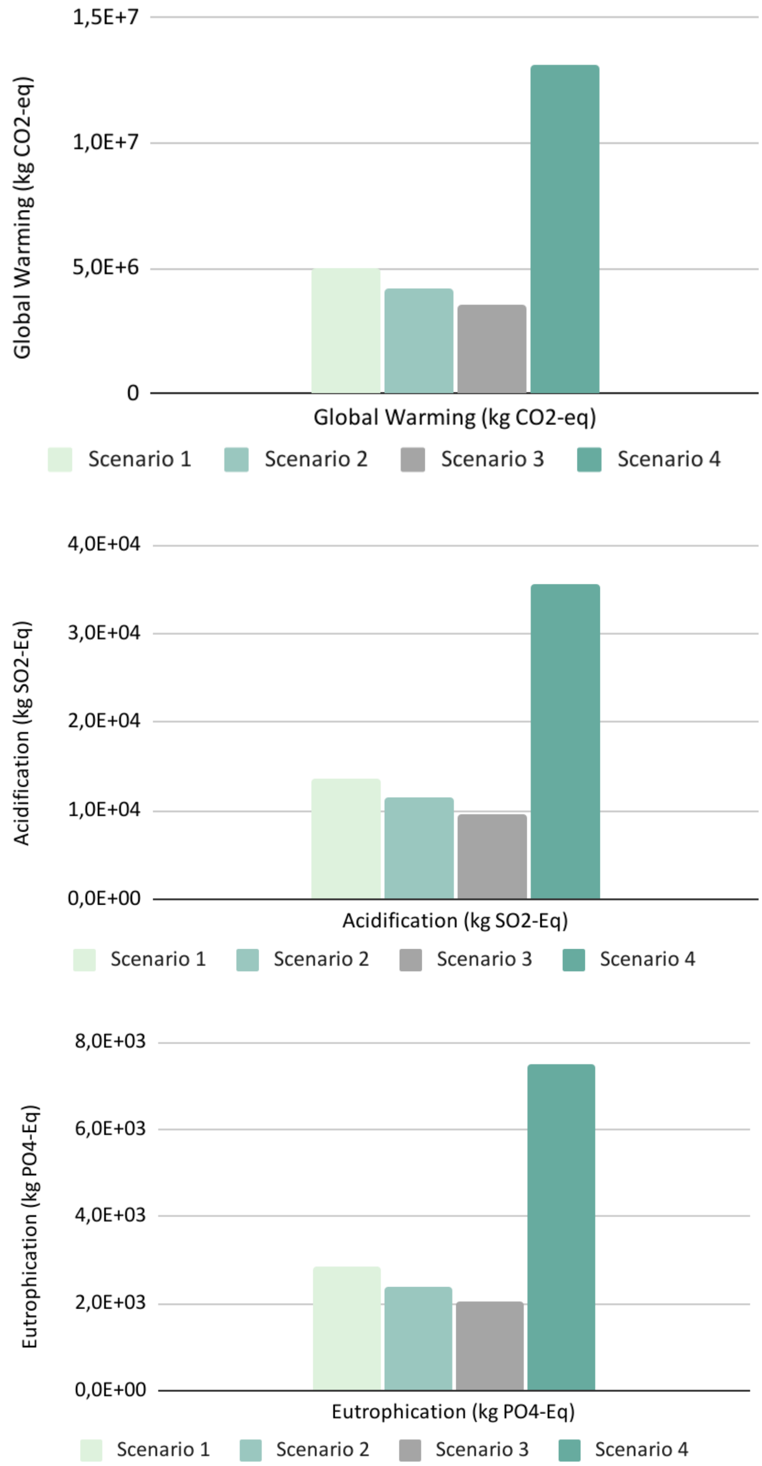


Figure 19: Mass flows in tons per year for all imported timber materials for each scenario. Transport distances are not included in this graph.

The relative impacts in the three impact categories for each scenario are shown in figure 20. The impacts follow the same pattern as the distribution of mass of imported goods since the same transport methods and routes are modelled for all material streams. This highlights that it is essential to maximise local material streams and minimise imported goods.



Figures 20 a,b, and c: Transport-related impact on the impact categories of global warming, acidification, and eutrophication. Assuming lorry transport for all imported material flows.

The impact of the additional transport on the climate change impact category, in comparison with the CLT-production-related emissions, is shown in figure 21. The CLT-production emissions do include transport from the forest to the sawmill and the CLT factory. About 14% of the entire CLT-production climate change impact and 51% of the acidification impact are related to the transport of timber (Nakano et al., 2020). The transport emissions of the fourth scenario contribute an additional 68% of the entire CLT-production emissions. For scenarios 1, 2 and 3 the share of added emissions was 26%, 22%, and 18% respectively. This means that transport emissions due to material imports increase by 50% to 100%. The green bar on the right shows the CLT production emissions when embedded carbon is accounted for. This puts these added emissions into perspective and shows that the carbon footprint of CLT still remains substantially negative.

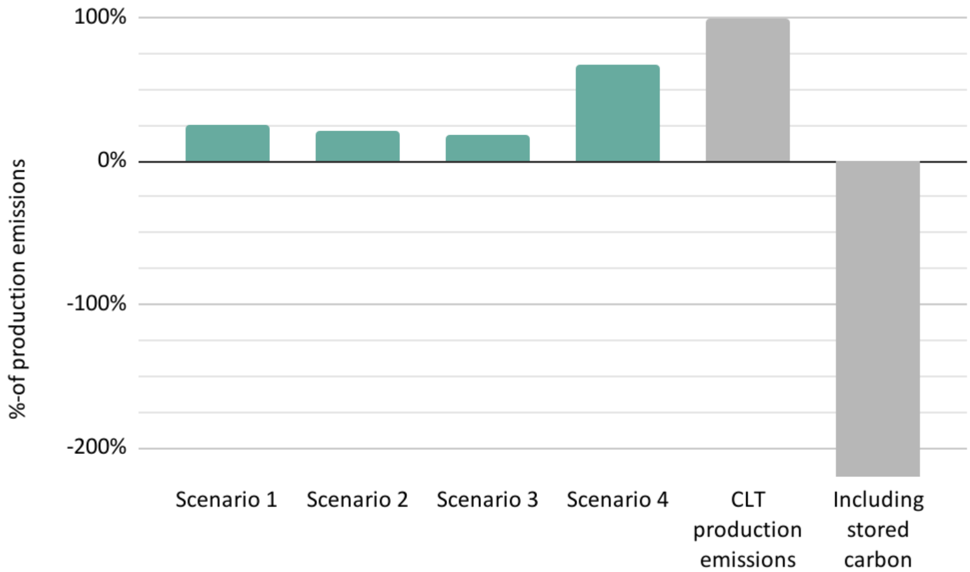


Figure 21: Comparison of modelled transport emissions compared to literature data on CLT production emissions. Note that the CLT production emissions do include transport of resources to the sawmill and the CLT factory. These generally account for 14% of the total CLT production emissions (Nakano et al., 2020).

The comparison made for the scenarios is greatly dependent on assumptions made for the transport method and the fuel source. For example, changing the fuel type to biofuel can greatly reduce the global warming impact of lorry transport (figure 22). This highlights that the added impact of material imports will reduce in the future due to technological advances.

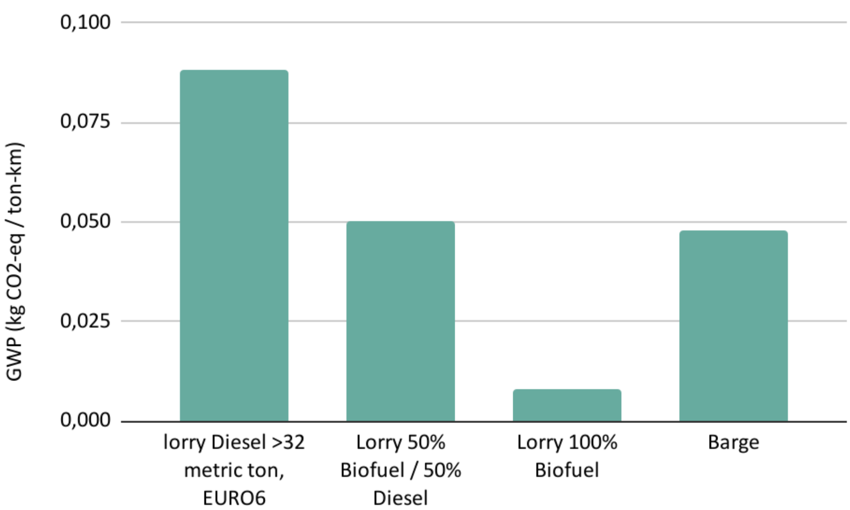


Figure 22: The impact on climate change for various fuel sources for lorry transport in relation to barge transport.

5.4.2 Jobs and Revenue

The amount of created jobs follows the increase of domestic production; more production activity reflects more jobs created. Overall, the number of jobs added is rather limited due to the low amount of labour required in the CLT production chain. For scenario 4, the highest production scenario, just over 150 full-time jobs are added. Most interestingly the third scenario, which is the least dependent on timber imports, scores rather high on the added jobs. This is because the largest share of added labour comes from the CLT production stage (46% to 63%). This highlights the opportunities for a regional CLT industry that depends on sawn timber imports.

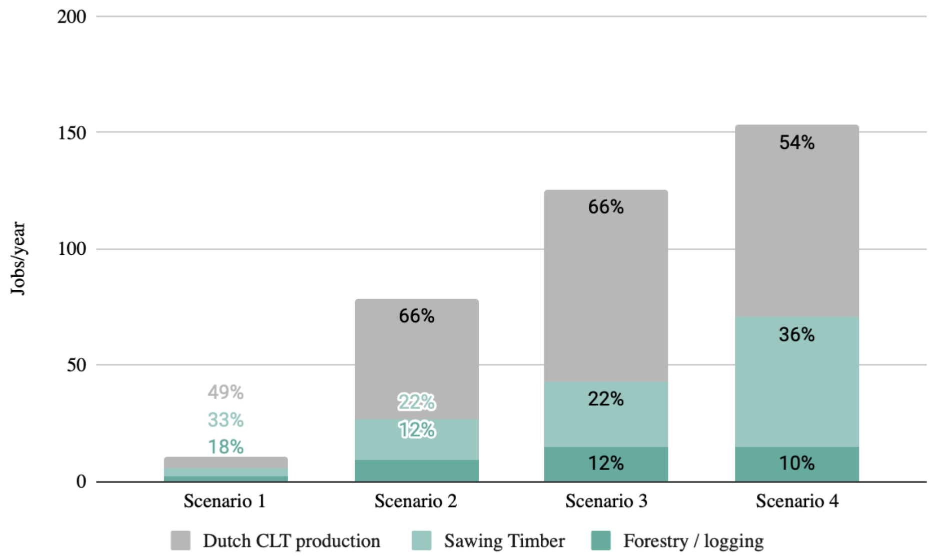


Figure 23: Jobs associated with the intermediate CLT production steps.

For all scenarios, the majority of the added value comes from the CLT production stage. Scenario 1 is largely based on the import of CLT, therefore the added revenue is the smallest. In this scenario, 5% of the CLT demand is regionally produced and only utilizes Dutch timber. This increases the relative share of added value from the forestry stage. If more sawn timber is imported the relative share of the wood production stages declines and the relative added value of CLT production increases. For scenario 4 the import of unsawn timber increases the added revenue from the sawing of timber. This increases the total revenue for this scenario by 10%, compared to scenario 3.

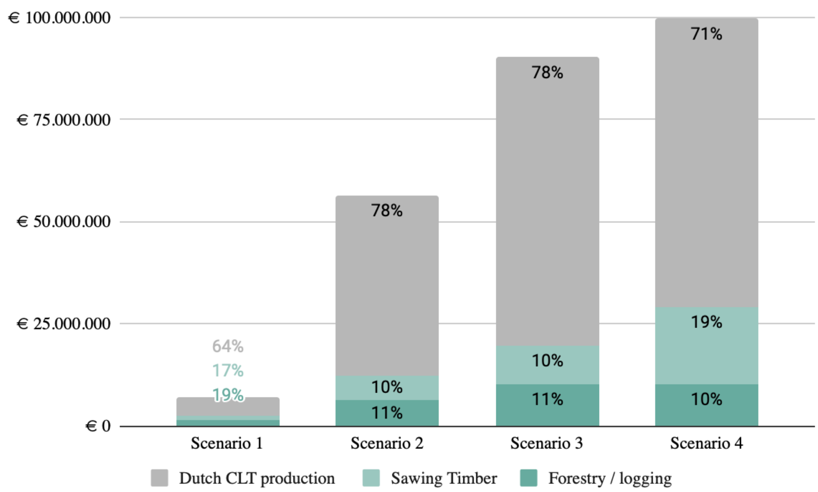


Figure 24: Revenue per scenario in millions of euros.

To put these numbers in relation to the revenue from the entire construction sector of PZH. As of 2017, the revenue from the entire PZH construction sector was about 23 billion euros annually (CBS, 2021). From this 23 Billion 40% can be attributed to the general-construction sub-sector, and another 40% to the specialized-construction sub-sector. The 100 million euros revenue from the various stages of CLT-production in scenario 4 would represent about 0.4% of the entire 2017 PZH construction sector revenue. However, this figure does not include the added value from the assembly and finishing stages.

6. Conclusion and Discussion

The research aim was to quantify the impacts of fulfilling 20% of the 2025 to 2035 PZH housing demand with CLT houses and to quantify how these impacts are affected by alternative methods of CLT and timber supply. A scenario-planning framework was used to create 4 scenarios, ranging from import focussed to largely focused on regional CLT production. Information on the various stages was acquired through extensive literature research, expert interviews, quantitative assessment, and open access governmental reports.

In the results sections, the scope was funnelled from the general context to the specific scenario analysis. In this concluding chapter, this order is reversed. First, the scenario comparison results are discussed, then the CLT-implementation baseline, and lastly the bio-based transition context is discussed. The latter will include policy recommendations and transition action points.

6.1 Scenario comparison

The main finding is that regional CLT production, even from imported sawn timber, is most beneficial, both from a socio-economic and environmental perspective. Therefore, it is recommended to instigate a regional CLT industry. Sustainable national timber production needs to be maximized and any remaining demand should be imported as sawn timber. Only dried and sawn timber materials should be imported since the added mass of unsawn timber greatly increases transport emissions. Transport methods need to be optimized based on location and the material type. Also, preferably sawn timber sources in nearby countries should be utilized and no timber should be imported from outside the EU.

CLT implementation has a positive effect on the environmental impact of the sector; fulfilling 20% of the housing demand with CLT can reduce the carbon footprint of the conventional housing sector by 26%. When scaled to the 20% CLT implementation goal, regional CLT production could create an additional 40 to 70 million euros of revenue and create an additional 80-150 full-time jobs annually. These numbers exclude the value creation and added job availability from the assembly and finishing stages.

The scenario-comparison section aimed to answer the following question: "*What scenario for a regional CLT industry can facilitate the material needs for the housing sector in the province of Zuid-Holland, in an integrated sustainable way?*"

- Scenario 1 is least desirable from a socio-economic perspective and scenario 4 is most desirable from a socio-economic perspective.
- Scenario 3 is most desirable from an environmental perspective since it requires the least amount of material imports.
- In practice, both the transport of sawn timber and of CLT can be optimized to an equal amount; since the densities of the materials are nearly identical. However, sawn timber imports will allow for more logistical freedom, due to more flexibility in the desired quantities, packaging, component size, and transport means. How these aspects specifically relate to transport optimization was not included in this research.
- Overall scenario 3 is most desirable. This scenario is focused the most on regional timber flows and regional production. It strikes a balance between low transport emissions from timber imports and relatively high added economic activity. Having the CLT production stage also increases opportunities for co-production and industrial symbiosis.

6.1.1 Transport emissions

Transport emissions from sawn timber and CLT imports from Austria are considerable compared to the CLT production emissions, but by far not high enough to negate the carbon stored in the timber. For scenario 2 the transport emissions from imported sawn timber equate to 22% impact of the total CLT-production emissions and for scenario 3 this is 18%. The transport emissions from the import of wet timber in scenario 4 added about 68% of the CLT-production emissions. If embedded biogenic carbon in the CLT is accounted for the carbon footprint of all scenarios is negative. For the 4th scenario, about 29% of the carbon embedded in the CLT is offset by the added transport emissions, for all other scenarios, this is around 10%.

Transport by barge reduces carbon emissions for each ton-kilometre, but it increases acidification and eutrophication impacts. However, in the modelled route the transport distance via river is substantially longer than by road. Therefore, barge transport from Austria does not seem beneficial, since carbon emissions are only marginally reduced (-20%) while acidification impacts and eutrophication impacts greatly increase (+85% and +121% respectively).

These transport-distance variables are strongly case-dependent and might differ for other production-facility locations. In practice, any of the material streams could be imported from a variety of places and actual emissions greatly depend on both the energy and fuel sources (Lindholm et al., 2005). For a different location, such as central Germany, the added distance resulting from transport via inland waterways can be more optimal. Assessing these variations is beyond the scope of this research.

6.1.2 Jobs and Revenue

The added jobs from regional CLT production and the sawing of timber are rather limited. In the scenario with the most domestic production (scenario 4), about 150 additional full-time jobs are estimated. For reference, this is about 15% of the jobs in the entire concrete production industry in Zuid-Holland (Kort, 2017). Note that this number of added jobs applies to the 20% CLT implementation aim. In scenario 4 the import of wet timber increased the jobs in the sawing stage. From scenario 3 to scenario 4 the extra jobs in the sawing stage resulted in an 18% increase in the total job availability. However, the majority of added labour comes from CLT production; 50% to 66%.

This same story is reflected in the added revenue from each production stage. From a financial perspective, the scenario with the most regional production is most desirable (scenario 4). The annual revenue for this scenario is estimated to be 99 million euros. The added revenue from the additional sawing step in scenario 4, opposed to the import of sawn timber in scenario 3 is 10%. However, the most added value is from the CLT production stage, 71% to 78%. This showcases that socio-economically it is most beneficial to have this stage of the production chain within the Netherlands.

6.1.3 Scenario-Comparison Limitations

The spatial distribution of the impact assessment differs for each indicator. The environmental impacts related to transport are addressed on a European level, while the socio-economic impacts are quantified on a regional level. Ultimately the added labour and revenue from moving production to the region will be at the expense of financial activity in another EU country. Environmental impacts are quantified but the spatial distribution and origin of these emissions are not addressed. Added environmental emissions are for the majority deposited in the country of origin.

Material origin is fixed in the scenarios, but in reality transport distances for each material may differ based on business relations and market dynamics. The different options for transport optimization for the various material types are also not sufficiently addressed. Therefore, the absolute value of the transport impact categories might not be representative of a real-world case or might change substantially over time. Innovations, such as changes in fuel type, could reduce the CO2 impacts of the various transport methods. For example, substituting 50% of the lorry fuel with biofuel could almost half the lorry transport emissions. Future decisions on transport methods should consider such innovations as fuel type.

The net addition of jobs and revenue caused by the forestry stage depends on the domestic timber market dynamics. The added value of the forestry stage reflects the value creation along the CLT supply chain but in practice, the forestry stage might not increase the regional economy. The added socio-economic benefits of the forestry stage depend on the increase in overall timber production as a result of increased demand. If existing timber flows are repurposed for CTL production there will not be an increase in forestry activities.

At the time of writing the sawn timber prices in the U.S. were almost 4 times higher than the average over the past decade (Timber Online, 2021). Although this inflation was caused by U.S. internal market dynamics it also affects European market dynamics. The increase in price affects the availability and price of sawn timber for CLT production and other timber products. However, in this analysis, the inflated prices for timber were not incorporated since at the time of writing prices were fluctuating heavily. Therefore, the timber prices were based on the average prices over the past decade.

6.2 Baseline

6.2.1 Socio-Economic Baseline

A key finding of this section is that fewer jobs and different types of jobs are required in CLT production and CLT assembly, thereby putting existing jobs at risk. However, at the start of the time frame, there is an estimated shortage of available labour in the Dutch construction sector. CLT construction could help alleviate some of the impacts caused by this labour shortage.

Economic cycles impact the demand for construction and thereby the demand for labour. It is estimated that at the start of the scenario timeframe there is increased demand for construction and labour, which will increase the shortage of employees and thereby the likelihood of delays. Therefore, the reduction in labour required for CLT construction and the improvement of working conditions are beneficial for the functioning of the construction sector as a whole. Since this will reduce the outflow of workers from the sector and reduce delays caused by employee shortages. During the scenario timeframe, the number of students in construction-related education is expected to increase as a response to this shortage. This new workforce should be trained with the skills relevant for a more industrialized construction sector, to prevent a future mismatch between required and available labour skills. In general, this means more complex skills are required.

There are two main varieties of CLT construction, flat-pack and modular, flat-pack construction allows more labour for subcontractors. For modular CLT construction, all miscellaneous jobs are also factory jobs, and there is likely a very limited need for sub-contractors. For flat-pack CLT construction, there is some overlap in the required labour skills in conventional and CLT construction, mainly specialized construction jobs such as electricians, plumbers, glazing, and finishing. Most of these traditional construction workers are not adapted to working with 3D renders, which hampers cooperation between CLT construction companies and sub-contractors. However, this research could not accurately quantify the estimated job loss jobs and the estimated gained jobs resulting from CLT assembly. This quantification is extremely case-dependent and will require additional market research.

6.2.2 Material Demand Baseline

The aim of 20% of the housing demand in CLT means an average of 2200 CLT houses need to be built annually, which will require an average of 110.000m3 CLT per year. This could reduce the total housing sector material demand by 16% and the carbon footprint by 26%, compared to a BAU case. If biogenic carbon sequestration is not accounted for the carbon footprint reduction is about 17%. The majority of the carbon footprint of a CLT building is caused by plasterboard, insulation materials, and other miscellaneous materials (such as plastics and metals). Solutions are needed for these other high-impact materials; bio-based alternatives for these materials are needed to further reduce the carbon footprint of CLT housing.

Switching from high-rise concrete buildings to CLT will greatly reduce material demand and production-related CO_2 emissions. This is in line with research performed by Lucassen, 2020 who described this to have the biggest impact on material reduction in the housing sector. Additionally, apartment size greatly affects the carbon footprint of a house. Since the growth in housing demand is mainly driven by individualisation and ageing, smaller average apartment sizes should be considered. This is confirmed by Lucassen, 2020 who states that increased implementation of smaller apartments could reduce virgin material usage by 27%. Apartment building design should also consider solutions to counteract loneliness and facilitate more shared facilities such as common gardens, sports, and living areas.

Another key finding is that domestic timber flows could suffice to sustainably produce enough CLT to enable a 20% implementation of CLT. Optimization of national timber flows could suffice to produce 130.000-200.000m3 CLT annually. On paper, there is enough previously unharvested surplus timber stock for about 3.6 to 5.5 million m3 of CLT. If utilization of these stocks is realistic and feasible is unclear and would require additional detailed research.

The scenario demand of 120.000m3 of CLT per year is sufficient to produce in a single large factory (or by 2 medium-sized ones). A regional industry of at least 50.000m3 annually seems realistic, on this scale, the production can be financially competitive with large-scale EU producers (Brandt et al.,2019). The import of sawn timber can function as a buffer to counteract any fluctuations in the availability of domestic timber. If Dutch timber flows appear to be sufficiently available and of sufficient quality for CLT production the production could be increased past the 50.000m3 mark.

In this study, the housing demand was scaled to PZH, if the national demand is assumed about 796 thousand houses are needed in the period between 2020-2030, of which 326 thousand are already planned (Groenemeijer et al., 2020). On a national level, the 20% CLT aim would result in 9400 CLT houses per year, which would require 470.000m3 of CLT. This shows there is sufficient potential for growing the CLT industry, even when foreign markets are not included.

6.3 Transition context and recommendations

This section proposes policy recommendations in relation to the general transition context, the baseline and the scenario comparison sections. The recommendations are presented in 3 sections; increasing timber availability, bundling demand, and shaping of markets. This section answers the following sub-question: *What policy actions need to be implemented to facilitate the transition towards this most desirable future scenario?*

6.3.1 Increasing timber availability

There are two essential aspects regarding the availability of national timber for CLT production; growing the standing timber stock and redistribution of the existing timber flows. A substantial share of the current annual timber flows (23,5%) is exported; while 15% would already suffice to produce enough CLT to reach the aim. Therefore, finding a national application for this share is desirable. Half of the annual timber flows come from rural and urban areas, these flows are mainly used for low-grade applications, such as firewood and biomass. Policies should target these timber streams and ensure they are used for high-grade applications, such as construction. Examples could be to prohibit solid timber to be sold as firewood and to regulate the shredding of timber wastes for energy generation and composting.

To ensure growth in the standing stock reforestation projects need to be increased and additional areas need to be converted to forest. Reforestation projects must be realized well in advance before harvesting pressures on existing forests are increased. Especially since the Netherlands currently is the least forested country in Europe. If reforestation projects are not executed in advance the added pressures for resource extraction will result in a further decrease in the forest area. The years leading up to the 2025 timeframe need to be used for this. Otherwise, the transition to bio-based housing will result in a temporal decrease in the total forest area.

To prevent burden-shifting there need to be regulations that prohibit unsustainably harvested timber and that enforce the use of sustainably harvested domestic timber or sustainably harvested timber from within the EU. Increasing regional timber production is preferable over import since this will increase resilience and reduce market uncertainties. Dependency on EU timber markets introduces a risk especially since price dynamics are influenced by international production dynamics and international politics. For example, currently, timber prices are inflated due to extremely high demand from the US and China. Therefore, it is important that policy is created, on a European level, that ensures that timber construction materials are sufficiently available and affordable. These policies need to prevent international trade dynamics from affecting the financial feasibility of bio-based housing.

Governmental agencies should consider embedding rules and regulations associated with wealth distribution from natural resource extraction. Instigation of a regional CLT industry will allow for the government to set the rules of the game, manage the value distribution from natural resources, and assure value reflow into society. These monetary flows could be used to counteract the socio-economic impacts resulting from automation. For example, automated production processes lead to lower labour demand and more wealth accumulation by a few large companies. Practical examples of such value distribution are the Alaska Permanent Fund and the Government Pension Fund of Norway.

Although not a specific requirement for a CLT-based construction sector; in the long term it is necessary to rethink labour as a financial basis of society. Automation is imminent in many sectors, such as automotive and logistics, therefore it is inevitable that also the construction sector becomes more automated. This automation is also referred to as the fourth industrial revolution. Artificial intelligence and robotics are changing the labour market, more general jobs are likely lost and especially more complex and high skilled jobs will be created (Bonekamp et al., 2015; Oschinski et al., 2018). Concepts such as a universal basic income could also play a role in this and should be up for discussion. This might ensure a steady financial baseline to dampen the impacts of job loss.

6.3.2 Sharing of knowledge and bundling demand

Steady and reliable demand for CLT housing is needed to kick start the transition. This will allow for larger investments from CLT producers and allow for a price reduction (economy of scale). The increased turnover rate also allows for a reduction of margins and increases the overall affordability of housing.

In practice, guaranteeing large-scale and long-term demand via more substantial municipal or provincial tenders is more nuanced than it seems at first glance. Long-term agreements for large amounts of buildings could bypass democratic processes, such as open tenders and development plans. Long-term agreements could lead to convoluted future situations where eventually the demand cannot be realized because it is conflicting with procedures or laws.

Currently, some initiatives try to bundle and standardize the demand for housing. An example of this is the project “Bouwstroom” initiated by Aedes, this project makes housing corporations collaborate and bundle their demand. Through shared commissioning, they try to speed up construction, make housing more affordable and facilitate more innovation. Housing corporations buy existing development concepts instead of developing them from scratch. This leaves more room for optimisation through scale increase and industrialized construction processes. Through Product-Market-Combinations (PMCs) the attempt is made to make housing corporations standardize their demand for certain types of housing, which allows the industry to adapt their product and processes (Aedes, 2020). This will stimulate supply chain optimization in the CLT production chain and stimulate supply-chain actors to increase communication, transparency, and cooperation.

The same line of thought applies to municipalities; structured frameworks, collaboration, and standardization could help municipalities to quickly realize integrated sustainable housing projects. The actors that have the power to instigate such projects also need to possess the knowledge and the vision to instigate such change; which might be one of the essential roadblocks in this transition. Knowledge on such possibilities needs to be facilitated to the parties that decide on the development of new housing areas, such as municipalities.

Therefore, a reliable demand should be created by structurally embedding sustainability-related demands in tenders. Such procedures could be formed internally by municipalities, but not all municipalities have adequate skills and sufficient knowledge to implement this in practice. To create more uniformity, guidelines for bio-based and circular tenders related to housing need to be made on a national level. These guidelines can then be universally adopted by all municipalities. Furthermore, it is important that municipalities are stimulated, or enforced, to incorporate these sustainability guidelines in a fixed share of their housing tenders.

The standardization of tender guidelines also needs to enforce integrated design, combining CO2 reduction goals, with greening, ecology, water, and energy generation goals. Such design goals need to be incorporated in municipal policy, tenders, and in the case of the Bouwstroom, they need to be incorporated in the PMCs. Consultancy firms might play an important role to help the government and municipalities in developing and formulating such complex aims and conditions. The national government or province could also play a role in facilitating such detailed guidelines. Possible policy areas where such demands could be combined are the Nationale Omgevingsvisie (NOVI) and the Provinciale Omgevingsvisie (POVI).

This integrated design is especially relevant for timber construction. Although modular CLT construction offers some flexibility, in general, it is more difficult to alter a CLT building after the design phase. Therefore, it is beneficial to force cooperation between various companies and already implement multiple essential design aspects early on in the design phase. As well as impose regulations that enforce the usage of sustainably harvested timber products from within the EU.

Modular CLT construction is very well suited for standardized, sustainable, and flexible construction. There are possibilities for semi-portable production facilities; such facilities could be very promising for the development of new areas or neighbourhoods. After construction is completed the production facility can be dismantled and the building can fulfil a different function within the neighbourhood. Many of the urban areas under development previously fulfilled industrial functions. A suitable intermittent solution could be to combine functions; having both CE-related industry and residential areas within the same neighbourhood. Such production facilities could ideally fulfil multiple functions, such as; CLT production, CLT assembly, education, energy generation, and recycling practices. This would create opportunities for industrial symbiosis in the field of electricity and heat. These above-mentioned possibilities need to be considered when developing the previously mentioned standardized guidelines.

If such plans are desired on a national or provincial level, the concerned governmental body must propagate the wishes for such a bio-based and CLT-based future. The general goals are already described in the formal documents that describe the provincial vision for a circular future. However, for the instigation of a regional timber-based housing sector, it can be beneficial to create more specifically formulated goals and to actively engage with parties that are willing to invest in CLT infrastructure. The province and the municipalities could also adapt regional development plans to include designated areas for integrated bio-based material production initiatives.

6.3.3 Shaping the markets

There are four remaining areas where interventions are needed to level the playing field and to aid the transition. These areas are; the attitude of the general public, education of construction workers, building regulations, and the construction-material markets. These four topics will be addressed in the following paragraphs.

Firstly, financial benefits are essential for a juvenile CLT production industry and for bio-based construction in general, since sustainable alternatives are often still marginally more expensive. A level playing field is required, which means environmental shadow costs need to be incorporated in material prices. Examples of such measures are the pricing of embedded CO2 or tax benefits for bio-based materials. Another option is increasing the tax on mineral construction materials and reducing the tax on labour simultaneously. This will benefit more sustainable materials while also stimulating the implementation of labour.

The latter paragraph addresses the financial discrepancies between conventional and bio-based construction. However, there are also concerns regarding price competition in the European timber market. In the first section of this subchapter, the increase of regional timber stocks is discussed. However, in the context of the transition, there is no use in increasing the availability of regional timber if it remains financially uncompetitive with imported timber from other EU member states. Therefore, it should be considered to regulate the prices of Dutch timber for national producers of timber construction materials. Whenever the EU timber prices are lower than the domestic timber prices, the prices could be matched by means of subsidies.

Secondly, the adaptation of the building code is needed to better suit bio-based construction methods, such as CLT. Building codes are identified to often hamper the growth of the CLT industry (Larasatie et al., 2020). An example of this is the maximum allowable height of a building; since CLT floors are generally thicker than concrete floors a comparable CLT building will be slightly higher. In certain cases, a CLT building might be conflicting with the building code, while a comparable conventional building would not be (Commu et al., 2021., 2021). Therefore, building codes need to be reassessed to evaluate if they are conflicting with or limiting bio-based housing.

Thirdly, the current education programs need to be adjusted to specifically include the skills and knowledge needed for timber construction. Prior to the estimated future increase in students, there must be educational programs in place that facilitate knowledge on timber construction, integrated design, woodworking skills, and ICT skills (such as structural 3D-rendering). These programs should be developed in cooperation with educational institutions. There are already education programs organized by the Economic board Zuid-Holland; these Human capital accord programs try to manage inter-sectoral labour developments. The aim is to facilitate job switches from specific sectors that have sufficient workforce to sectors that have shortages of employees.

Lastly, promotional campaigns that show the benefits of timber could prove beneficial in changing the public's attitude towards timber as a construction material and showcase the role timber plays in a circular economy. Building with timber is a good solution on paper, but the attitude of the general public also needs to be considered. The Netherlands historically has a strong mineral-based construction sector and timber is generally seen as an inferior material. The civil attitude towards wood as a construction material could hamper the demand for timber construction and the support for timber harvesting. This positive attitude is likely needed to ensure sufficient societal support if the harvest will be increased in the future. For reforestation projects and the harvesting of forests, it is essential to create trust through clear communication, transparency, and the involvement of citizens.

6.4 Limitations and Future studies

This study aimed to evaluate the system-wide advantages and disadvantages of the implementation and production of CLT but not to solve case-specific sustainability questions. For the scenario modelling data from the literature, datasets and interviews were averaged. In relation to the research aim, the validity is sufficient to grasp the underlying dynamics. The validity is not sufficient to directly extract absolute values that can be directly implemented in other cases. However, the line of reasoning associated with the scenarios and the baseline quantification can be extrapolated to various divergent cases.

CLT construction in general and regional CLT production are beneficial for the transition to a circular economy, both environmentally and socio-economically. There are however multiple crucial aspects that need to be carefully assessed and more thoroughly researched. These aspects will be addressed in the following paragraphs.

Multiple variables linearly affect the impacts associated with material use and transport. Alterations in these variables can severely alter the demand for CLT, both positively and negatively. Examples of such variables are; material densities, CLT production efficiencies and the m3 of CLT required per house.

Intricate assessment of the value creation in the assembly stages after the CLT-panel production is lacking in this study. These dynamics were too case-dependent to address within this research. Extensive market research and actor mapping could clarify these relations and help to more accurately quantify the added revenue and job opportunities.

Having regional CLT production facilities might have multiple miscellaneous benefits associated with EoL opportunities. These benefits are not substantially addressed in this study. Benefits might be associated with added opportunities for remanufacturing, reusing components, and eventually energy generation. Also, the demands for storing components were not addressed. It is important to store timber materials under the right moisture conditions; this should be addressed in future research on material hubs and urban mining.

Detailed assessment of the opportunities for increasing national timber production was not included in this research. A scenario study specifically addressing this topic would be interesting to quantify the following developments over time; how much timber could be produced domestically, what types of trees should be planted, on what soil type should they be grown and how quickly could it become available. Attention should be put on the opportunities and conflicts associated with this land-use change and on the best practices for reforestation projects.

Sustainable forestry policies and practices were not extensively discussed in this study. However, these form the foundation of a truly sustainable timber-based housing sector. Future research needs to quantify the availability of sustainably harvested timber, which is suitable for CLT production, both on a European and a domestic level. The environmental impact resulting from these added pressures on forest ecosystems also needs to be assessed, such as land-use change, biodiversity loss, and soil erosion.

The transition agendas of other EU member states and the associated demand for bio-based materials were mentioned as a critical uncertainty. This study did not extensively map these dynamics. These dynamics grow in importance when the dependency on foreign markets remains and the development of national resource production does not increase. Therefore it is recommended to map the predicted future demand for timber materials on a European level, both to quantify the need for EU-wide reforestation projects and to quantify the risk of dependency on the EU timber market.

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7.2 Interviews

Interview 1. KLH, P. Greven - Representative in the Netherlands, April 6th, 2021 9:00, over the telephone

Interview 2. Element Buildings, F. Steenland, March 26th, 2021, 17:00, over the telephone

Interview 3. Woodteq, E.Laarman, April 9th, 2021 12:38, over the telephone

Interview 4. Dutch Modular CLT construction company, requested confidentiality, May 6th, 2021, via MS Teams

8. Appendix

8.1 Literature searches

Searches were performed on Google Scholar using the following keywords; CLT, LCA, timber construction, carbon footprint, material usage, and bio-based materials

Topic	Used for	Search engine	Search Terms
Environmental Emissions	Primary Drivers	Google Scholar	Carbon pricing, ETA, CO2 tax, carbon emission costs, air quality, PM emissions, nitrogen emissions,
Impact of CE on the job market	Socio-Economic Baseline	Google Scholar	Impact of circular economy, economic growth, job market, socio-economic impact
Material demand conventional	Environmental Baseline	Google Scholar	Material usage constructions sector, material demand, comparative LCA; CLT and conventional, Dutch housing construction
Material demand CLT	Environmental Baseline	Google Scholar	CLT, LCA, timber construction, carbon footprint, material usage, cross-laminated timber, comparative LCA
Transport emissions	Scenario Indicators	Google Scholar	timber transport, freight transport, barge, inland waterways, lorry transport, transport emissions, the impact of freight transport, transport LCA
Value of timber products	Scenario Indicators	Google Scholar	CLT production, the value of CLT, the economics of CLT production, techno-economic

Table 11: Overview of literature searches and their outcomes

8.2 Diagrams

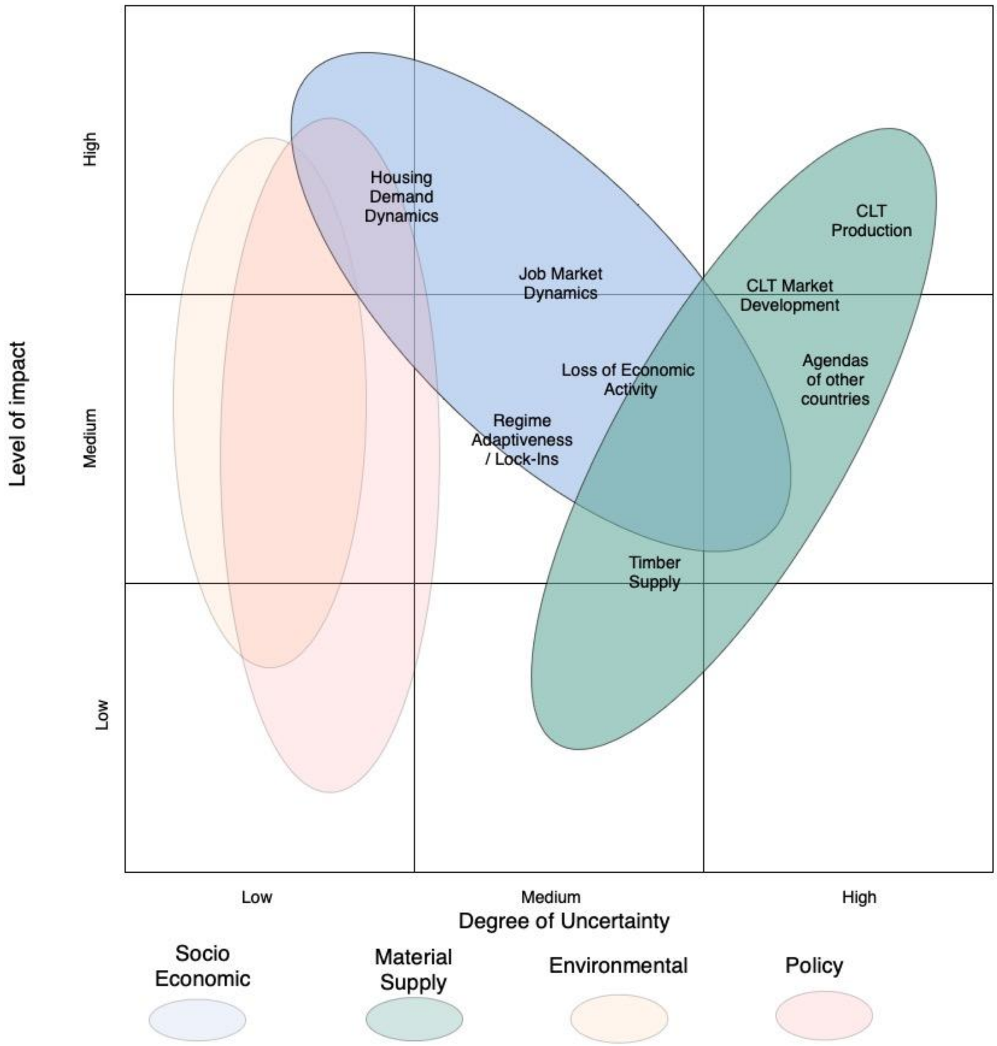

figure 25: Impact versus uncertainty diagram. This diagram was constructed to evaluate what uncertainties are labelled as critical.

8.3 Data

8.3.1 Material demand

Variables	Unit	Value	Source
CLT implementation (% of entire demand)	%	0,2	Fixed baseline value
m3 CLT per house	m3	50	Commu et al., 2021
Embedded CO2 per conventional house	tons CO2-eq / house	65,7	1*)For conventional houses 65,67 tons CO2-eq per house in materials (Metabolic, 2020)
Construction emissions	% of embodied emissions	20%	1*) assumed 20% (15-25%) of total embodied emissions are construction emissions (Robertson et al., 2012).For cast-in-place concrete construction
Total Embedded CO2 per conventional house	tons CO2-eq / house	82,1	Calculated from above-mentioned numbers
Embedded CO2 per	tons CO2-eq / house	11,9	2*)based on data from Dodoo et al. 2014 and Darby et al.,

CLT house			2013.		
Carbon stored in timber	tons CO2-eq / house	22,61			
Biogenic carbon storage factor	-	1,9	3*) Biogenic carbon stored is assumed to be 1,9 times the production emissions (1,8 to 2) (Dodoo et al.,2014; Nakano et al., 2020)		
Net carbon emissions per house	tons CO2-eq / house	-10,71			
Average floor area	m2 living space	146	Dodoo et al., 2014		
Values from literature					
		average	**lowest value literature**	**highest value literature**	**source**
Embedded CO2 CLT house	kg CO2-eq /m2	121	114	127	2*)based on data from Dodoo et al. 2014
Embedded CO2 emissions per CLT house	tons CO2-eq /house	18	17	19	
Total embedded CO2 CLT house(including construction)	kg CO2-eq /m2	127	120	133	2*)based on data from Dodoo et al. 2014
Total embedded CO2 per CLT house	tons CO2-eq /house	18,5	17,5	19,4	

table 12

Emissions saved from 20% CLT implementation						
Emissions 100 % conventional (tons CO2-eq) (1*)	**Emissions 20% CLT houses (tons CO2-eq)(2*)**	**80% conventional + 20% CLT (no biogenic carbon) (tons CO2-eq)**	**% of conventional**	**Net carbon emissions 20% CLT (Tons CO2-eq)**	**80% conventional + 20% CLT (with biogenic carbon storage) (tons CO2-eq)**	**% of conventional**
1112698	77889	968047	87%	-70100	820058	0,74
697693	48839	606993	87%	-43955	514200	0,74

CLT building material demand					
Common floor area (m2)	130	Apartments (no)	16	Living Area (m2)	928
Data were taken from Dodoo et al, 2014					
	Material demand			**Embedded carbon emissions**	
	tons / apartment building	**tons / m2 of living space**	**Material use (tons / apartment)**	**kg CO2-eq / m2 of living area**	**kg CO2-eq / apartment**
Total	708	0,76	44,3	105	6090
Lumber	*47,9*	0,05	3,0		
CLT	*54,8*	0,06	3,4		
Glulam	*20,2*	0,02	1,3		
Plywood	*6,7*	0,01	0,4		

Laminated wood floor	*4,9*	0,01	0,3		
Particle board	*6,0*	0,01	0,4		
Timber materials	**140,5**	0,15	8,8	16	928
Crushed stone	**315,4**	0,34	19,7	2	116
Concrete	**114,9**	0,12	7,2	7,5	435
Plasterboard	**72,3**	0,08	4,5	22	1276
Stone wool insulation	**26,0**	0,03	1,6	19	1102
Mortar	**17,7**	0,02	1,1	0,5	29
Steel	**5,2**	0,01	0,3	8	464
Other (PVC, Polyurethane, EPS, Aluminium Zinc and copper Glass Paint Putty and fillers)	**16,1**	0,02	1,0	30	1740

Table 13

Conventional Construction material demand						
Newly constructed housing in 2014		**Data from EIB, 2020 #1**				
Number of houses	45170	Average area apartment (m2)		86	The average area per house (m2)	146
	Materials			**Embedded CO2 emissions**		
	ktons / year (80% of average demand)	**tons/year (2014)**	**tons / house**	**kton / year (80% of average demand)**	**kton in 2014**	**tons CO2 /house**
Timber	53	273600	6	29	146,5	3,24
Concrete	1425	7296000	162	153	783,8	17,35
Steel & Iron	71	364800	8	235	1205	26,68
Brick	71	364800	8	18	93,5	2,07
Glass				42	213,6	4,73
Bitumen				0	1,7	0,04
Ceramics				2	9,4	0,21
Copper				1	5,7	0,13
Plastics				9	44,6	0,99
Other				4	19,1	0,42
Other metals				12	60,8	1,35
Paper				0	1,5	0,03
Other stone				29	147,2	3,26
Sand				0	0,5	0,01
Plaster				1	6,8	0,15
Insulation				44	226,4	5,01

Total Other	160	1185600	18	0		
Total All	1781	9120000	202	579	2966,1	65,67

table 14

8.3.2 Socio-Economic data

8.3.2.1 Jobs

Estimated No of added FT jobs					
	Forestry / logging	**Sawing Timber**	**Dutch CLT production**	**CLT Assembly**	**Total**
Scenario 1	1,9	3,5	5,2		10,53
Scenario 2	9,4	17,4	51,7		78,47
Scenario 3	15,1	27,8	82,7		125,56
Scenario 4	15,1	55,6	82,7		153,34
Percentage of total	**Forestry / logging**	**Sawing Timber**	**Dutch CLT production**	**CLT Assembly**	**Total**
Scenario 1	18%	33%	49%		100%
Scenario 2	12%	22%	66%		100%
Scenario 3	12%	22%	66%		100%
Scenario 4	10%	36%	54%		100%

Table 15

No of Jobs per production stage		
CLT production		
Annual production per job (m3)	**Source**	
1000	Larasatie et al., 2020	
1200	https://ec.europa.eu/regional_policy/en/projects/Austria/factory-construction-project-in-southern-austria-will-create-new-jobs-strengthen-local-economy	
1000	Group, P. (1948). PASSION FOR TIMBER.	
1066,67	**average**	
Sawing Timber		
	Annual production per FT job (m3)	
no co-production	1100	
co-production	1630	
co-production	1785	
co-production	2380	
co-production	2630	**Source:** Pfeifer Group, 2021 - PASSION FOR TIMBER. (2021). Retrieved from
Average	**1905**	https://www.pfeifergroup.com/en/downloads/general-information/
Forestry/harvest Source: Nabuurs, G. J., Schelhaas, M. J., Oldenburger, J., De Jong, A., Schrijver, R., Woltjer, G., … Hendriks, C. M. A. (2016). Nederlands bosbeheer en bos- en houtsector in de bio-economie. Scenario's tot 2030 in een internationaal bio-economie perspectief. Retrieved from http://dx.doi.org/10.18174/390425%0Ahttps://www.probos.nl/rapporten-2016/1315-nederlandsbosbeheer-en-bos-en-houtsector-in-de-bio-economie		

Period	Costs (€/year)	Revenue (€/year)	Harvest (m3/year)	Employment (no. of jobs)	m3 of harvest per job
2014-2018	3,5E+07	1,3E+08	2,1E+06	2,4E+02	8,70E+03
2019-2023	3,2E+07	1,1E+08	2,0E+06	2,2E+02	9,39E+03
2024-2028	3,2E+07	1,1E+08	2,0E+06	2,2E+02	9,20E+03
2029-2033	3,2E+07	1,1E+08	1,9E+06	2,2E+02	9,02E+03

Table 16

8.3.2.2 Revenue

Material value					
	Unit	Logs	Sawn Timber	CLT panel	CLT-pre cut
average	€/m3	75	178	600	1000
max	€/m3	90	241	700	
min	€/m3	60	115	500	
Brandt, K., Wilson, A., Bender, D., Dolan, J. D., & Wolcott, M. P. (2019). Techno-economic analysis for manufacturing cross-laminated timber. BioResources, 14(4), 7790–7804. https://doi.org/10.15376/biores.14.4.7790-7804					
Estimated Value of material flows per scenario					
	Forestry / logging	**Sawing Timber**	**Dutch CLT production**	**CLT Assembly**	**Total Value**
Scenario 1	€ 1.286.141	€ 1.177.790	€ 4.411.200		€ 6.875.131
Scenario 2	€ 6.430.703	€ 5.888.952	€ 44.112.000		€ 56.431.655
Scenario 3	€ 10.289.124	€ 9.422.323	€ 70.579.200		€ 90.290.647
Scenario 4	€ 10.289.124	€ 18.844.646	€ 70.579.200		€ 99.712.970
Percentage of various stages to total CLT production chain revenue					
	Forestry / logging	**Sawing Timber**	**Dutch CLT production**	**CLT Assembly**	**Total**
Scenario 1	19%	17%	64%	0%	100%
Scenario 2	11%	10%	78%	0%	100%
Scenario 3	11%	10%	78%	0%	100%
Scenario 4	10%	19%	71%	0%	100%
CLT associated forestry compared to entire Dutch Forestry sector					
	Dutch timber usage (m3)	**%-of the national annual harvest**	**Estimated revenue**	**%-of total sector revenue**	
Scenario 1	1,7E+04	0,88%	€ 1.286.141	1,2%	
Scenario 2	8,6E+04	4,42%	€ 6.430.703	5,9%	
Scenario 3	1,4E+05	7,07%	€ 10.289.124	9,5%	
Scenario 4	1,4E+05	7,07%	€ 10.289.124	9,5%	
20% from Ducth CLT only	3,43E+05	17%	€ 25.722.810	23,7%	

Table 17: Annual Dutch timber harvest data from Nabuurs et al., 2016

8.3.3 Environmental impact data

8.3.3.1 Means of Transport

CMLCA impact category output for various transport methods (emissions per ton*km)					
	transport, freight, lorry >32 metric ton, EURO6_transport, freight, lorry >32 metric ton, EURO6[RoW]	transport, freight, inland waterways, barge_market for transport, freight, inland waterways, barge[GLO]	transport, freight train_transport, freight train, electricity[Europe without Switzerland]	transport, freight train_market for transport, freight train[Europe without Switzerland]	
Impact category	**Lory Timber transport**	**Inland waterway**	**Train transport Electric**	**Market for train transport (including Diesel)**	**Unit**
('CML 2001', 'acidification potential', 'average European')	2,4E-04	3,5E-04	2,3E-04	2,9E-04	kg SO2-Eq
('CML 2001', 'climate change', 'GWP 100a')	8,8E-02	4,8E-02	4,2E-02	4,9E-02	kg CO2-Eq
('CML 2001', 'eutrophication potential', 'generic')	5,0E-05	8,9E-05	1,1E-04	1,2E-04	kg PO4-Eq
('CML 2001', 'freshwater aquatic ecotoxicity', 'FAETP infinite')	8,3E-03	5,5E-03	2,1E-02	1,9E-02	kg 1,4-DCB-Eq
('CML 2001', 'human toxicity', 'HTP infinite')	4,7E-02	1,4E-02	3,7E-02	3,6E-02	kg 1,4-DCB-Eq
('CML 2001', 'photochemical oxidation (summer smog)', 'high NOx POCP')	1,4E-05	7,9E-06	1,1E-05	1,2E-05	kg ethylene-Eq
('CML 2001', 'stratospheric ozone depletion', 'ODP steady state')	1,7E-08	7,1E-09	3,8E-09	5,7E-09	kg CFC-11-Eq
('CML 2001', 'terrestrial ecotoxicity', 'TAETP infinite')	2,2E-04	8,0E-05	1,6E-04	1,5E-04	kg 1,4-DCB-Eq
ADPminerals, 1999 (NEW;ICMM)	2,9E-06	4,0E-07	1,1E-06	1,1E-06	kg Sb-Eq
ADPfossils	1,4E+00	6,4E-01	6,0E-01	6,9E-01	megajoule

Table 18

Comparison between sources (literature on transport and CMLCA output) - Unit: per ton*km				
Lorry				
Source	**Name**	**GWP (kg CO2-eq)**	**Acidification (kg SO2-Eq)**	**Eutrophication (kg PO4-Eq)**
CMLCA	lorry >32 metric ton, EURO6[RoW]	0,088	2,4E-04	5,0E-05
Literature (Lindholm et al.)	Lorry Diesel	0,093	varying units	varying units
Literature (Lindholm et al.)	50% bio-fuel / 50% Diesel	0,050	varying units	varying units
Literature	Average all Biofuel	0,008	varying units	varying units

(Lindholm et al.)				
Waterways (barge)				
CMLCA	Inland waterways, barge[GLO]	4,81E-02	3,5E-04	8,9E-05
Literature (McKinnon et al.)	Inland Water	3E-02 to 4E-02	-	-
Literature (McKinnon et al.)	Coastal Shipping	7E-03 to 6E-02	-	-

Table 19

8.3.3.2 Timber flows

Housing demand				
	Housing demand	Annual Housing demand	20% CLT (m3 CLT / year)	Timber demand (m3 / year)
2025-2030	67.780	13.556	135.560	421592
2030-2035	42.500	8.500	85.000	264350
Average over entire time period	**110.280**	**11.028**	**110.280**	342971

Table 20

Material Variables			
Variable	**Average value**	**Source**	**Range**
Density Log Timber (kg/m3)	870		
Density Dried Timber (kg/m3)	466	Chen et al., 2019	350 to 520
Density CLT (kg / m3)	472	Chen et al., 2019	
m3 Timber / m3 CLT	3,11	Nakano et al 2020	
m3 Sawn timber / m3 CLT	1,2	(Commu et al., 2021)	

Table 21

Volumetric CLT flows per scenario (m3/year)						
	EU CLT	**EU CLT (%)**	**Total Dutch CLT**	**Total Dutch CLT (%)**	**Dutch CLT from Dutch Timber (%-of total)**	**Dutch CLT from imported EU Timber (%-of total)**
Scenario 1	104.766	95%	5514	5%	5%	0%
Scenario 2	55.140	50%	55140	50%	25%	25%
Scenario 3	22.056	20%	88224	80%	40%	40%
Scenario 4	22.056	20%	88224	80%	40%	40%

Table 22

Timber flows annual (m3/year)							
Timber	**Dutch CLT from Dutch Timber %**	**Dutch Timber (logs) (m3)**	**Sawn timber production from Dutch logs**	**Sawn timber production from EU logs**	**Dutch CLT from EU Timber %**	**Imported EU sawed timber (m3)**	**Imported EU Timber (logs) (m3)**
Scenario 1	100%	17149	6616,8	0	0%	0	0
Scenario 2	50%	85743	33084	0	50%	33084	0
Scenario 3	50%	137188	52934,4	0	50%	52934,4	0
Scenario 4	50%	137188	52934,4	52934,4	50%	0	137188

Table 23

Volumetric Timber flows per scenario (m3/year)							
	Dutch CLT from Dutch Timber %	Dutch Unsawn Timber	Sawn timber production from Dutch logs	Sawn timber production from EU logs	Dutch CLT from EU Timber %	Imported EU sawn timber	Imported EU unsawn timber
Scenario 1	100%	17149	6616	0	0%	0	0
Scenario 2	50%	85743	33084	0	50%	33084	0
Scenario 3	50%	137188	52934	0	50%	52934	0
Scenario 4	50%	137188	52934	52934	50%	0	137188

Table 24

Mass material flows (tons per year)									
	Imported CLT	Imported sawn timber	Imported unsawn timber	Dutch CLT	Dutch Unsawn timber	Dutch Sawn timber	Upstream Sawn timber	Upstream Unsawn timber	total
Scenario 1	4,9E+04	0,0E+00	0,0E+00	2,6E+03	1,5E+04	3083	5,9E+04	2,8E+05	4,1E+05
Scenario 2	2,6E+04	1,5E+04	0,0E+00	2,6E+04	7,5E+04	15417	3,1E+04	2,2E+05	4,1E+05
Scenario 3	1,0E+04	2,5E+04	0,0E+00	4,2E+04	1,2E+05	24667	1,2E+04	1,8E+05	4,1E+05
Scenario 4	1,0E+04	0,0E+00	1,2E+05	4,2E+04	1,2E+05	49335	1,2E+04	6,0E+04	4,1E+05

Table 25

Transport routes			
Route	type	Distance (km)	source
Rotterdam-Linz	River barge	1335	https://www.danube-logistics.info/travel-time-calculator/
Rotterdam-Goteborg	Open Sea Barge	1120	http://ports.com/sea-route/port-of-rotterdam,netherlands/port-of-vienna,austria/#/?a=0&b=2780&c=Port%20of%20Rotterdam,%20Netherlands&d=Port%20of%20Goteborg%20(Gothenburg),%20Sweden
Linz - KLH	Road transport	190	google maps
Rotterdam - Frankfurt	River barge	528	https://www.danube-logistics.info/travel-time-calculator/

Table 26

8.3.3.3 Transport impact modeling

Ton* km of lorry transport						
	CLT EU	CLT NL	Timber NL	Sawn Timber EU	Timber EU	Total ton-km lorry transport
Scenario 1	5,7E+07	0,0E+00	0,0E+00	0,0E+00	0,0E+00	5,7E+07
Scenario 2	3,0E+07	0,0E+00	0,0E+00	1,8E+07	0,0E+00	4,8E+07
Scenario 3	1,2E+07	0,0E+00	0,0E+00	2,8E+07	0,0E+00	4,0E+07
Scenario 4	1,2E+07	0,0E+00	0,0E+00	0,0E+00	1,4E+08	1,5E+08

Table 27

Transport Emissions per scenario			
Emissions per scenario	Global Warming (kg CO2-eq)	Acidification (kg SO2-Eq)	Eutrophication (kg PO4-Eq)
Scenario 1	5,01E+06	1,4E+04	2,9E+03

Scenario 2	4,2E+06	1,1E+04	2,4E+03
Scenario 3	3,6E+06	9,6E+03	2,0E+03
Scenario 4	1,3E+07	3,6E+04	7,5E+03

Table 28

Comparison between transport emissions and CLT production emissions		
Total m3 of CLT (EU+NL)	110.280	
Emissions per scenario	**Global Warming (kg CO2-eq)**	**%-of production emissions**
Scenario 1	5,01E+06	26%
Scenario 2	4,20E+06	22%
Scenario 3	3,55E+06	18%
Scenario 4	1,31E+07	68%
CLT production emissions	1,95E+07	100%
Including stored carbon	-4,50E+07	-231%

Table 29

Carbon emission CLT production		
kg-CO2-eq / m2 of living space	**Source**	**Notes**
711	Nakano et al 2020	No-biogenic (Not a residential building, Japan)
485	Nakano et al 2020	Biogenic storage included
120	Dodoo et al 2014	Conventional (no-biogenic C)
133	Dodoo et al 2014	Low-Energy (no-biogenic C)
kg-CO2-eq / m3 of CLT	**Source**	**Notes**
221	Nakano et al 2020 #2	Environmental impacts of cross-laminated timber production in Japan
187	Nakano et al 2020 #2	Environmental impacts of cross-laminated timber production in Japan (allocation of co-products)
156	Nakano et al 2020 #2	Washington
142	Nakano et al 2020 #2	Washington (allocation of co-products)

Table 30