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# From waste streams to high-value biobased building materials

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ABSTRACT: Biobased construction can offer a more sustainable alternative to mineral-based methods, reducing emissions and creating more room to build new housing with the same CO2 budget. The Dutch government aims to use significantly more biobased materials in the Dutch construction sector by 2030. Innovations are crucial for achieving this target, but the sector faces challenges, including limited knowledge and research facilities. To address these issues, efforts are being made to process secondary timber towards high-quality building materials like Glulam and Cross Laminated Timber (CLT), utilizing state-of-the-art digital technologies. Additionally, converting current agricultural bio-waste streams that are widely available into bio-composites through (biobased and binderless) binding methods in combination with fiber pretreatment and hot pressing. Collectively, these processes are the foundation of an innovation center which should provide sufficient freedom to enable flexible prototype production and aim to drive innovations in biobased building materials, ultimately helping to reduce emissions of the construction sector.

## 1 INTRODUCTION

Biobased construction has the potential to be more sustainable, compared to mineral-based construction. The usage of biobased building materials can contribute to addressing significant ecological challenges, such as the full decarbonization of the construction sector by 2050 (United Nations, 2024). In the Netherlands, the government has established a target to increase the use of biobased building materials (current share is only ~2%) by 2030, for which innovation is key (Arcadis, 2022; Ministerie van Binnenlandse Zaken, et al., 2023) Substantial innovations and developments are necessary to ensure reliable, sustainable, and affordable use of biobased products in construction. Companies in the Dutch market are pioneering in this new field, but often lack the capacities to tackle complex innovation challenges, with access to research and development facilities being limited. The shortages of opportunities and space for pilot setups, monitoring, measurements, and the production of novel materials and products are hindering the transition. Therefore, it is of great urgency to establish state-of-the-art facilities for developing biobased building materials in the Netherlands. This paper will outline four main objectives which will be the foundation of an innovation center for biobased materials, all enabling the conversion of various virgin or reclaimed/secondary biobased feedstocks to high-value building products, such as Cross Laminated Timber (CLT) and biobased fiberboard.

The supply of locally sourced wood in the Netherlands is low. However, the feedstock of wood harvested from, e.g., demolition sites, has a higher potential when recycled correctly. Various studies have demonstrated the use of secondary timber as (laminated) building material (Cavalli, et al., 2016; Risse, et al., 2019; Chúláin, et al., 2023; Dong, et al., 2024; Vonk, et al., 2024; Vonk, et al., in preparation; Niederwestberg, et al., in preparation), thereby extending the storage of the embodied carbon. However, most secondary wood in the

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Netherlands is currently incinerated for energy generation, partially because re-use is deemed inviable due to the labor-intensive process of dealing with contaminants like metal fasteners, chemicals, and wood rot (Dong, et al., 2024; Crews & MacKenzie, 2008). Therefore, automated sorting and processing of secondary wood for re-use is desired, stating the first objective. To this end, state-of-the-art digital technologies are explored, such as X-ray Computed Tomography (CT) scanning for detection and automated contaminant removal possibilities.

The potential of secondary timber in laminated timber elements such as glulam and CLT has been demonstrated (Chúláin, et al., 2023; Dong, et al., 2024; Vonk, et al., 2024; Vonk, et al., in preparation). Hence, the second objective is enabling laminated timber element prototype production. Production freedom is considered vital to stimulate innovations. The incorporation of other biobased (fiber) panels is one of many possibilities, like oriented strand board or the panels explained below, into CLT-like panels for improved shear capacity (Niederwestberg, et al., 2018), or mixes of secondary and virgin timber in glulam. To this end, various woodworking, glue processing, and panel pressing technologies are explored.

Next to the focus on wood, other biobased materials can be produced from secondary streams. The agricultural and greenhouse industry within the Netherlands produces more than 25 MT of bio and animal waste (Centraal Bureau voor Statistiek, 2022), e.g., vegetable (plant) branches (De Natuurverdubbelaars, 2020), straw, hemp, flax, etc. (Leendertse, et al., 2020; Building Balance, 2023). The bio 'waste' is either used in the livestock industry or incinerated for energy production. These end-of-life options should be the last options if no other valorization step can be taken. To maximize their potential, the third objective is to search for valorization steps to convert fibrous (waste) materials under extreme pressure and temperature to support the biobased panel industry. This pressing process is not new, however, the market is struggling to develop and scale up the production to supply the construction industry and find the right binder under increasingly stringent toxicity regulations (Fraunhofer WKI, 2023; European Commision, 2023; Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2023).

Finally, to ensure the adhesion strength needed for the above-mentioned wood products and biobased fiber panels, the fourth objective is to develop adequate processing and assessment methods for adhesives and binders. Similarly, the cohesion strength of binderless products needs to be assessed. In order to push towards a 100% biobased engineered product, there will be a strong focus on the processing and application of (biobased) binders and glues, as well as binderless processes.

To summarize, the above-described four objectives should stimulate innovations in the production and usage of (circular) biobased building materials, thereby reducing the emissions produced by the building sector. In the following, the workflow of for the four objectives is elaborated and feasibility studies are described, which will aid in designing the inventory required.

## 2 SECONDARY TIMBER

The purpose of the first objective is to automatically process secondary timber to enable (i) direct re-use as solid timber, or (ii) production of timber elements such as CLT, glulam, frames for doors and windows, etc. In two previous studies (Vonk, et al., in preparation; Vonk, et al., 2024), TNO investigated the potential of secondary timber in CLT. The established production processes serve as a basis for the processes described here. Firstly, the sourced secondary timber must be sorted to check if the quality is sufficient for re-use. The sorting can be done manually, however, to enable large volumes, an automated system, consisting of, e.g., cameras, robotics, and a smart sorting algorithm, possibly supported by Artificial Intelligence (AI), is desired. Next, the secondary timber may yield irregular ends due to various damages. A chainsaw or radial arm saw can be used to remove these ends and obtain clean cut timber after processing. Further, the moisture content (MC) of the secondary timber must be determined, and, if necessary, dried to 12% to ensure dimensional stability, using, e.g., a kiln dryer. The MC can be measured using handheld devices or faster, by pass-through MC sensors. Since the history of the secondary wood is unknown, chemical analysis is required to enable safe use in future construction. This analysis can be done using handheld devices based on X-ray Fluorescence, Near-Infrared spectroscopy, and Laser-Induced Breakdown Spectroscopy.

One of the biggest issues with secondary wood is various contaminants, such as rot, chemicals, and metal fasteners like nails, screws, staples, etc. These metal fasteners are most critical, as fasteners (larger than 0.5 mm in diameter) damage subsequent equipment in the woodworking process. To realize processing large volumes of secondary wood, automated detection and removal e.g., by robotics, is key. A study was conducted in which various techniques were explored to detect metal fasteners in secondary wood, including 2D X-ray scanning, 3D X-ray CT, and stereo camera imaging. This study indicated that 3D (X-ray CT) characterization is desirable for adequate detection and subsequent removal, due to the complex shapes of, e.g., (strongly) bent fasteners. Therefore, a feasibility study was performed in which various secondary wood pieces were scanned using a Mito 500 X-ray CT scanner (Microtec, Italy). This study is elaborated in the following.

For scanning, a voxel size of 300 μm (sufficient to detect fasteners with a diameter larger than 0.5 mm), voltage of 180 kV and current of 5.5 mA, and a rotational (gantry) speed of 2 RPM are deemed sufficient. A CT scan of a secondary wood specimen including the grey value distribution of the voxels is given in Figure 1 (a). The grey value relates to the density of the materials, e.g., air, wood, and metal would identify as light gray, gray, and black, respectively. Because the limits of gray value spectrum are very wide, only the fasteners can somehow be identified in the CT scan. Therefore, post-processing is necessary. To separate the materials, the first (very) large peak indicates air, which will be labelled transparent in the post-processed reconstruction. The second, small peak, assumed to indicate wood, is labelled green. All gray values after the wood peak (invisible here) are assumed to be metal, and are labelled brown, resulting in the Figure 1 (b).

Figure 1 (b) is a clear improvement to Figure 1 (a), however, the quality is compromised by the artifacts around the fasteners, and the visibility of, what looks like, the transportation belt of the X-ray CT scanner. To circumvent these issues, filtering is required. After iterative optimization, a Gaussian filter with size 3 generates the best results, as displayed in Figure 1 (c). The Gaussian filter averages the gray value of a number of neighboring voxels towards a single gray value for that volume, consequently reducing the visibility of noise and artifacts, at the cost of losing some spatial resolution (blurring). In Figure 1 (c), the fasteners are identified, artefacts are greatly reduced, and the shape of the wood is visible. To localize the fasteners, the voxelized data is quantified using the voxel size (300 μm), resulting in Figure 1 (d). Note that in order to reduce computational time, the CT scan is given by sparse dots. Furthermore, fasteners should be isolated from each other and be identified as single volumes in the agglomerated CT scan. To this end, an edge detection algorithm is employed which identifies the boundary between materials, e.g., wood and

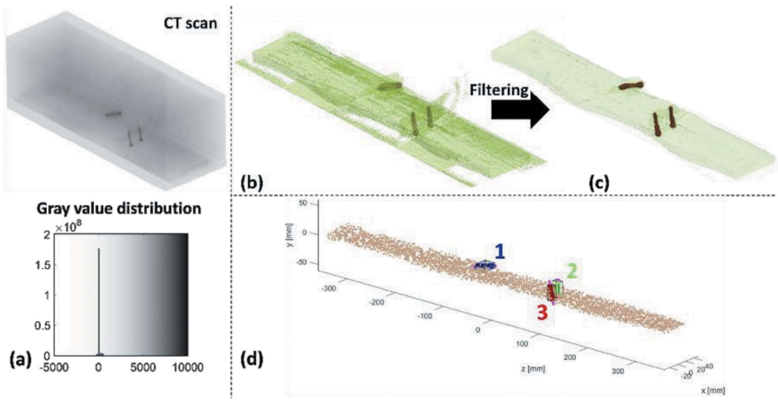


Figure 1. CT scan of a secondary wood specimen, with (a) the original scan and gray value distribution of the voxels, (b) gray value segregation and labeling, (c) filtering, and (d) fastener localization, identification, and orientation, and specimen orientation.

metal, resulting in the different colors of the fasteners in Figure 1 (d). Next, for robotic approaching, the orientation of each fastener is determined by fitting a linear line through the fastener volumes, indicated by the pink lines in Figure 1 (d). Finally, each piece of secondary wood requires a coordinate system to enable transportation without losing the locations of the fasteners. The secondary wood is rotated along the (local) x-, y-, and z-axis, to align with the coordinate system of the CT scanner, and the origin is shifted to be the center of mass of the specimen, resulting in the Figure 1 (d).

The obtained processing algorithm is applied to three more pieces of secondary timber, which are displayed in Figure 2. Figure 2 (a) contains a hinge (red) and three staples, while Figure 2 (b) and (c) clearly only contain nails and screws.

After fastener detection, automated removal is required. In a follow-up study, various methodologies will be explored which enable adequate fastener removal, i.e., high throughput combined with limited waste. The following techniques will be explored and assessed: metal and wood milling, sawing, drilling, cutting, and pulling. In the end, it is likely that a combination of removal techniques will be employed. It is important that these removal techniques can be automated and fixed to, e.g., robot arms and computer numerical control (CNC) setups. Besides fasteners removal, the above-described techniques must also enable wood rot and decay removal.

After fastener removal, the wood has to be scanned by a pass-through metal detector as a final check. Afterwards, the wood must be sorted to determine its next step, e.g., finger

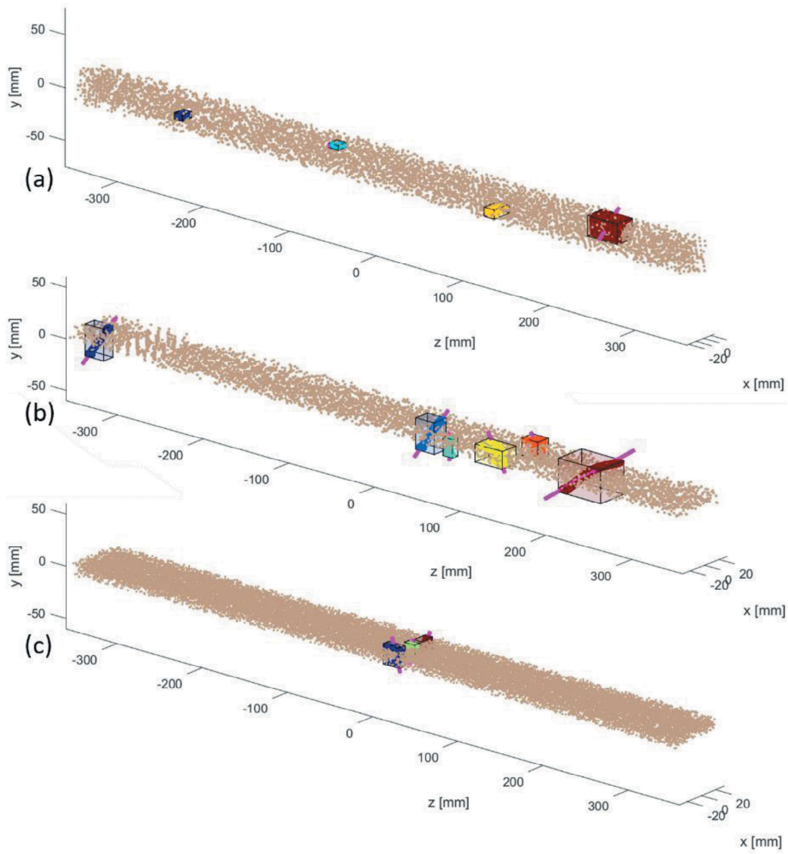


Figure 2. Processed CT scans of three secondary timber specimens (a), (b and c, including identification, localization and orientation of the fasteners.

jointing to produce glulam, CLT, or frames for windows or doors. For these purposes, the wood might need to be reshaped, which can be done by various sawing and planing techniques.

Lastly, non-destructive testing is essential to assess the strength and stiffness of the secondary timber. However, due to often unknown factors, such as wood species, loading/degradation history, effect of cavities, chemical treatment, etc., reclassification is challenging (Cavalli, et al., 2016; Crews & MacKenzie, 2008). Therefore, various methodologies, including visual grading (Smith, 2012), stress waves (Osuna-Sequera, et al., 2020), ultrasonic analysis (Kránitz, et al., 2014), and X-ray CT scanning (Tamke, et al., 2024), are studied to tackle to the aforementioned challenges (Bather, 2022). The most promising reclassification options which can be incorporated in the above-described process, are based on the eigenfrequency (stress wave) analysis (both in-line or handheld grading) (Moltini, et al., 2022) and the acquired X-ray CT data (Tamke, et al., 2024; Huber, 2021; Huber, et al., 2022), or a combination. These options will be explored in future work (Niederwestberg, et al., in preparation).

## 3 TIMBER ELEMENT PRODUCTION

The purpose of the second objective is to combine the (secondary) timber to produce timber elements such as Glulam and CLT, which can be used in construction. In previous studies (Vonk, et al., 2024; Vonk, et al., in preparation), TNO investigated the potential of secondary timber in CLT. The remainder of the steps of the established methods for CLT panel production serve as a basis for the process described here. Finger jointing can be used to combine timber pieces with similar cross-sections to obtain the required length for the timber elements. The laminates must be planed to realize specific tolerances required to produce the timber elements (CEN European Committee for Standardization, 2021), which can be done using a 4-sided planer. In the previous studies, the planed laminates were edge glued to create single layers, however, this is not required in traditional CLT. To create the combined timber elements, various pressing methods can be considered, e.g., traditional presses or vacuum pressing (Dong, et al., 2024). A traditional press has the benefit of producing large volumes because it can easily be automated, while a vacuum press provides more flexibility, e.g., variations in the layers and shapes, and requires a much smaller floor area. For an innovation center where high throughput is subordinate to flexibility, a vacuum press should suffice. After element production, sanding and milling is required to attain the final product that can be used in construction. These steps can be performed using an automated CNC or robot arms.

## 4 BIOBASED FIBERBOARD PRODUCTION

The third objective is the valorization of current agricultural waste streams (e.g., vegetable (plant) branches, straw, hemp, flax, etc.) into building materials. To gain experience in the process of fiberboard production, a case study was performed.

Five different fibers – straw, bell pepper stems, hemp shives, pruning waste and shredded waste wood were each combined with a commercial PU wood adhesive as a binder to produce biobased fiberboards. These fibers were selected because of their upcycling potential and high availability in the Netherlands (Building Balance, 2023). Straw and hemp shives are mainly used as bedding or feed supplements for horses and ruminants. Bell pepper stems, pruning waste, and wood waste are usually incinerated for energy recuperation, releasing their embedded CO2 in the process. These emissions can be postponed by turning these low-grade fibers into much-needed building materials, storing CO2 during the material's lifetime, reducing the concentration in the atmosphere.

In the present study, boards of 30 $\times$ 30 cm were produced in a non-heated press with a specific pressure of 4.5 kg/cm2 and a press time of 30 minutes. These boards allowed a short optimization step to tune the amount of fibers, binder and moisture added to the mixture for the different fibers described above. The next step was the production of 244 $\times$ 122 cm

Figure 3. Five decorative portals with biobased fiberboards on a wooden support (left portal); from left to right: Douglas wood support structure, pruning waste, straw, waste wood, hemp shives and bell pepper stems.

boards, a size which is workable in construction. These boards were produced in a bigger non-heated press with the parameters found in afore optimalisation step. Unfortunately, the quality was insufficient as the fiberboards fell apart during further manipulation and testing. In the end, the fiberboards were glued to a support to produce five portals for decorative reasons. The result was presented at the Houtbouwbeurs 2024 at 's-Hertogenbosch (see Figure 3).

Although decorative, the portals give an insight in some of the challenges present into some of the challenges present in the fiberboard industry from agricultural waste. To conclude, better mixing with dedicated equipment, a heated press and a more suitable binder were necessary to allow fiberboards with high stiffness, bending and internal bond strength. The end goal of this exploration is the comprehension of 'binderless' pressing technology for wood composites (Dunky, 2023a) as it will allow circumventing any regulations regarding the use of toxic binders for the wooden fiberboard industry.

## 5 ADHESIVES AND BINDERS

Adhesives find their purpose in construction and engineered timber elements such as glulam and CLT. Binders, on the other hand, are vital in the production of fiberboards. These products are indispensable in the timber industry. However, because of ecological reasons, their use is being limited and more eco-friendly options have to be found in order to maintain production and quality. Low formaldehyde or formaldehyde-free adhesives and binders such as urethane-containing options are available, but these are also being restricted.

Efforts are being made to produce an eco-friendly, preferably biobased alternative. A large number of reports and papers can be found about naturally-based, engineered adhesives and binders (Dunky, 2023b) based on protein (soy protein) (Bacigalupe & Escobar, 2021; Dunky, 2021a), carbohydrates (starch) (Dunky, 2021b), tannin, and lignin (Dunky, 2021c) for wood and wood-based panels. Their industrial implementation, however, remains limited and is dedicated to niche products. Three reasons can be addressed: the really good performance of synthetic wood adhesives, the still missing good performance of biobased options, and the availability of their resources. The lower resistance to moisture compared to synthetic adhesives is one example but is very important in the timber industry, especially for exterior applications.

To follow up on the innovations in adhesives manufacturing, the biobased innovation center will allow characterization of biobased adhesives and binders in timber elements. An autoclave will be available for conditioning and curing adhesives in CLT and in finger joints according to EN16531 (CEN European Committee for Standardization, 2021) and EN14080 (CEN - European committee for Standardisation, 2013). Shear and tensile setups will be among the possibilities for mechanical testing of the internal bond strength of laminated elements and fiberboards.

## 6 AN INNOVATION CENTER FOR BIOBASED BUILDING MATERIALS

An innovation center for biobased building materials will accommodate the required equipment to allow further support of the research and development and upscaling activities of the four above-described objectives. Secondary timber will be processed for re-use as individual members or in glue-laminated products. To accommodate the Dutch timber market, a first goal is set to produce 2500 $m^3$ of glue-laminated (secondary-sourced) timber elements. Agricultural fibrous waste streams and binder combinations will be processed toward fully biobased fiberboards with competitive properties compared to current fiberboards. Regarding the fiberboards, a large hot-plate press will be installed to make hybrid combinations of biobased fiberboards with CLT in the mentioned volumes possible. Finally, this specialized equipment will be operated by skilled professionals. The innovation center will be accessible to all entities, including companies, universities, and pioneers. Collaborations can be set up in many forms, including through public/private funding.

## 7 CONCLUSION & OUTLOOK

This paper outlined four different objectives which will be the foundation of a biobased innovation center, including secondary timber, engineered wood element production, biobased fiber panel production, and glue and binder processing. Regarding secondary timber, X-ray CT scanning is a promising methodology to detect nails. The biggest challenges ahead are the automated removal of nails and strength classification. Regarding biobased fiber panel production, this industry is moving fast in the Netherlands. A lot of different fibers have been valorized into building materials and found their way onto the market. However, there are some hurdles left to be taken, and these are the upscaling of the production, and the search for an eco-friendly, preferably biobased, binder to comply with regulations. These last hurdles could be overcome with the implementation of the binderless technology. However, more research effort is needed in this field before its implementation into the market.

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## REFERENCES

Arcadis 2022. *De urgente belofte van biobased bouwen.*

Bacigalupe, A. & Escobar, M. 2021. Soy Protein Adhesives for Particleboard Production – A Review. *Journal of Polymers and the Environment* 29: 2033–2045.

Bather, M. 2022. *The assessment of the mechanical and physical properties of in situ timber*. Edinburgh: Edinburgh Napier University.

Building Balance 2023. *Overzicht vezelgewassen - 1 okt 2023.*

Cavalli, A., Cibecchini, D., Togni, M. & Sousa, H. S. 2016. A review on the mechanical properties of aged wood and salvaged timber. *Construction and Building Materials* 114: 681–687.

CEN - European Committee for Standardisation 2013. *EN 14080 - Timber structures - Glued laminated timber and glued solid timber - Requirements*. Brussels: CEN.

CEN European Committee for Standardization 2021. *EN 16351: Timber structures - Cross laminated timber - Requirements*. Brussels: CEN.

Centraal Bureau voor Statistiek 2022. *Afvalbalans, afvalsoort naar sector; nationale rekeningen*. [Online] Available at: https://www.cbs.nl/nl-nl/cijfers/detail/83554NED [Accessed 20 9 2024].

Chúláin, C. U. et al. 2023. *Bending characteristics of CLT from recovered spruce*. Oslo, World Conference on Timber Engineering 2023 (WCTE 2023).

Crews, K. I. & MacKenzie, C. 2008. *Development of grading rules for re-cycled timber used in structural applications*. Miyazak, World Conference on Timber Engineering (WCTE 2008).

De Natuurverdubbelaars 2020. *Factsheet: Het verwerken van reststromene uit de paprika- en tomatenteelt*, De Natuurverdubbelaars.

Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs 2023. *Chemicals: The EU restricts exposure to carcinogenic substance formaldehyde in consumer products*. [Online] Available at: https://single-market-economy.ec.europa.eu/news/chemicals-eu-restricts-exposure-carcinogenic-substance-formaldehyde-consumer-products-2023-07-14_en [Accessed 20 9 2024].

Dong, W., Rose, C. M. & Stegemann, J. A. 2024. Cross-laminated secondary timber: Validation of non-destructive assessment of structural properties by full-scale bending tests. *Engineering Structures* 298: 117029.

Dunky, M. 2021a. Wood Adhesives Based on Natural Resources: A Critical Review: Part I. Protein-Based Adhesives. In: K. L. Mittal, ed. *Progress in Adhesion and Adhesives*: 203–336. Beverly, MA: Scrivener publishing.

Dunky, M. 2021b. Wood Adhesives Based on Natural Resources: A Critical Review: Part II. Carbohydrate-Based Adhesives. In: K. L. Mittal, ed. *Progress in Adhesion and Adhesives*: 337–382. Beverly, MA: Scrivener publishing.

Dunky, M. 2021c. Wood Adhesives Based on Natural Resources: A Critical Review: Part III. Tannin- and Lignin-Based Adhesives. In: K. L. Mittal, ed. *Progress in Adhesion and Adhesives*: 383–529. Beverly, MA: Scrivener publishing.

Dunky, M. 2023a. Activation of Wood Surfaces and "Binderless" Wood Composites. In: K. L. Mittal, ed. *Bio-based Adhesives: Sources, Characteristics and Applications*: 579–620. Beverly, MA: Scrivener publishing.

Dunky, M. 2023b. Naturally-Based Adhesives for Wood and Wood-Based Panels. In: K. L. Mittal, ed. *Bio-based Adhesives: Sources, Characteristics and Applications*: 517–578. Beverly, MA: Scrivener publishing.

European Commision 2023. COMMISSION REGULATION (EU) 2023/1464 of 14 July 2023 amending Annex XVII to Regulation (EC) No 1907/2006 of the European Parliament and of the Council as regards formaldehyde and formaldehyde releasers. *Official Journal of the European Union*, 180/12-20.

Fraunhofer WKI 2023. *News: EU-wide regulation of formaldehyde limits from August 6, 2026: Fraunhofer WKI offers "REAC-H-CHO" certification*. [Online] Available at: https://www.wki.fraunhofer.de/en/departments/qa/profile/news/certification-reach.html [Accessed 20 9 2024].

Huber, J.A. 2021. *Numerical modelling of timber building components to prevent disproportionate collapse*. Luleå University of Technology: Doctoral dissertation.

Huber, J. A. et al. 2022. A method for generating finite element models of wood boards from X-ray computed tomography scans. *Computers & Structures* 260: 106702.

Kránitz, K., Deublein, M. & Niemz, P. 2014. Determination of dynamic elastic moduli and shear moduli of aged wood by means of ultrasonic devices. *Materials and structures* 47: 925–936.

Leendertse, P. et al. 2020. *Bijdrage van vlas en hennep aan milieu- en klimaatdoelstellingen van het toekomstig EU-landbouwbeleid*, Culemborg: CLM Onderzoek en Advies.

Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, Ministerie van Infrastructuur en Waterstaat, Ministerie van Landbouw, Natuur en Voedselkwaliteit, Ministerie van Economische Zaken en Klimaat 2023. *Nationale aanpak biobased bouwen - van boerenland tot bouwmateriaal*, Den Haag: Rijksoverheid.

Moltini, G., Íñiguez-González, G., Cabrera, G. & Baño, V. 2022. Evaluation of Yield Improvements in Machine vs. Visual Strength Grading for Softwood Species. *Forests* 13(12).

Niederwestberg, J., Weijs, H. J. J. & Vonk, N. H., in preparation. Structural Potential of Reclaimed Timber as a New Resource in the Netherlands.

Niederwestberg, J., Zhou, J. & Chui, Y. H. 2018. Mechanical properties of innovative, multi-layer composite laminated panels. *Buildings* 8(10) 142.

Osuna-Sequera, C., Llana, D. F., Íñiguez-González, G. & Arriaga, F. 2020. The influence of cross-section variation on bending stiffness assessment in existing timber structures. *Engineering Structures* 204: 110082.

Risse, M., Weber-Blaschke, G. & Richter, K. 2019. Eco-efficiency analysis of recycling recovered solid wood from construction into laminated timber products. *Science of The Total Environment* 661: 107–119.

Smith, M. J. 2012. *An investigation into the strength properties of reclaimed timber joists*. Newcastle: Master's thesis, University of Northumbria.

Tamke, M. et al. 2024. *Non-Destructive Assessment of Reclaimed Timber Elements Using CT Scanning: Methods and Computational Modelling Framework*. Oslo, Springer Nature.

United Nations 2024. *Global Status Report for Buildings and Construction: Beyond foundations: Mainstreaming sustainable solutions to cut emissions from the building sector*. Nairobi: United Nations.

Vonk, N. H., Niederwestberg, J. & De Jong, J. D., in preparation. c-CLT: the potential of secondary and locally sourced timber in CLT.

Vonk, N. H., Niederwestberg, J., Oorschot, R. W. A. & De Jong, J. D. 2024. *Upcycling of Single-use Pallet Wood to Cross Laminated Timber*. Oslo, Springer Nature.