World Conference on
Timber Engineering
Oslo 2023

3DP BIOWALL – CIRCULAR ECONOMY IN WOOD CONSTRUCTION THROUGH ADDITIVE MANUFACTURING OF FULLY RECYCABLE WALLS

Benjamin Kromoser[1], Sara Reichenbach[2], Roman Myna[3], Raphaela Hellmayr[4], Bernhard Reinholz[5], Rupert Wimmer[6]

ABSTRACT: To further increase the environmental potential of renewable raw materials, a new construction concept for fully recyclable bio-based wall elements assembled by additive manufacturing, called 3DP Biowall, is presented. The proposed concept considers the entire life cycle from material converting, to manufacturing and application, over to recycling and restarting a new construction phase. With the help of this method the materials are kept significantly longer in a closed material cycle, with conceptually no waste production. A fully biobased material mixture of wood particles and Biomix (sodium lignosulfonate and starch) is used. The present paper describes the basic approach, first production experiments as well as the achieved mechanical performance within compression and flexural tests performed with first test specimens. Furthermore, the potential of the closed material loop approach is assessed through an LCA and by comparing the 3DP Biowall to other well-known exterior wall systems. All production life cycle phases were regarded and experimentally investigated. The successful production tests and the achieved mechanical characteristics prove the feasibility and potential of the new approach. The performed LCA points out further optimisation potential regarding the mixture with the starch component having a comparatively high impact at the environmental footprint of the material mixture.

KEYWORDS: 3D Printing, Additive Manufacturing, Cradle-to-Cradle, Biobased Building Construction, Life Cycle Assessment (LCA), Renewable Materials, Recycling

1 INTRODUCTION

There are different approaches to obtain resource-efficient constructions, for one by choosing an appropriate material, for the other by optimizing the structure and furthermore by optimizing the production processes [1]. New methods and processes can be found throughout the industry and in literature, with renewable materials and additive manufacturing showing great potential (e.g. [2]). Unfortunately, most additive manufacturing concepts for production of whole building components or buildings rely on the use of mineral-bound materials such as mortar or concrete which have a very high environmental footprint. To push forward a more sustainable building mentality other materials have to be brought into the equations, with wood constructions showing great potential as wood is able to partly store CO_2 during the tree's growth phase.

However, wood is also a limited resource and currently a considerable amount of the processed raw material ends up in a secondary stream and directly used as an energy source. In 2019, approximately 40% of harvested trees was not used for sawn timber products [3].

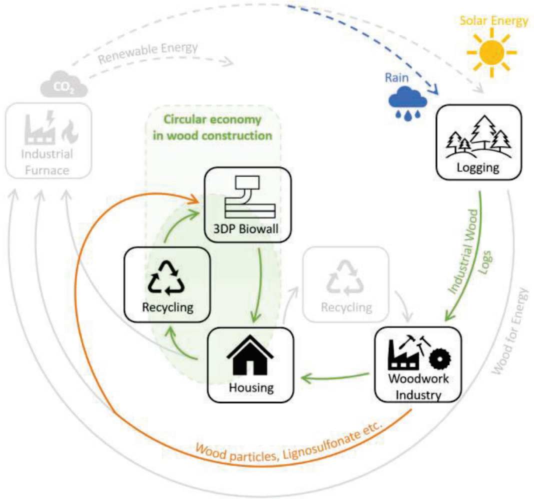


Figure 1: *Circular economy in wood construction based on* ***[4]****, including the future 3DP Biowall concept.* ***[5]***

---

[1] Institute of Green Civil Engineering, University of Natural Resources and Life Sciences, Vienna (BOKU), Austria, benjamin.kromoser@boku.ac.at

[2] Institute of Green Civil Engineering, BOKU, Austria, sara.reichenbach@boku.ac.at

[3] Institute of Green Civil Engineering, BOKU, Austria, roman.myna@boku.ac.at

[4] Institute of Wood Technology and Renewable Materials BOKU, Austria, raphaela.hellmayr@boku.ac.at

[5] Institute of Green Civil Engineering, BOKU, Austria, bernhard.reinholz@boku.ac.at

[6] Institute of Wood Technology and Renewable Materials BOKU, Austria, rupert.wimmer@boku.ac.at

https://doi.org/10.52202/069179-0460

This together with material consumption surpassing the growth of population significantly [6], reveals that a circular approach, structure optimised design and use of secondary streams for manufacturing construction components is indispensable. The newly presented 3DP Biowall construction concept combines the high environmental friendly potential of grown renewable raw material mainly coming from secondary streams (e.g. wood particles, lignosulfonate) including a completely new binding concept [5,7], which allows for a closed-loop process (Figure 1), with a new production strategy resulting in new truly resource-efficient construction method.

2 MATERIAL CONCEPT

Various boundary conditions were set for the printing material to be used within 3DP Biowall: (1) A pure mixture of grown renewable materials, (2) Preferably side stream resources; (3) Recyclability of the end product, as well as (4) Ability to be extruded and develop a sufficient bond to the previously deposited layer. The resulting material mix consists of diverse wood particles (Figure 2c) and a bio-based binder (consisting of industrial starch and lignosulfonate, Figure 2 a) and b), respectively) which can be mixed in a dry state before water is added within the printing process.

The use of lignosulfonate adhesives has a long tradition in commercial use for paper glues. As technical lignins are not able to act as a binder without crosslinking agents or other additives [8], the material is currently mainly burnt for energy production processes [9]. The hydrophobic behaviour it shows due to its aromatic moieties, together with the presence of the hydroxyl groups suggests its compatibility with starch, a renewable resource that is also often used within adhesives production, especially for the paper industry. When applying starch as wood adhesive, the biggest challenge is its water resistance.

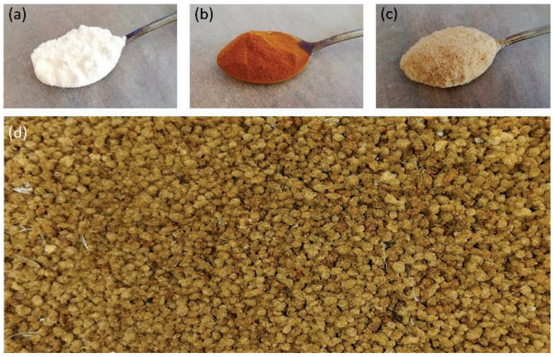


Figure 2: *Components for biobased wall systems* ***[5]***

The results of blending starch and lignin show very good mechanical behaviour for wood bonding as well as full recyclability [7], while the hydrophilicity can be adjusted using different measures. Within in the bio-based binder lignosulfonate acts as a dispersant, whereas the use of starch ensures the strength development of the bond line.

For good adhesion a homogenous distribution of the particulate mixture is critical. This can be supported by using triboelectric charging, where different components receive opposite charges. The created electrostatic potential attracts the individual Biomix and wood particles to each other. Unlike commonly used 3D-printing techniques, which are either based on thermoplastic melting and solidification or chemical reacting of fluid material, the proposed production method is based on dry extraction with minimal water dispersion afterwards.

3 PRODUCTION CONCEPT

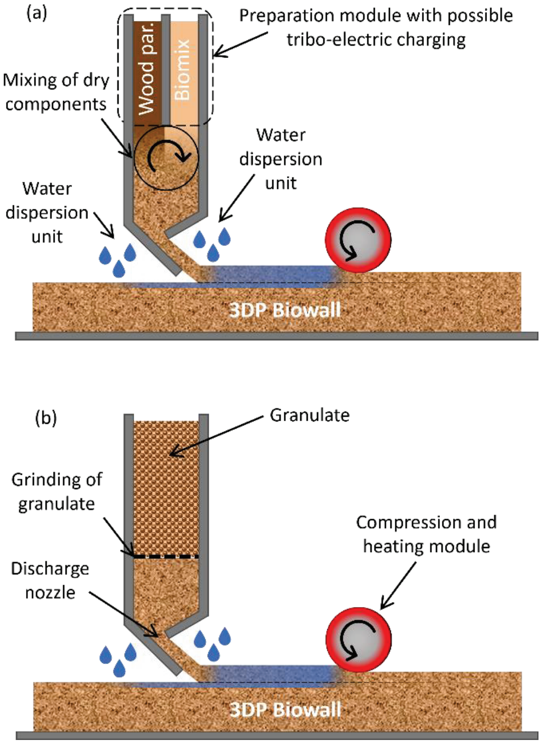


Figure 3: *Printing head concept for a (a) fully-integrated production (b) granulate-based production* ***[5]***

Two concepts (Figure 3) for the material preparation and the printing head are being developed to provide a continuous printing process of the 3DP Biowall. The first approach is a fully integrated production (a), where mixing of all components is implemented in the printing head for immediate application. The second approach is a granulate-based production (b), with the granulate (Figure 2(d)) produced beforehand. Advantages and disadvantages of both production processes are listed in Table 1.

Within option (a) the dry materials (wood particles with Biomix) must be mixed properly in dry state before the extrusion (Figure 3 (a)). Integrating a triboelectric mixing device into the printing head could be a promising supplement resulting in a more homogeneous distribution.

To ensure proper bonding, the bottom layer and the extruded mixture need to be moistened e.g., using water vapor prior to compressing and heating.

Table 1: *Assets and drawbacks of a (a) fully integrated production (b) granulate-based production* ***[5]***

	Fully integrated	Granulate based
Advantages	• Well suited for dry recycled wood components • Easy (automated) adaption of process parameters (mixture ratio) • Higher degree of compression possible, therefore ideal for hollow wall elements • Very homogeneous distribution of the different materials resulting in higher compression strength • All work steps are integrated in one tool • Shorter time frame from shredding to printing	• Fresh wood particles (high moisture content) can be directly used in granulate production without drying • Easy storage and transport, simplifying the printing on site • Can be used for other applications, e.g. ceiling filling • The high moisture content of the wood particles results in significantly less water consumption • Printing head has a simple design, therefore robust and reliable • Production of granulate can take place e.g. at sawmills, creating further added value
Disadvantages	• Materials have to be dried for transport otherwise they can be affected by rot • Higher complexity of the printing head • High water consumption	• Mixing ratio of individual components cannot be adapted in the printing head • Additional crushing unit needed in the printing head • Lower degree of compression possible

For the granulate-based production (Fig. 3 (b)), the granulate is produced directly after gathering of the wood particles, e.g. in the saw mill. By mixing the fresh wood particles with the Biomix-blend, a process of self-agglutination of the components is initiated. The adjustment of size and properties of the granulate is done either via variation of raw materials and mixing proportions or by choosing different process parameters.

The 3D-printing process allows Biowalls to be designed and produced with variable thicknesses and densities. Either a solid or hollow wall structure is conceivable, while the latter allows for an addition of further materials to match desired criteria like thermal insulation, fire resistance or sound insulation. Even complex and structural optimised patterns are achievable by applying selective material distribution/moistening/curing.

For that, the following aspects need to be considered and optimised in the printing process: (1) used material composition (Biomix – wood particles mixing ratio), (2) layer thickness, compression force and temperature as well as their interaction to obtain a homogeneous structure, (3) amount and time at which water is added for optimal wetting of the Biomix– wood particles mixture without clogging the printing nozzle, as well as the (4) production speed.

The independent development of the printing head and carrier system allows for an application und various conditions, e.g. on-site construction with a robot or portal system or off-site using an indoor robot system, as shown in Figure 4.

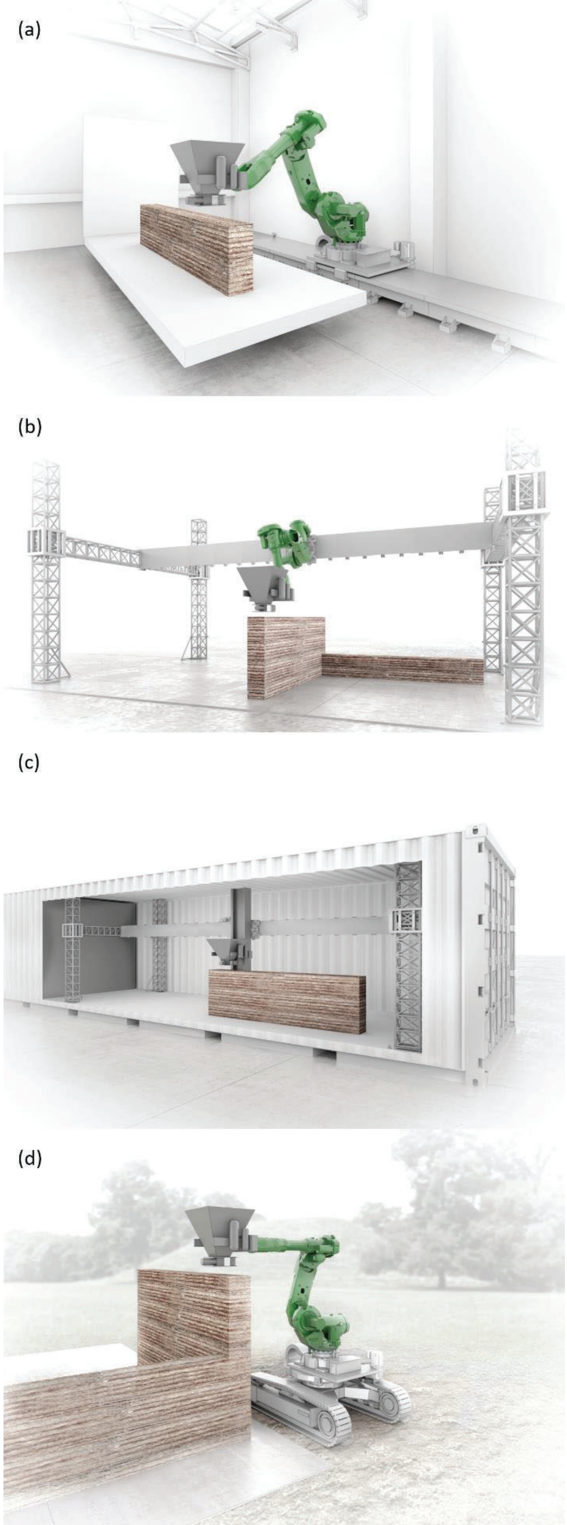


Figure 4: *Illustration of possible carrier systems for the printing head and construction strategy* ***[5]***

The successful implementation on the indoor robot-system of the institute is shown in Figure 5(a). This setup allows to study the fully automated production in future under constant laboratory conditions.

4 RECYCLING CONCEPT

As the 3DP Biowall is completely bio-based, reusing the material offers great potential. In comparison with well-established wood products, the material of the 3DP Biowall is designed for direct and true recycling (without downcycling or the addition of supplemental material) and therefor is in line with the shown principle of a circular economy (Figure 1). To reopen the created glue lines, an optimised disaggregation process needs to be defined, in which moisture treatment together with mechanical disintegration take place without changing the size or form of the wood particles. An essential step towards a fully reuse of the recycled material is a proper separation of the wood particles from each other. This leads to a conceptionally endless process, where multiple printing of 3DP Biowalls without the addition of adhesives is conceivable. As the used material is neither harmful to humans nor the environment, pyrolysis or composting could be a possible end-of-life scenario.

3DP Biowalls are not foreseen to replace the current solid wood applications, but rather to give the opportunity to increase the yield rate by means of using secondary material streams.

5 PRELIMINARY DATA AND ENVIRONMENTAL IMPACT

The data derived from first preliminary experiments on 3DP Biowall specimens consisting of a 1:1 mixture of dry wood particles and Biomix (50% sodium lignosulfonate and 50% corn starch). In addition to this blend, further Biomix variations were prepared adding sodium chloride and ash.

The production of small-scale specimens (Figure 5(c)) followed the four specific steps for each layer:

I) Application of water onto the bottom layer using high-pressure spray guns
II) Distribution of the dry mixture with constant layer thickness as shown in Figure 5(b)
III) Application of water onto the new layer with low pressure to not disrupt the particles
IV) Compression of the new layer using a hydraulic press at temperatures higher than 150°C

The process was repeated until the specimen height reached 40mm. After production it was stored at standard conditions (20°C and 65% rel. hum.) for one week before being cut [5].

The developed prototype of the printing head allowed a semi-automatically production of the specimens, with only step (IV) needed to be done manually. Currently the integration of automated compression and heating in order to automate the entire process are being developed and tested. A variety of small-scale specimens with different compression, amount of water to dry material ratios and various additives (NaCl and Ash) were produced and tested against their fire resistance, their water sorption behaviour and mechanical behaviour, including flexural and compressive strength. For the flexural strength measurement prisms with the dimensions of 160mm by 40mm by 40mm were tested, before being cut to 40mm cubes for the subsequent compression tests. The cubes can be seen in Figure 5(d). The alternating shade of color is a consequence of boundary layer development between the printed layers during the process.

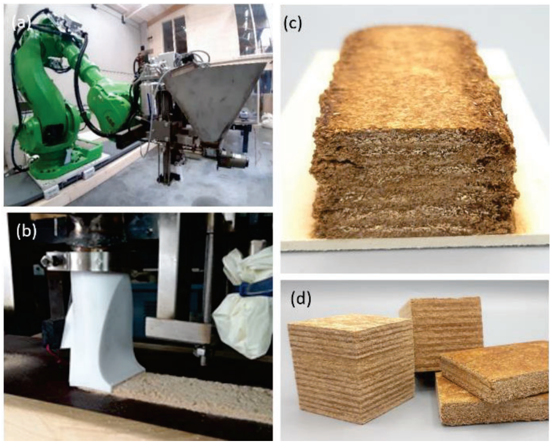


Figure 5:** Production of 3DP Biowall specimens **[5]

The results, including the Young's modulus, are shown in Figure 6 with the Biowall specimens named Biowall or Regular, NaCl or Ash.

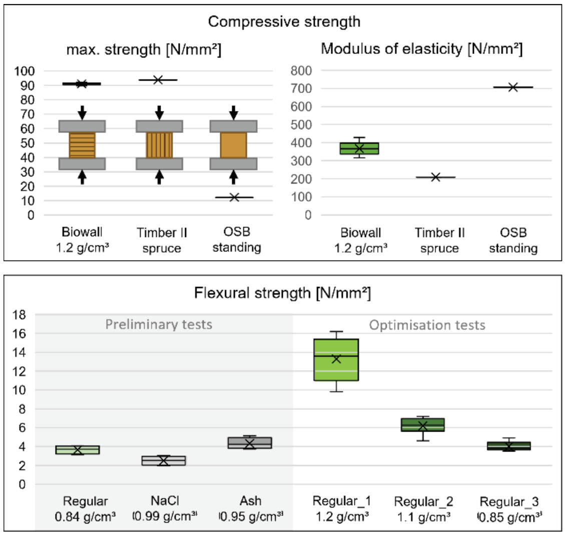


Figure 6:** Mechanical properties **[5]

Within the DVS measurement different relative humidity levels (from 0 % to 95 %) were set until equilibrium and the mass of the sample (10mm x 10mm x 1.5mm) was continuously recorded by a microbalance in the device. The results of the DVS measurement are presented in Figure 7 and show a wood like behaviour. The Biowall samples reached a 15% higher fibre saturation point compared to solid wood; a characteristic that is linked to lignosulfonate and its hydrophilic behaviour.

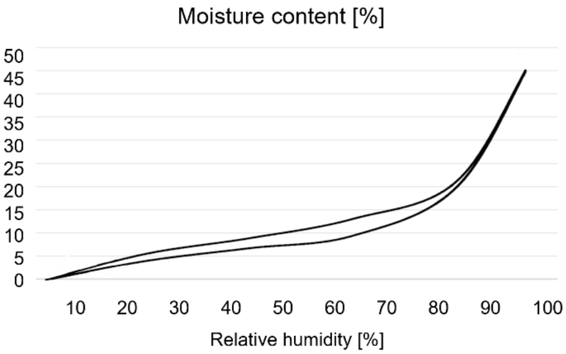


Figure 7:*DVS measurement* ***[5]***

The single flame source test results according to EN ISO 11925-2 were very promising. As a reference solid spruce was chosen. The 40mm by 40mm by 150mm samples were placed directly to the flame source having a 45° tilted orientation plane, with an exposure time of 30s. No ignition occurred for the Biowall specimens. The average flame size was 18mm x 40mm, showing anisotropic behaviour. Additionally, the time required resulting in a flame front height of 150mm was evaluated. After 30 min exposure the flame front had a height of 80mm without ignition, so the test was stopped. The reference sample showed a flame front of 2.5mm by 8.1mm after only 30 seconds with the height of the flame front exceeding 150mm after 3 min.

In addition to these tests the material was subjected to microscopic analysis. The images show the interaction between the two ingredients of the Biomix (Figure 8 (a)) and the dispersion of the binder within the saw dust when dry-blended (Figure 8 (b)). The tensile shear stress of Biomix was investigated in [7], and showed promising properties compared to urea formaldehyde, a conventional adhesive in wood industry.

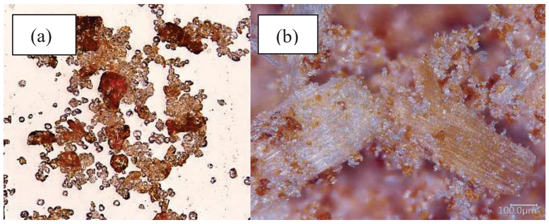
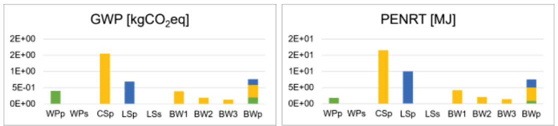


Figure 8: *Microscopic images* ***[5]***

In order to make a statement on the resource-efficiency and the ecologic aspect of the newly developed material an LCA focussing solely on the material production (Figure 9) was conducted. In a second step the material was considered within the boundaries of a constructed exterior wall system including insulation. In comparison with other well-known exterior wall systems (Figure 10) with similar U-values the environmental indicators consistently decrease with every further recycle cycle and therefor proof the closed material loop approach.

Within this paper only the Global Warming Potential (GWP) in kgCO2-equivalent and Primary Energy Non-Renewable - Total (PENRT) in MJ are presented with further environmental impact indicators discussed in [5]**.**

Evaluating the material itself a distinction is made between primary and secondary resources, where secondary resources are by-products or even waste and primary resources products produced specifically to obtain that specific resource. The analysis shows the high impact of starch on each indicator. Therefore, to reduce the environmental footprint alternatives need to be considered, to either substitute the starch completely or partly.



WPp	Wood particles (prim. res.)
WPs	Wood particles (sec. res.)
CSp	Maize starch (prim. res.)
LSp	Sodium lignosulfonate powder (prim. res.)
LSs	Sodium lignosulfonate (sec. res.)
BW1	Composite of sec. res if possible (WPs+MSp+LSs)
BW2	BW1 recycled once (two 3D-printcycles)
BW3	BW1 recycled twice (three 3D-printcycles)
BWp	Composite of prim. res. (WPp+MSp+LSp)

GWP	Global warming potential
PENRT	Total use of non-renewable primary energy res.

🟩	wood component
🟨	starch component
🟦	sodium lignosulfonate component

Figure 9: *LCA of the material (wood+Biomix)* ***[5]***

A	AWm 01a concrete
B	AWm 06a masonry
C	AWl 02a timber
D	AWh 01a timber
BW1	Biowall sec. res.
BW2	BW1 recycled
BW3	BW2 recycled

GWP	Global warming potential
PENRT	Total use of non- renewable primary energy resources

🟩	load-bearing structure
🟨	remaining structure

Figure 10: *LCA of complete wall systems* ***[5]***

https://doi.org/10.52202/069179-0460

Compared to wall systems that are currently in service, see Figure 11, the environmental evaluation for the production phase per functional unit of 1m^2 wall the 3DP Biowall showed elevated values of both GWP and PENRT, when not considering recycle cycles. Recycling the Biowall composite drives these values down on every cycle.

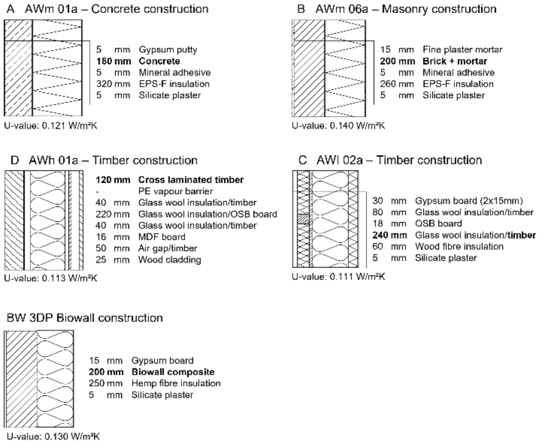


Figure 11: *Cross sections of considered wall systems* ***[5]***

6 THEORETICALLY FEASIBLE PROJECTS

According to Austrian standards no differentiation between one and four storey building is made in terms of the fire resistance requirements of load-bearing structures. Therefor and in order to show economically and environmental feasibility the mechanical properties of the introduced 3DP Biowall should developed in such a manner so that the wall system can be used for these types of buildings.

Examples for such state-of-the-art buildings, made of timber, are “Kleiner Prinz” in Munich (GE) and “Max-Mell-Allee” in Graz (AT), with both having four floors and built using timber frame construction technique with outer walls similar to the wall type awrhhi01a-03 [10]. Based on these designs a maximum design compressive load under normal conditions of around 60 kN/m arises. For this load case the resulting compression stresses and height decreases of the 3DP Biowalls with different wall thickness are summarised in Table 2 based on the model as shown in Figure 12, where the height H is 3 meters.

The stresses for the assumed load are lower than 1N/mm^2 while the mean maximum strength of Biowall under compression is around 90N/mm^2 according to Figure 6. This gap of order two suggests that not only four storey buildings but buildings with even more than four floors can be designed with the 3DP Biowall.

The modulus of elasticity for calculating the compression strain and therefor the compressions is also taken from Figure 6 and approximated with 350N/mm^2. Here again the authors are aware of the 350N/mm^2 not being the characteristic value typically used in a proper dimensioning tasks. The maximum compression is about 5mm for a 100mm thick Biowall and therefore of one magnitude smaller than the expected reduction in height as a consequence of drying shrinkage and creep for a two storey log cabin with a 94mm thick wall made of softwood [11].

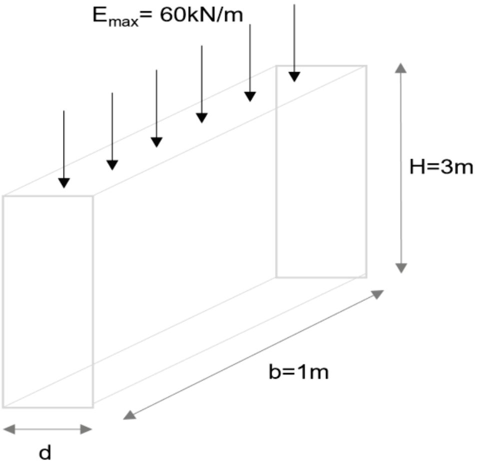


Figure 12: Wall model used for calculation

Taking into account the thermal resistance of the complete wall system, Figure 11 suggests to combine a 200mm thick Biowall with a 250mm hemp fibre insulation. For this Biowall thickness stress and strain are halved.

Table 2: *Stress and Compression for Biowall*

Thickness d [mm]	100	200	300	400
Stress [N/mm2]	0.60	0.30	0.20	0.15
Strain [mm/m]	1.71	0.86	0.57	0.43

The Biowall section can also be split into two pieces sitting on both sides of the insulation layer with each part having a thickness of for example 100mm. This would also increase the flexural stiffness by a factor of approximately seven as well as the sound insulation.

Additionally it is conceivable to replace the hemp fibre by Biowall material with less density as outboard sections of the wall. The material characterisation regarding is thermal insulation potential is part of the project too and will be done in future work.

7 CONCLUSIONS

The positive results of the first preliminary tests and the LCA show that, although challenging obstacles like the further development of the material mix, the production process and the optimisation of their interaction must be overcome to be truly competitive in terms of both environmentalc and economic reasons, 3DP Biowall has the potential to establish closed material loops and implement automation within the construction process, resulting in wood being used in a completely new form full of possibilities.

https://doi.org/10.52202/069179-0460

ACKNOWLEDGEMENT

This research is funded by FFG under the THINK.WOOD initiative. The authors like to thank FFG for that. In addition we like to thank our company partners Rubner Holzindustrie Gesmb, CRS Control & Robot Service GmbH and AustroCel Hallein GmbH as well as the Department of Forest Biomaterials and Technology from Swedish University of Agricultural Sciences for their support.

REFERENCES

[1] Kromoser B. Betonkalender 2021: Fertigteile; Integrale Bauwerke - III Ressourceneffizientes Bauen mit Betonfertigteilen. Wien: Ernst & Sohn GmbH; 2021.
[2] Home | ICON 2021. https://www.iconbuild.com/ (accessed June 1, 2021).
[3] Branchenbericht 2019/2020: Ein Rohstoff voller Leben. Holz. Fachverband der Holzindustrie Österreichs; 2020.
[4] TripleWood 2021. https://www.triplewood.eu/de/bauen-mit-holz/kreislaufwirtschaft_de (accessed September 15, 2021).
[5] Kromoser B, Reichenbach S, Hellmayr R, Myna R, Wimmer R. Circular Economy in Wood Construction – Additive Manufacturing of Fully Recyclable Walls Made from Renewables: Proof of Concept and preliminary Data n.d.;Construction and Building Materials.
[6] OECD. Global Material Resources Outlook to 2060: Economic Drivers and Environmental Consequences. OECD; 2019. https://doi.org/10.1787/9789264307452-en.
[7] Hellmayr R, Myna R, Reichenbach S, Kromoser B, Wimmer R, Šernek M, et al. Heat bonding of wood with starch-lignin mixtures creates new recycling opportunities. Materials Today Sustainability 2022.
[8] Dunky M. Wood Adhesives Based on Natural Resources: A Critical Review Part II. Carbohydrate-Based Adhesives. Reviews of Adhesion and Adhesives 2020;8:333–78. https://doi.org/10.7569/RAA.2020.097310.
[9] Mäki E, Saastamoinen H, Melin K, Matschegg D, Pihkola H. Drivers and barriers in retrofitting pulp and paper industry with bioenergy for more efficient production of liquid, solid and gaseous biofuels: A review. Biomass and Bioenergy 2021;148:106036. https://doi.org/10.1016/j.biombioe.2021.106036.
[10] Dataholz. Wohnunsbau Kleiner Prinz 2023. https://www.dataholz.eu/anwendungen/holzbauprojekte/wohnungsbau-kleiner-prinz-prinz-eugen-park-muenchen-de.htm.
[11] Ein Holzhaus! Aber für welche Bauweise entscheide ich mich? 2023.

https://doi.org/10.52202/069179-0460