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ADDITIVE MANUFACTURING OF WOOD COMPOSITE PARTS BY INDIVIDUAL LAYER FABRICATION-THE PRODUCTION PROCESS AND RESPECTIVE MACHINERY

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ABSTRACT: Additive manufacturing processes that are using wood particles as feedstock material either require large amounts of binder or have relatively poor mechanical properties. This paper details the novel Individual Layer Fabrication (ILF) process and the respective machinery which allow for the additive manufacturing of objects with a low binder content and high strength values. With flexural properties exceeding those of conventional particle boards, an application of objects produced via ILF in the construction industry is possible.

KEYWORDS: additive manufacturing, 3D-printing, binder jetting, sheet lamination, wood composites, wood adhesive processing

1 INTRODUCTION

1.1 CHALLENGES IN THE CONSTRUCTION INDUSTRY

The construction industry is currently facing a multitude of challenges. A deficit in skilled labor inhibits growth and delays or even prevents building projects and the demographic change will most likely worsen this issue in the coming years [1]. Digitalization and automation could offer a solution to this problem, where robots or other machinery fill gaps in the work force, especially for labor intensive and hazardous tasks [2]. A further challenge for the construction industry is to reduce its high environmental impact. According to the 2020 Global Status Report for Buildings and Construction [3] the construction industry as a whole is responsible for around 38 % of the global CO_2-emissions. The report recommends using digital solutions, like automated prefabrication or additive manufacturing (AM - colloquially called “3D-printing”) to minimize waste and improve logistics during building construction. Another benefit of digital methods is the possibility to optimize buildings concerning their energy demand during use, which is an even larger contribution to emissions than the construction itself [3]. Employing additive manufacturing processes in the construction industry offers a multitude of opportunities such as improving workplace conditions, reducing construction time and minimizing waste material [4].

Another way of reducing the environmental impact of the construction industry is the usage of wood and other bio-based materials. These can serve as carbon sinks and thus offset CO_2-emissions that were created during construction [3, 5]. However, an increased usage of wood as building material also leads to an increased amount of logging, which can damage and even destroy whole ecosystems [6]. At the same time the waste from the wood industry (during harvest, during processing and at the end of life) is increasing continuously [7]. Hence, using this waste is essential to employ the full sustainability potential of the wood industry. If this is then coupled with additive manufacturing processes, the overall construction industry gains a powerful tool to become more environmentally friendly.

1.2 ADDITIVE MANUFACTURING OF WOOD COMPOSITES

While for example the AM process of concrete extrusion is on its way to commercial success [8], large scale processes that use wood as feedstock material have not yet moved past the experimental or laboratory status [9].

Using wood particles incorporated into a thermoplastic matrix in the fused filament fabrication process for small-scale objects is well established. Here the mixture is

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molten and then extruded in strands on top of each other thereby creating objects layer by layer. The respective material is commercially available for example from [10]. Also, a large number of projects have investigated the properties of wood particles mixed into various polymeric materials like PLA [11] or ABS [12]. However, comparatively few projects used this method to build large-scale objects. Gardner et al. [13], for example, used PLA and 20 wt% of wood particles to create a boat roof tooling mould. A Finnish Company, UPM, 3d-printed a small pedestrian bridge using an undisclosed thermoplastic material with 20 wt% wood particles [14]. In the United States, in a collaboration between the University of Maine and the Oak Ridge National Laboratory, researchers printed a fully bio-based house out of an also undisclosed polymer containing wood particles [15]. The disadvantage of mixing wood particles into a polymer matrix for the fused filament fabrication process is that higher contents of wood particles (above 40 wt%) drastically reduce the mechanical properties of the composite [16]. Hence, wood is limited to the role of filler material with this process.

Significantly higher contents of wood can be achieved with the so-called liquid deposition modeling process. As in concrete extrusion, a paste of wood particles, binder and water is extruded in strands. Here, a wood content of up to 89 wt% is possible [17]. Various binders were investigated so far, ranging from synthetic urea formaldehyde binders [18] to fully biodegradable mycelia [19]. As the paste liquefier water evaporates during hardening, significant shrinkage makes the process challenging to control [20] and only comparatively low mechanical strength values are achieved [18, 20].

Kromoser et al. [21] propose a different extrusion process to create degradable "3DP Biowalls". A mixture of wood particles, starch and lignosulfonate is extruded in a strand, activated by water and then pressed under heightened temperature to create a rigid wall, layer by layer.

Already in 2012 Henke & Treml [22] investigated the possibility to additively create objects through selective binding of wood particles with mineral and biodegradable binders for the use in construction. The binder (cement, gypsum or starch) was dry mixed with wood particles and spread thinly over a vertically movable build plate. Then one layer of the object was created by locally applying water to activate the binder. This spreading and selective activation was repeated until the desired object was finished (see Figure 1: Truncated cone generated by 3D printing with chips of spruce and gypsum as binder (Credit: [22])Figure 1).

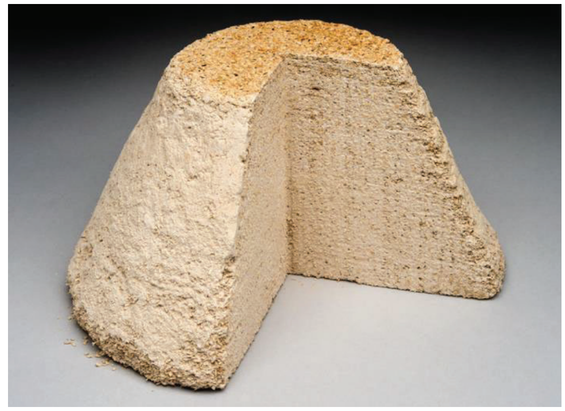

Figure 1: *Truncated cone generated by 3D printing with chips of spruce and gypsum as binder (Credit: [22])*

2 THE ILF PROCESS

2.1 GENERAL PRINCIPLE

The approach of the project presented in the following differs from the previously described ones. The main goal is to develop a process to additively manufacture large-scale, wood composite objects with a high content of wood material and strength values suited for applications in construction. This is accomplished by additively manufacturing thin, individually contoured panels that are stacked and laminated onto one another, thus forming the desired object. [23]

In the course of the project multiple process variants are explored and the necessary machinery is developed in iterative steps. Evaluation of these variants is done by investigating the mechanical properties of the resulting objects as well as the geometric capacity of the processes. Additionally, multiple demonstrators are fabricated for showcase purposes (see Figure 2).

Figure 2: *An Enneper minimal surface demonstrator made via the ILF process.*

The general principle of the ILF process, depicted in Figure 3, can be divided into the following steps. A thin layer of wood particles is scattered (a) and bound by selectively dispensing adhesive according to the target geometry of the object (b). After dispensing the adhesive, the wood particle layer is pressed under heat, curing the adhesive (c). By pressing the amount of required adhesive is drastically reduced while, at the same time, the mechanical properties of the wood composite are increased. Finally, the unbound material is removed and the contoured panel of bound material is laminated onto the stack of previously produced panels (d). [24]

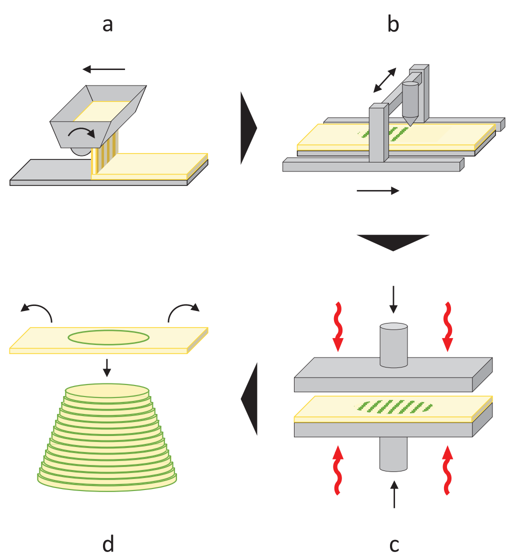

Figure 3: *The basic principle of the ILF process (Credit: [24])*

2.2 MACHINERY

Each step of the ILF process requires specialized machinery. It is either developed or acquired and modified if necessary. In the course of the overall project, multiple process variants and machines are tested and evaluated. The currently used process variant and machinery, with which the object in Figure 2 was created, will be presented in the following chapter.

Initially, a layer of wood particles is scattered on a horizontal moving transportation plate with a size of 500 mm by 500 mm. This is accomplished identically as described in [24], where the particles are picked up out of a material hopper by the needles (length: 10 mm) of a scatter roller. A brush roller (bristle length: 25 mm) rotating faster than the scatter roller brushes out the particles from the needles onto the moving plate below (see Figure 4).

Figure 4: *The particle scattering station*

The plate with the scattered particles then moves to the adhesive dispensing station, displayed in Figure 5, where the pattern of one slice of the final desired object is applied. This is done line by line similar to [24], where one line of adhesive consisted of multiple droplets. However, now the adhesive is not dispensed dropwise but in a continuous stream, thereby drastically increasing the life expectancy of the valve. An increase of temperature, and thus a significantly decrease in adhesive viscosity, allows for this method.

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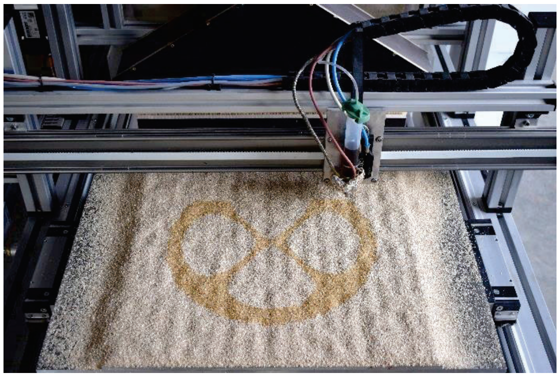

Figure 5: *The adhesive dispensing station*

After dispensing of the pattern, a second layer of wood particles is scattered onto the plate, forming a sandwich structure with the adhesive between two particle layers. This sandwich structure is then pressed under heat (up to 40 bar and 200°C), distributing and solidifying the adhesive and creating a panel with bound and unbound wood particles. The two scattered layers of particles are always of such a thickness that no adhesive can intrude them down- or upwards and preventing the panel from sticking to the press plates. The panel production is done fully automatic by the Panel Printer displayed in Figure 6.

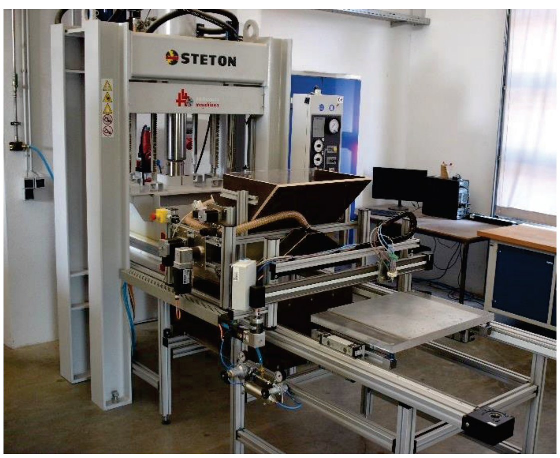

Figure 6: *Panel Printer consisting of the scattering station in the middle, the dispensing station in the front with the transportation plate and the heat press in the back.*

In the following process steps, the unbound particles are removed and the individually contoured panels are laminated onto one another to form the final object. First automated methods and prototypes have been developed for these tasks. However, as these prototypes are not yet reliable, especially for more complex geometries, manual labor is still involved. All demonstrators displayed in this paper were cleaned and laminated by hand. However, all test specimens were processed with the automated machines to ensure reproducible results.

3 MATERIAL TESTS

3.1 MATERIAL PROPERTIES OF INDIVIDUAL PANELS

Already in [24] multiple flexural test specimens were fabricated from the processes intermediate product, the panels, and investigated according to DIN EN 310: 1993-08 [25]. In doing so, a comparison to conventionally fabricated particle boards is possible. As wood particles spruce particles produced by Fraunhofer WKI with a sieve retention mesh size between 0.6 mm and 1.25 mm were used. As adhesive a polymeric methylene diphenyl diisocyanate (pMDI) called I-BOND PB PM 4350 from Huntsman LLC was used. The results are displayed in Figure 7 where the modulus of rupture (MOR) is displayed in megapascal (MPa) and the modulus of elasticity (MOE) is displayed in gigapascal (GPa). Through an alteration of processing parameters, the adhesive content and connected with that the density of the specimens was varied.
The specimens had an average flexural strength of 25.95 to 52.45 MPa and an average stiffness of 3.04 to 5.34 GPa. With these values they all fulfill and largely surpass the flexural requirements of particle boards according to DIN EN 312: 2010-12 [26]. Similarly, also the investigation of tensile properties showed strength and stiffness values exceeding those of conventional particle boards.

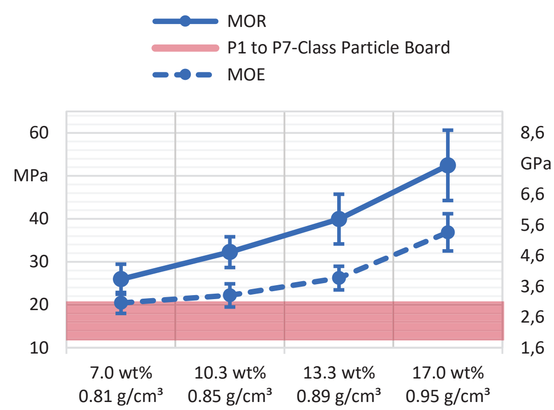

Figure 7: *Flexural properties of individual panels. MOR (left) and MOE (right) as a result of adhesive content (upper) and density (lower). The red area contains bending requirements for P1 to P7 particle boards.*

3.2 PROCESS PARAMETER STUDY

Further investigations regarding the influence of process parameters on flexural strength (MOR in MPa) and density (in g/cm³) of the panels were done. As these flexural test specimens were directly printed and not cut or milled, they deviated from the geometry required according to DIN EN 310: 2010-12. On average they had a thickness of 3 mm, a width of 55 mm and a length of 160 mm. Furthermore, they were stored at room temperature and humidity and not at a precisely defined climate. Because of this the values displayed in Figures 8

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to 10 cannot be seen as absolute but rather their change is important. All test specimens were produced in the same way with the parameters displayed in Table 1 kept constant, except for the one that was varied. The results of varying the adhesive content is displayed in Figure 8, the result of varying the pressing force in Figure 9 and the results of varying the pressing duration in Figure 10. Cubic wood particles with the name of Lignocel 9 from J. Rettenmaier & Söhne GmbH were used with a moisture content of 7 wt%. These wood particles have an average diameter of 0.8 mm to 1.1 mm. As adhesive the same type of pMDI as in [24] was used.

Table 1: *Constant production parameters for the parameter variation study*

Parameter	Value
Adhesive Content	12.5 wt%
Pressing Force	31.25 bar
Pressing Duration	180 seconds

Generally, the test specimens behaved as expected from conventional engineered wood. An increase in adhesive content and an increase in pressing force increased the density of the panels, which in turn increased the mechanical properties [27].

When comparing the flexural strength values in Figure 7 with the ones in Figure 8, the significantly lower values of the latter become apparent. Partly this is due to the lower density values of the test specimen in Figure 8. However, the factor of particle morphology also has to be taken into consideration. The test specimens of Figure 7 were fabricated with wood particles specifically produced for particle boards with a relatively high length to width ratio [27]. For the specimens in Figure 8 commercially available wood particles for smoking of foods or horse bedding were used. The two kinds of particles are displayed in Figure 11. A high length to width ratio significantly improves the mechanical properties of the final composite.

A comparison of Figure 8 and 9 indicates that while an increase of density certainly increases mechanical properties, the process parameter of pressing force has only a limited influence. An increase of adhesive content, and a consecutive slight increase in density, leads to a significant increase in mechanical properties in Figure 8. Whereas a very large variation of density through pressing force only marginally varies the mechanical properties in Figure 9. These results seem to contradict the findings of [28] where the main factor of increased flexural strength was panel density and not adhesive content.

The graphs of Figure 10 suggest only a minor influence of pressing duration on flexural strength if a certain time has passed. In this case the minimal necessary pressing time for maximal mechanical properties lies between 30 and 60 seconds or 10 and 20 mm/s (at 3 mm thickness). This is in accordance with literature [29] where a pressing duration of 12 seconds per mm thickness of material is given as necessary for full curing of the adhesive.

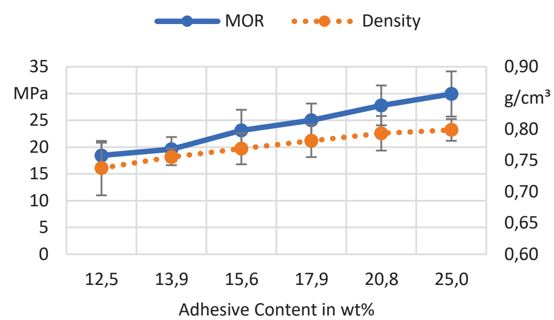

Figure 8: *Flexural modulus of rupture (left) and density (right) as a result of adhesive content variation*

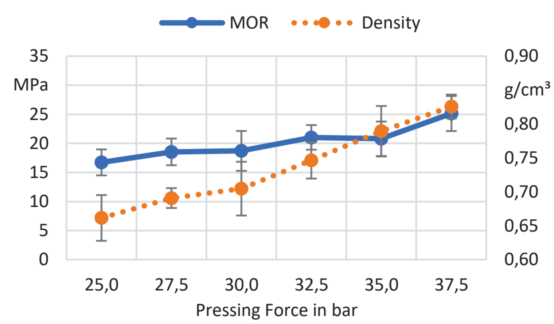

Figure 9: *Flexural modulus of rupture (left) and density (right) as a result of pressing force variation*

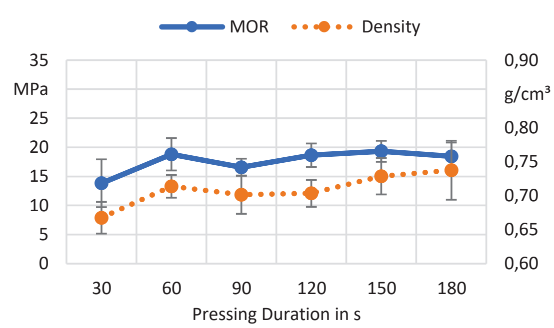

Figure 10: *Flexural modulus of rupture (left) and density (right) as a result of pressing time variation*

Figure 11: *On the left side the wood particles with a high length to width ratio and on the right side the more cubic particles.*

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3.3 ANISOTROPIC PROPERTIES OF ILF-OBJECTS

With the same materials as in the parameter study (Lignocel 9 as wood particles and I-BOND PB PM 4350 as adhesive), square panels with the process parameters displayed in Table 2 were fabricated. 50 of these single panels were laminated onto one another with the polyurethane adhesive Jowapur 686.60 from JOWAT Swiss AG. After adhesive application they were pressed. The lamination's adhesive application and pressing parameters are also displayed in Table 2. From the resulting blocks two kinds of flexural test specimen were cut out to the dimensions of 150 mm length, 50 mm width and 10 mm thickness as given in DIN EN 310: 1993-08 [25]. Eight test specimens were cut in a way so that the orientation parallel to the stacked panels could be tested. Another eight were cut in a way so that the orientation perpendicular to the panels could be tested. This made it possible to analyse the anisotropic behaviour of the overall material properties.

Table 2: *Production parameters for anisotropic flexural test specimens*

Parameter	Value
Panel Adhesive Content	8.9 wt%
Panel Pressing Force	31.25 bar
Panel Pressing Duration	180 seconds
Lamination Adhesive Content	9.4 wt%
Lamination Pressing Force	7.50 bar
Lamination Pressing Duration	24 hours

The results of the density and flexural investigation are shown in Table 3 with the average (AVG) values of the eight specimen and the respective standard deviation (SD). Similar to the 25.0 wt% adhesive content specimens from Figure 8, which have a MOR of 29.92 MPa, the parallel oriented specimens, with a total adhesive content of 18.3 wt%, have a MOR of 29.86 MPa. However, as two different materials are compared, such a comparison must be considered with care.

A significant difference in MOR and MOE can be observed between the parallel and perpendicular oriented specimen. The MOR of the parallel oriented specimen is greater than the ones of the perpendicular oriented by a factor of 20. The MOE is greater by a factor of 10. This behaviour is well known from conventional engineered wood materials, where the tensile strength perpendicular to the fibres is only a fraction of the one parallel to the fibres [27]. Also in [28] the transverse tensile strength of the panels was identified to be in the same order of magnitude as the one observed for the perpendicular oriented flexural specimens. In the investigations of single panels some form of arithmetic average of mechanical properties is calculated. Whereas, in a stack of laminated panels only the weakest panel is decisive for the overall mechanical properties.

Table 3: *Results of the anisotropic to panel orientation done flexural and density investigations.*

Parallel oriented	AVG	SD
Density	0.88 g/cm³	0.04 g/cm³
MOR	29.86 MPa	4.73 MPa
MOE	3.31 GPa	0.23 GPa

Perpendicular oriented	AVG	SD
Density	0.88 g/cm³	0.02 g/cm³
MOR	1.44 MPa	0.26 MPa
MOE	0.31 GPa	0.05 GPa

4 APPLICATION

In the course of the overall project multiple demonstrators are fabricated. Next to purely geometric demonstrators, like the Enneper minimal surface in Figure 2 that demonstrate the capabilities of the ILF process, also functional demonstrators are produced. One example is shown in Figure 12. Here a Helmholtz resonator is displayed. A Helmholtz resonator is a bottle like unit made of an airtight material that has a defined cavity. Additionally, the resonator has a neck with an opening that connects the cavity with the surrounding air. This geometry can absorb a certain sound frequency from the surrounding atmosphere. By changing the size of the cavity volume and the length and width of the neck, the sound frequency that is absorbed is changed as well [30]. One possible application for the ILF process is to create wall or ceiling elements that contain a multitude of different sized Helmholtz resonators. With these elements it would be possible to change the sound or filter unwanted acoustic frequencies in e.g. concert halls or lecture rooms.

Another possible application of the ILF-process is to use it as a tool to fabricate optimized parts. This optimization can be in regard to e.g. weight reduction, thermal insulation, fire safety or even combinations thereof. As designs that are created this way are oftentimes geometrically complex their fabrication using conventional methods can become challenging. However, with additive manufacturing methods, like the ILF-process, where the required effort and cost are largely independent of the design’s complexity, creating optimized parts is easily feasible. This makes optimization and additive manufacturing an ideal match. Accordingly, optimization tools, like topology or shape optimization, have already been applied to additively manufactured construction elements [31].

Figure 12: *Bottle like Helmholtz resonator (Credit: Korbinian Schwab & Birger Buschmann)*

An example of combining structural optimization with the ILF process is shown in Figure 13. Here, a ceiling element was designed with topology optimization. This was done in such a way that the total volume was reduced by around 75 % in comparison to a massive block. At the same time the original stiffness in regard to an even distributed force from the top was maintained. One corner of this design was selected and printed. The result is shown in Figure 13 (bottom) while the original design can be seen in Figure 13 (top). With conventional fabrication this object would have resulted in a large amount of waste material, whereas with the ILF-process it can be created out of waste material.

5 CONCLUSION

In this paper a new process was presented that enables the additive manufacturing of large-scale wood composite objects. The process was detailed and the respective machinery presented. At more than 80 wt% wood content the objects produced with the process showcased comparatively high mechanical properties at a flexural strength of 29.86 MPa and a stiffness of 3.31 GPa. The overall material properties were identified to be anisotropic in regard to panel orientation with a difference in flexural strength by a factor of 20 and in flexural stiffness by a factor of 10. As relevant production parameters the particle morphology, the adhesive content and the pressing force were identified.
Furthermore, first examples of possible application fields were presented. These include functionalized objects that can e.g. be used for building acoustics or structural elements, designed with the aid of digital optimization tools. Hence, the ILF-process allows for the production of individualized, free-formed structures made primarily of renewable material and with mechanical properties suited for applications in construction.

Figure 13: *A topology optimized ceiling element (top) and a corner of the ceiling element produced with the ILF process (bottom). (Credit: Dr. Reza Najian Asl & Birger Buschmann)*

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REFERENCES

[1] M. Müller, *Fachkräfteengpässe im Bauhandwerk beeinträchtigen zunehmend den Wohnungsbau.* [Online]. Available: https://www.kfw.de/PDF/Download-Center/Konzernthemen/Research/PDF-Dokumente-Fokus-Volkswirtschaft/Fokus-2018/Fokus-Nr.-221-August-2018-Fachkraefteengpaesse-im-Bauhandwerk.pdf (accessed: Jan. 7 2022).

[2] Bauen Aktuell, *Automatisierung in der Baubranche: Welches Potenzial Roboter bieten.* [Online]. Available: https://www.bauen-aktuell.eu/automatisierung-in-der-baubranche-welches-potenzial-roboter-bieten/

[3] United Nations Environment Programme, “2020 Global Status Report for Buildings and

https://doi.org/10.52202/069179-0086

Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector," Global Alliance for Buildings and Construction, Nairobi, 2020. [Online]. Available: https://globalabc.org/sites/default/files/inline-files/2020%20Buildings%20GSR_FULL%20REPORT.pdf
[4] M. A. Hossain, A. Zhumabekova, S. C. Paul, and J. R. Kim, "A Review of 3D Printing in Construction and its Impact on the Labor Market," *Sustainability*, vol. 12, no. 20, p. 8492, 2020, doi: 10.3390/su12208492.
[5] G. Churkina *et al.,* "Buildings as a global carbon sink," *Nat Sustain*, vol. 3, no. 4, pp. 269–276, 2020, doi: 10.1038/s41893-019-0462-4.
[6] M. Beck-O'Brien, V. Egenolf, S. Winter, J. Zahnen, and N. Griesshammer, *Everything from Wood: The Resource of the Future or the Next Crisis?* How footprints, benchmarks and targets can support a balanced bioeconomy transition. [Online]. Available: https://www.wwf.de/fileadmin/fm-wwf/Publikationen-PDF/Wald/WWF-Study-Everything-from-wood.pdf (accessed: Feb. 2 2023).
[7] Zimmer, A., T., K. Weitz, A. Padhye, S. Sifleet, and Gabriele, H., S., "Wood Waste Inventory: Final Report," United States Environmental Protection Agency, Cincinnati, USA, Jul. 2018. Accessed: Jan. 9 2022. [Online]. Available: https://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=537332&Lab=NRMRL
[8] G. Ma, R. Buswell, W. R. Da Leal Silva, L. Wang, J. Xu, and S. Z. Jones, "Technology readiness: A global snapshot of 3D concrete printing and the frontiers for development," *Cement and Concrete Research*, vol. 156, p. 106774, 2022, doi: 10.1016/j.cemconres.2022.106774.
[9] K. Henke, D. Talke, and B. Buschmann, "Use of Wood in Additive Manufacturing in Construction," in *Proceedings of the 17th Rapid.Tech 3D Conference Erfurt, Germany, 22 -23 June 2021*, M. Kynast, Ed., München: Hanser, Carl, 2021, pp. 177–187.
[10] Stora Enso, *DuraSense® for 3D printing.* [Online]. Available: https://www.storaenso.com/en/products/granules/3dprinting (accessed: May 21 2021).
[11] N. Knez, M. Kariž, F. Knez, N. Ayrilmis, and M. Kitek Kuzman, "Effects of Selected Printing Parameters on the Fire Properties of 3D-Printed Neat Polylactic Acid (PLA) and Wood/PLA Composites," *Journal of Renewable Materials*, vol. 9, no. 11, pp. 1883–1895, 2021, doi: 10.32604/jrm.2021.016128.
[12] Y. Huang, S. Löschke, and G. Proust, "In the mix: The effect of wood composition on the 3D printability and mechanical performance of wood-plastic composites," *Composites Part C: Open Access*, vol. 5, p. 100140, 2021, doi: 10.1016/j.jcomc.2021.100140.
[13] D. J. Gardner, J. Anderson, H. L. Tekinalp, S. Ozcan, and P. Sauerbier, "Lignocellulosic-filled polymer feedstocks for large scale additive manufacturing of low cost composites," in *Proceedings of the Internaional Forest Products Congress, Trabzon, Turkey, 2018*, pp. 12–22.
[14] S. Peltola, *Steps on a 3D-printed bridge.* [Online]. Available: https://www.upm.com/news-and-stories/articles/2018/10/steps-on-a-3d-printed-bridge/ (accessed: Jan. 30 2022).
[15] T. Ward, *First 100% bio-based 3D-printed home unveiled at the University of Maine.* [Online]. Available: https://umaine.edu/news/blog/2022/11/21/first-100-bio-based-3d-printed-home-unveiled-at-the-university-of-maine/ (accessed: Jan. 20 2023).
[16] M. Kariž, M. Sernek, M. Obućina, and M. K. Kuzman, "Effect of wood content in FDM filament on properties of 3D printed parts," *Materials Today Communications*, vol. 14, pp. 135–140, 2018, doi: 10.1016/j.mtcomm.2017.12.016.
[17] M. Rosenthal, C. Henneberger, A. Gutkes, and C.-T. Bues, "Liquid Deposition Modeling: a promising approach for 3D printing of wood," *Eur. J. Wood Prod.*, vol. 76, no. 2, pp. 797–799, 2018, doi: 10.1007/s00107-017-1274-8.
[18] M. Kariž, M. Sernek, and M. K. Kuzman, "Use of wood powder and adhesive as a mixture for 3D printing," *Eur. J. Wood Prod.*, vol. 74, no. 1, pp. 123–126, 2016, doi: 10.1007/s00107-015-0987-9.
[19] E. Soh, Z. Y. Chew, N. Saeidi, A. Javadian, D. Hebel, and H. Le Ferrand, "Development of an extrudable paste to build mycelium-bound composites," *Materials & Design*, vol. 195, p. 109058, 2020, doi: 10.1016/j.matdes.2020.109058.
[20] M. Rosenthal, M. Rüggeberg, C. Gerber, L. Beyrich, and J. Faludi, "Physical properties of wood-based materials for liquid deposition modeling," *RPJ*, 2022, doi: 10.1108/RPJ-09-2022-0322.
[21] B. Kromoser, S. Reichenbach, R. Hellmayr, R. Myna, and R. Wimmer, "Circular economy in wood construction – Additive manufacturing of fully recyclable walls made from renewables: Proof of concept and preliminary data," *Construction and Building Materials*, vol. 344, p. 128219, 2022, doi: 10.1016/j.conbuildmat.2022.128219.
[22] K. Henke and S. Treml, "Wood based bulk material in 3D printing processes for applications in construction," *Eur. J. Wood Prod.*, vol. 71, no. 1, pp. 139–141, 2012, doi: 10.1007/s00107-012-0658-z.
[23] K. Henke, D. Talke, F. Bunzel, B. Buschmann, and C. Asshoff, "Individual layer fabrication (ILF): a novel approach to additive manufacturing by the use of wood," *Eur. J. Wood Prod.*, 2021, doi: 10.1007/s00107-020-01646-2.
[24] B. Buschmann, K. Henke, D. Talke, B. Saile, C. Asshoff, and F. Bunzel, "Additive Manufacturing

of Wood Composite Panels for Individual Layer Fabrication (ILF)," *Polymers*, vol. 13, no. 19, 2021, doi: 10.3390/polym13193423.
[25] *DIN EN 310:1993-08, Holzwerkstoffe; Bestimmung des Biege-Elastizitätsmoduls und der Biegefestigkeit; Deutsche Fassung EN_310:1993*, Berlin.
[26] *DIN EN 312:2010-12, Spanplatten_-Anforderungen; Deutsche Fassung EN_312:2010*, Berlin.
[27] P. Niemz and W. U. Sonderegger, *Holzphysik: Physik des Holzes und der Holzwerkstoffe : mit zahlreichen Bildern und Tabellen*. München: Fachbuchverlag Leipzig im Carl Hanser Verlag, 2017. Accessed: Aug. 22 2021.
[28] C. Asshoff, F. Bunzel, B. Buschmann, D. Talke, B. Saile, and K. Henke, "Individual Layer Fabrication (ILF) - Additive Fertigung durch selectives Binden von Holzspänen zu Einzelschichten," *Holztechnologie*, vol. 62, no. 4, pp. 5–13, 2021.
[29] M. Dunky and P. Niemz, *Holzwerkstoffe und Leime*. Berlin, Heidelberg: Springer Berlin Heidelberg, 2002.
[30] A. I. Komkin, M. A. Mironov, and A. I. Bykov, "Sound absorption by a Helmholtz resonator," *Acoust. Phys.*, vol. 63, no. 4, pp. 385–392, 2017, doi: 10.1134/S1063771017030071.
[31] G. Vantyghem, W. de Corte, M. Steeman, and V. Boel, "Density-based topology optimization for 3D-printable building structures," *Struct Multidisc Optim*, vol. 60, no. 6, pp. 2391–2403, 2019, doi: 10.1007/s00158-019-02330-7.

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