4D Printing of Hygroscopic Wood Based Actuators for Climate Responsive Skin

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Adaptive building systems aim to enhance user comfort and reduce energy consumption in buildings. However, sensing the environment and generating relevant motion requires complex systems. The high costs associated with the installation, maintenance, and energy consumption of traditional systems hinder their widespread adoption. A more efficient alternative can be found in nature by harnessing the intrinsic properties of materials. Recent studies inspired by pinecones showed that wood bilayers with different swelling and shrinking ratios can passively shape change in response to environmental humidity. The morphing direction is determined by fiber orientation, which can be controlled by extrusion-based 3D printers. The existing literature highlights several challenges in utilizing hygroscopic wood actuators for climate-responsive building skins, including the predictability of motion, response speed, and scalability. Hence, this research investigates the design space at both mesostructural and macrostructural levels for controlled, scaleable motion. To this end, a series of experiments were conducted in a controlled environment to observe the actuation dynamics. The experiments explored design parameters including thickness, porosity, bilayer ratio, layer orientation, and 3D printing parameters such as layer thickness and printing order. Collected data were utilized to construct a model that can predict the actuation and find the configuration for the required motion. Two implementations of this model are proposed. While the first design makes use of combined actuators for motion amplification, the latter employs pre-stressed bistability to control the timing of motion. Both designs were tested at scales of ½ and 1 to 1, using a wood-based filament and wood veneer as actuators, respectively. The results demonstrate that the use of multiple joined actuators significantly increases the actuation speed. Moreover, it is shown that the humidity level required to trigger the shape-shifts can be tuned thanks to the pre-stressed bistable structures. This is promising in terms of adaptability to diverse climates and enhancement of energy efficiency in buildings.

Keywords: *4D Printing Wood, Biomimicry, Hygroscopic Actuators, Pre-stressed Bistability, Climate-Responsive, Responsive Architecture*

INTRODUCTION

A building's lifecycle energy consumption is dominated by its operational energy, which accounts for 80% to 90% (Ramesh et al., 2010). One significant factor influencing energy efficiency is building envelopes, making it a critical parameter for reducing the reliance on active systems (Méndez Echenagucia et al., 2015). While adaptive building envelopes have shown potential in improving buildings' internal environment and performance characteristics (Loonen et al., 2013), traditional systems relying on sensors and motors face challenges when it comes to sensing the environment, processing data, and generating relevant motion at a building scale (Menges & Reichert, 2012). These systems are burdened by complexity and maintenance costs that compromise their effectiveness (Holstov et al., 2017).

Consequently, responsive materials that change shape in response to environmental stimuli without requiring additional energy input hold considerable promise for climate-responsive skins (López et al., 2017). Among these materials, wood possesses several unique advantages that make it well-suited for use as a responsive material for façade elements. The swelling and shrinking characteristic of wood in response to environmental humidity, which varies significantly throughout the day, is promising for responsive skins (Holstov et al., 2015; Zuluaga & Menges, 2015). Besides the scalability to architectural scale, the renewability and biodegradability of wood-based facade elements offer notable advantages for advancing the circularity of buildings (Cambiaso & Pietrasanta, 2014; Dicker et al., 2014).

State of the art

In terms of sustainability and design freedom, extrusion-based 3D printing of wood-based materials outperforms the traditional approach of bilayering wood veneers. By utilizing wood flour derived from waste products and local production, 3D printing reduces both the environmental impact and cost (Mazzanti et al., 2016, 2019). Furthermore, the filament production process and shear-induced stress during printing align the wood fibers, enabling greater design space and more predictable motion through designed print-paths (Le Duigou et al., 2020; Zuluaga & Menges, 2015).

However, 4D printing of wood by FDM is restricted to wood-based filaments available in the market (Gauss et al., 2021). These materials lack robustness, display delamination of bilayers (Correa et al., 2020), and are responsive to water immersion rather than environmental humidity (Tahouni et al., 2020). Even though customized filaments can enhance responsiveness (Tahouni et al., 2022), small nozzle diameters of FDM printers limit the printable wood content of the filaments (Kariz et al., 2018). This results in a slow and limited shape change in response to environmental humidity (Correa et al., 2015). For that reason, several methods are employed for higher response speed and greater shape change, such as origami (Tahouni et al., 2020) and biomimicry (Poppinga et al., 2020).

Another limitation of FDM technology is that filament moisture should be reduced as much as possible, to prevent possible shortcomings in mechanical properties (Wichniarek et al., 2021). Unlike the bilayering method, this dictates the active material's humidity level at the printed state. Therefore, the RH range for actuation can not be tuned for different climatic conditions.

Research Aim

To overcome the challenges associated with wood-based climate-responsive skins, this research proposes reinforcing the responsiveness of wood with the high control and complexity of 3D printed structures. Coupling and the integration of pre-stressed bistable structures to hygroscopic wood actuators are suggested to enhance motion control, response speed, and the ability to adapt to various climatic conditions.

Reasoning of Bistability Integration to Hygroscopic Actuators

Bistable structures are defined as structures with two mechanically stable shapes separated by a critical level of potential energy (Cao et al., 2021). When an impact above this energy level is applied, a snap-through action is triggered, input energy is amplified, and a large magnitude of movement is created, resulting in a simple but precise and reliable motion (Cao et al., 2021).

Moreover, the integration of hygroscopic actuators as a source of activation for bistable structures is especially promising (Chen et al., 2022).

Since the moisture transfer to reach equilibrium between the environment and wood-based actuators is an exponential function of time (Time, 1998), the displacement and kinetic energy produced also drops constantly. This means that the first half of the actuation occurs at a higher speed than the second half. Therefore, a bistable structure that is triggered by the first half of the actuator's total displacement could amplify the response speed. Because the rest of the displacement will be realized by the triggered bistable structure.

The required energy for shape-shifts between the states of bistable structures can be asymmetrically manipulated (Faber et al., 2018), and threshold energy for different directions can be tuned (Jeong et al., 2019). Introducing pre-stress results in a trade-off of thresholds, where the threshold for one shape-shift is increased while the reverse is decreased. Tuneable asymmetry in motion can be a useful tool for climate-responsive skins because it also means a trade-off between the time range of shape-shifts. For instance, the speed of actuation at night can be decreased for the sake of faster actuation during the day. Moreover, thresholds can be tuned for adaptivity to various climatic conditions. Tuning the triggering humidity level for different climatic zones or even for seasonal changes is crucial to maintaining the high performance of the skin.

METHODOLOGY

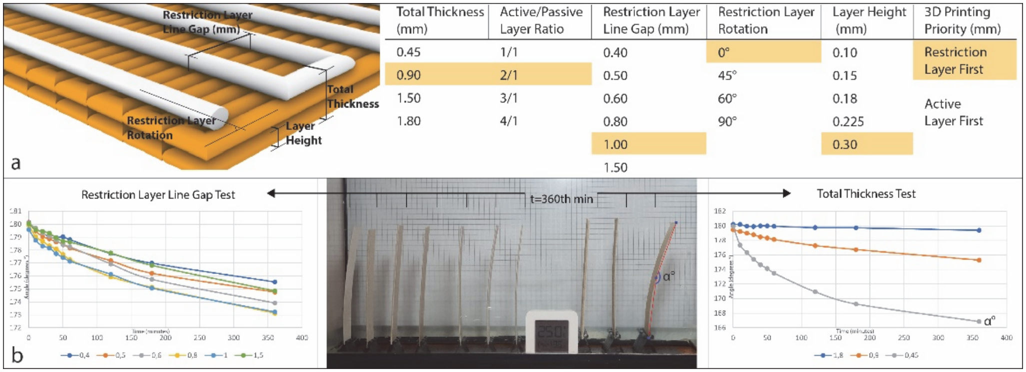
This research is composed of three stages. In the first stage, a set of experiments was conducted to observe the relationship between key parameters that affect the response time and shape change. Collected data is used to construct a model that can predict the actuation and find the configuration for the required motion. In the second stage, two prototypes are developed using this model. The former utilizes the coupled actuators and the latter uses pre-stressed bistability for both amplified response speed and motion control. The final stage of the experiments was conducted on a one-to-one scale to evaluate the reliability of the amplified and controlled motion on a larger scale and with a different wood-based material. For this experiment, a climate-responsive skin prototype is designed with a quadrangular grid to deploy coupled actuators and joined textile elements.

Observing the Actuation Dynamics

In the first step of the experiments, key parameters that affect the hygroscopic actuation were identified. Porosity, total thickness, bilayer ratio, and layer orientation are identified as 3D geometry parameters while layer thickness and printing order are identified as 3D printing parameters. A different set of experiments was arranged for each parameter. While the values of the tested parameter were changed, the values of the other parameters remained constant at highlighted values as seen in Figure 1a.

Custom g-codes are created by using Grasshopper plug-in Droid, and samples (2x10 cm) are 3D printed with a single extruder desktop printer. PLA-Wood filament (30% wood content) is used as active material while PLA is used as restrictive material. Printing is paused and the filament is changed when needed. The motion of fabricated samples in a humid environment (~90% humidity) is tracked by photos taken in 0, 10, 20, 30, 40, 50, 60, 120, 180, and 360th minutes. An image analysis software called ImageJ is used to calculate the bending angle of each sample by the photos. Angles are measured by drawing lines from the endpoints to the middle point and calculating the intersection of these two lines as shown in Figure 1b.

Overall, the experiments’ results (Figure 2) are parallel to the literature. The thinnest sample (0.45mm) in the total thickness test, the sample with the lowest AL/RL ratio (1/1) in the bilayer ratio test, and the sample with perpendicular RL to AL in the layer rotation test showed the greatest shape change. In the restriction layer line gap test, 0.8 and 1 mm samples are bent approximately the same and showed the greatest shape change at the end of 360th minutes.



Total Thickness (mm)	Active/Passive Layer Ratio	Restriction Layer Line Gap (mm)	Restriction Layer Rotation	Layer Height (mm)	3D Printing Priority (mm)
0.45	1/1	0.40	0°	0.10	Restriction Layer First
0.90	2/1	0.50	45°	0.15	
1.50	3/1	0.60	60°	0.18	Active Layer First
1.80	4/1	0.80	90°	0.225	
		1.00		0.30	
		1.50			

Figure 1
a) Illustration of the printing parameters and the table of constant values while other parameters are tested
b) Example photograph from the experiments and measurement method of bending angle (middle) Documented bending angle over time for each sample (left and right)

The layer height test is conducted based on studies that report the higher orientation of the fibers due to the shear-induced stress during printing (Compton & Lewis, 2014; Correa et al., 2015). In line with these reports, the sample printed with the thinnest layer height showed the greatest shape change. Another fabrication parameter tested is the 3D printing priority. During the experiments, it is realized that when the porous restriction layer is printed first with certain gaps between the lines, the active layer printed on top of this layer flows to these gaps. This strengthens the bonding of the bilayers and results in an increased bending angle. To test this hypothesis samples with restriction layers are printed in reverse printing order. Results proved that printing the restriction layer first increases the shape change.

Collected data demonstrated the effect of each parameter on bending angle, thus, allowing the construction of a reliable model to predict hygroscopic actuators' actuation. This enabled the selection of the best configuration of actuators in terms of response speed and shape change. However, results also showed that displacement speed is not enough to meet the requirements of climate-responsive skin. Therefore, in the next stages of this research, parameters of the sample that result in the highest response speed are used and strategies for further amplification are investigated.

Total Thickness (mm)	0.45
Active/Passive Layer Ratio	1/1
Restriction Layer Line Gap (mm)	0.8
Restriction Layer Rotation	0°
Layer Height (mm)	0.1
3D Printing Priority	RL

Figure 2
Parameter values that displayed the greatest shape change in the experiments

Implementation of Pre-stressed Bistability

This experiment is conducted to prove the foreseen merits of pre-stressed bistability integration to hygroscopic actuators. Two porous restriction layers (PLA) are 3D printed at once with a flexible layer (TPU Shore A95) in between for required elasticity during shape-shifts. Maple wood veneer is used as an active material for a larger actuation force. The wood veneers equalized at 65% humidity are glued on the restriction layers.

A simple square template is designed with joints for bistable samples. Following a series of experiments, three different joints with rotation of 15°, 10°, and 5° degrees have been found promising to demonstrate sequential activation. The joints are 3D printed along with a control joint without rotation. Fabricated samples are attached to joints and placed in a humid environment (~90%) for twenty minutes. Shape-shifts are triggered in the order of no pre-stress to highest pre-stress so that no inference to each other's motion is observed. Then, samples are placed in a relatively dry environment (~45%) for twenty minutes. The order of the shape-shifts is reversed, and the last sample that triggered is the one with no pre-stress (Figure 3). The results of these two experiments proved that the response speed of snap-through actuation can be reduced for the sake of increasing the speed in the reverse direction. Tuning the response speed also means adjusting the threshold humidity level, thus, allowing adaptivity to various climatic conditions.

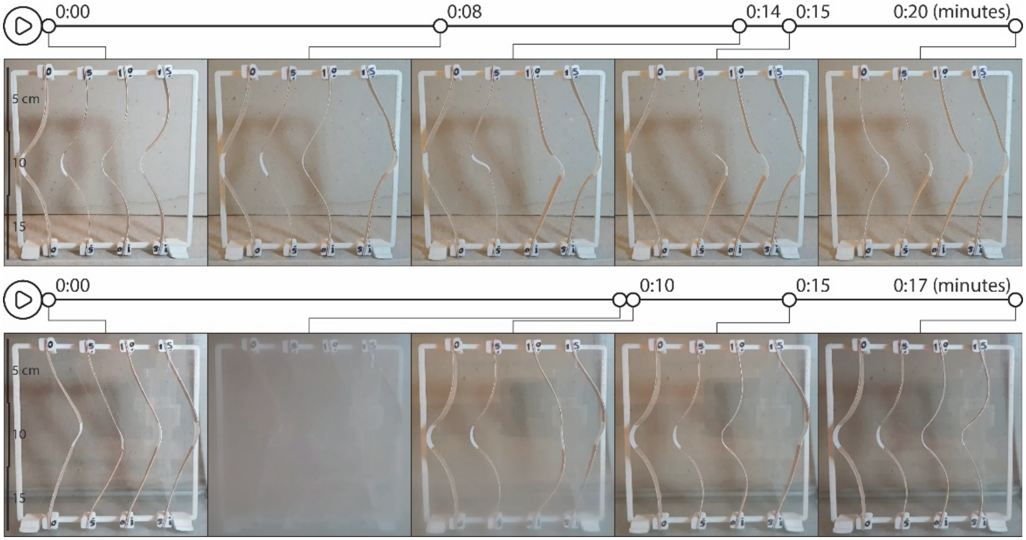


Figure 3
Sequential actuation of bistable samples with different pre-stress levels in dry and humid environments

Proposed Coupled, Rotational Design

The first leg of the experiments showed that the response speed of the 4D printed samples can not fulfill the requirements of a climate-responsive skin. Therefore, hygroscopic actuators are combined to amplify motion while securing dimensional stability. Two vertical elements with 45-degree print paths perpendicular to each other are printed for rotational actuation. On the vertical actuator connection point, where the highest momentum occurs, the two horizontal linear actuators are printed in reverse order (Figure 5a). Four identical samples are attached in a square template and placed in a humid environment (~90%) for 2 hours (Figure 4). Results showed that vertical elements significantly contributed to the rotational motion and response speed is enhanced by the coupling of actuators.

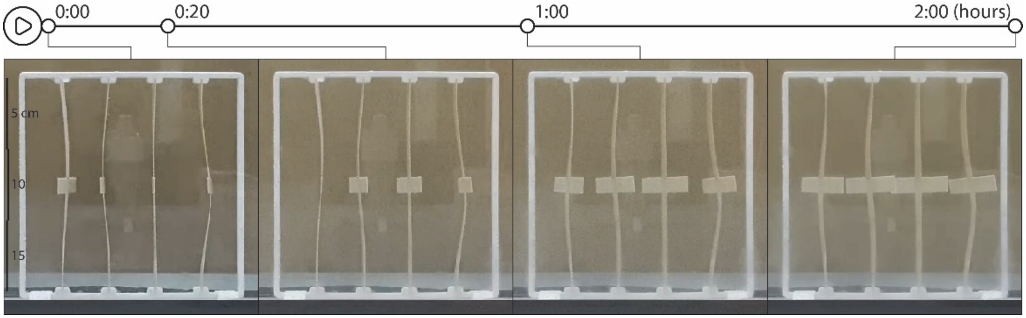


Figure 4
Rotational actuation of coupled, 4D printed samples in a humid environment

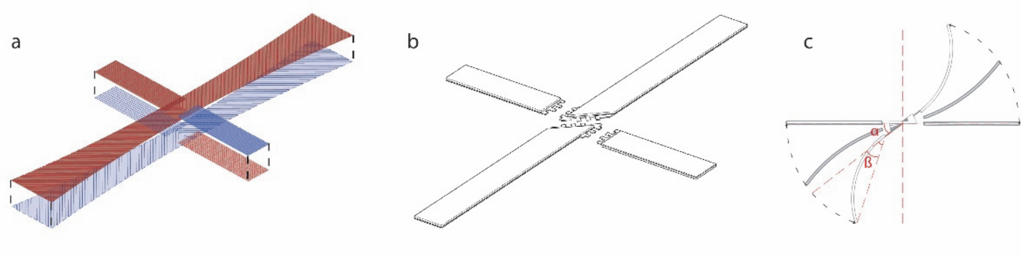


Figure 5
a) Print-paths of coupled, rotational design (blue: PLA, red: PLA-Wood)
b)Upscaled design with dovetail joints
c)Top view of rotational movement of vertical (α) and horizontal (β) elements

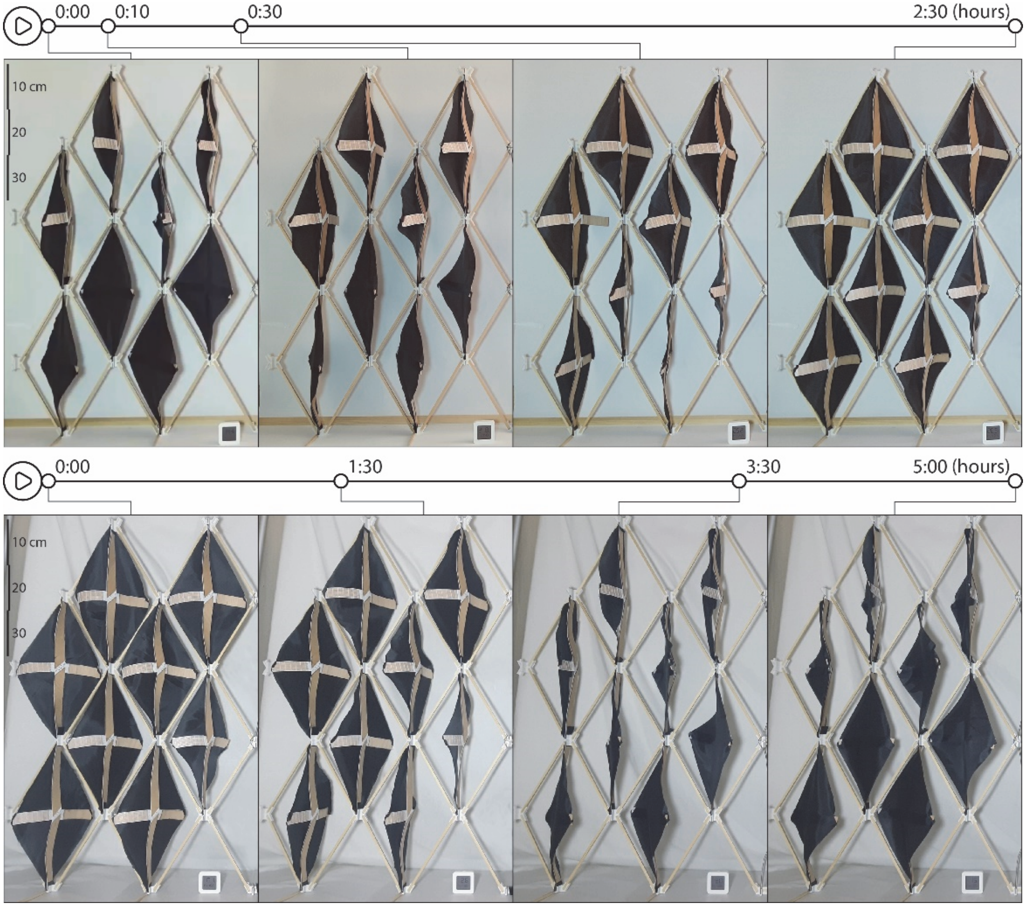


Figure 6
Large scale prototype of coupled, rotational design with textile elements in dry and humid environments

Large Scale Experiment

To prove that controlled actuation of the design is scaleable, large scale experiments are conducted. Due to the print bed's size limitations, dovetail joints are used for the connection of actuators (Figure 5b). Both joints and restriction layer are printed at once with PLA but the wood veneer is used as an active material instead of PLA Wood filament, because of the limited wood content and actuation. Vertical and horizontal elements' contribution to the rotational motion can be seen in Figure 5c.

Two different modules of the same design are fabricated to demonstrate the adaptability to various climatic conditions. To achieve this, the wood veneers are equalized at different humidity levels and are glued with restriction layers. The four upper modules were equalized at 75% humidity while the four modules at the bottom equalized at 60%. Modules are placed in a dry environment (~30%) for two and a half hours and a humid environment (~90%) for five hours. Results of the experiment demonstrated that bilayering at different humidity levels causes a pre-stress in modules and different open/close states can be achieved in the same environmental conditions (Figure 6).

APPLICATION

This research questioned the applicability of hygroscopic wood-based materials as a climate-responsive façade component. For this purpose, a series of experiments are conducted. The wood-based filament is used as an active material for small scale experiments. Gained knowledge projected to large scale experiments utilizing hygroscopicity of wood veneer. Similar actuation behavior was observed in both experiments which proved the scalability of the designs. Then, collected experimental data is used to develop the imagined model in Grasshopper. The array of the components at the façade of a room can be seen in Figure 7. Tuned at different pre-stress levels, actuators are at various open and closed states in the same humidity level.

Figure 7
Imagined array of the components at the façade of a room

Configuration, scale, and pre-stress level of the components can be adjusted for various climatic conditions. Even each façade of a building can be designed before the installation to maximize energy efficiency and user comfort.

DISCUSSION

Responsive skins that utilize the passive actuation of wood bilayers offer distinct advantages over electric or motor-driven skins. These advantages include reduced installation and maintenance costs, simplicity, and a lower carbon footprint, making them highly promising for future applications. However, passive responsive skins currently lack adaptability to both climatic and seasonal changes, as well as occupant preferences.

One approach to address this limitation is by programming the triggering humidity level for shape change during the actuator's bilayering process. By adjusting the humidity of the active material, the triggering humidity level can be set. However, once programmed, the triggering humidity cannot be reprogrammed, limiting the adaptability of the skin to seasonal changes.

To overcome this challenge, external forces can be employed to pre-stress the actuators and tune the triggering humidity. This research has demonstrated that pre-stressed bistable design by angled joints allows significant control over the threshold levels. However, a strategy to dynamically tune the pre-stress on an architectural scale is currently unknown. Such a system that can be tuned by occupants would enable both the adaptability to climatic changes and user preferences.

Limitations and Future Work

Compared to conventional building materials, the renewable and biodegradable nature of wood holds great significance for the future of the construction industry. At every stage, from forestry to commercial use, wood production generates a considerable amount of waste. Utilization of wood waste through 4D printing for the creation of responsive skin would greatly contribute to the circularity of the construction sector. However, the maximum wood content that can be used in filaments for FDM printers is limited due to the risk of nozzle blockage. This limitation has a detrimental effect on hygroscopic actuation, resulting in reduced response speed and displacement.

On the other hand, recent advancements in material and fabrication technologies have demonstrated the potential of LDM printers in wood printing. This innovation opens up the possibility of using printing materials with higher wood content, leading to improved response speed. Future works will focus on leveraging this technology to develop sustainable, large scale climate-responsive building skins.

CONCLUSION

Systematic experiments were performed to parameterize the hygroscopic actuation of 4D-printed wood-based bilayers. The knowledge gained from these experiments transferred to develop prototypes of climate-responsive skin. Two implementations, one employing coupled actuators and the other incorporating pre-stressed bistability are fabricated. Experiments in a controlled humid environment at both small and larger scales demonstrated notable improvements in response speed, enhanced control over the actuation, and increased adaptability to different climatic conditions.

REFERENCES

Cambiaso, F., & Pietrasanta, M. V. (2014). Innovative Timber Construction: Sustainability and Gigh Performance Building Skin. *International Journal of Engineering and Technology*, *6*(1), 47–54. https://doi.org/10.7763/IJET.2014.V6.664

Cao, Y., Derakhshani, M., Fang, Y., Huang, G., Cao, C., Cao, Y., Derakhshani, M., Fang, Y., Cao, C., & Huang, G. (2021). *Bistable Structures for Advanced Functional Systems*. https://doi.org/10.1002/adfm.202106231

Chen, E., Lu, G., Barnik, L., & Correa, D. (2022). Fast and Reversible Bistable Hygroscopic Actuators for Architectural Applications based on Plant Movement Strategies. *Proceedings of the International Conference on Education and Research in Computer Aided Architectural Design in Europe*, *1*, 261–270. https://doi.org/10.52842/conf.ecaade.2022.1.261

Compton, B. G., & Lewis, J. A. (2014). 3D-printing of lightweight cellular composites. *Advanced Materials (Deerfield Beach, Fla.)*, *26*(34), 5930–5935. https://doi.org/10.1002/ADMA.201401804

Correa, D., Papadopoulou, A., Guberan, C., Jhaveri, N., Reichert, S., Menges, A., & Tibbits, S. (2015). 3D-Printed Wood: Programming Hygroscopic Material Transformations. *3D Printing and Additive Manufacturing*, *2*(3), 106–116. https://doi.org/10.1089/3dp.2015.0022

Correa, D., Poppinga, S., Mylo, M. D., Westermeier, A. S., Bruchmann, B., Menges, A., & Speck, T. (2020). 4D pine scale: biomimetic 4D printed autonomous scale and flap structures capable of multi-phase movement. *Philosophical Transactions of the Royal Society A*, *378*(2167). https://doi.org/10.1098/RSTA.2019.0445

Dicker, M. P. M., Duckworth, P. F., Baker, A. B., Francois, G., Hazzard, M. K., & Weaver, P. M. (2014). Green composites: A review of material attributes and complementary applications. *Composites Part A: Applied Science and Manufacturing*, *56*, 280–289. https://doi.org/10.1016/J.COMPOSITESA.2013.10.014

Faber, J. A., Arrieta, A. F., & Studart, A. R. (2018). Bioinspired spring origami. *Science*, *359*(6382), 1386–1391. https://doi.org/10.1126/SCIENCE.AAP7753/SUPPL_FILE/AAP7753S3.MOV

Gauss, C., Pickering, K. L., & Muthe, L. P. (2021). The use of cellulose in bio-derived formulations for 3D/4D printing: A review. In *Composites Part C: Open Access* (Vol. 4, p. 100113). Elsevier. https://doi.org/10.1016/j.jcomc.2021.100113

Holstov, A., Bridgens, B., & Farmer, G. (2015). Hygromorphic materials for sustainable responsive architecture. *Construction and Building Materials*, *98*, 570–582. https://doi.org/10.1016/j.conbuildmat.2015.08.136

Holstov, A., Farmer, G., & Bridgens, B. (2017). Sustainable Materialisation of Responsive Architecture. *Sustainability 2017, Vol. 9, Page 435*, *9*(3), 435. https://doi.org/10.3390/SU9030435

Jeong, H. Y., An, S. C., Seo, I. C., Lee, E., Ha, S., Kim, N., & Jun, Y. C. (2019). 3D printing of twisting and rotational bistable structures with tuning elements. *Scientific Reports*, *9*(1), 1–9. https://doi.org/10.1038/s41598-018-36936-6

Kariz, M., Sernek, M., Obućina, M., & Kuzman, M. K. (2018). Effect of wood content in FDM filament on properties of 3D printed parts. *Materials Today Communications*, *14*, 135–140. https://doi.org/10.1016/J.MTCOMM.2017.12.016

Le Duigou, A., Correa, D., Ueda, M., Matsuzaki, R., & Castro, M. (2020). A review of 3D and 4D printing of natural fibre biocomposites. In *Materials and Design* (Vol. 194, p. 108911). Elsevier. https://doi.org/10.1016/j.matdes.2020.108911

Loonen, R. C. G. M., Trčka, M., Cóstola, D., & Hensen, J. L. M. (2013). Climate adaptive building shells: State-of-the-art and future challenges. *Renewable and Sustainable Energy Reviews*, *25*, 483–493. https://doi.org/10.1016/J.RSER.2013.04.016

López, M., Rubio, R., Martín, S., & Ben Croxford. (2017). How plants inspire façades. From plants to architecture: Biomimetic principles for the development of adaptive architectural envelopes. *Renewable and Sustainable Energy Reviews*, *67*, 692–703. https://doi.org/10.1016/J.RSER.2016.09.018

Mazzanti, V., Malagutti, L., & Mollica, F. (2019). FDM 3D printing of polymers containing natural fillers: A review of their mechanical properties. In *Polymers* (Vol. 11, Issue 7, p. 1094). Multidisciplinary Digital Publishing Institute. https://doi.org/10.3390/polym11071094

Mazzanti, V., Mollica, F., & El Kissi, N. (2016). Rheological and mechanical characterization of polypropylene-based wood plastic composites. *Polymer Composites*, *37*(12), 3460–3473. https://doi.org/10.1002/pc.23546

Méndez Echenagucia, T., Capozzoli, A., Cascone, Y., & Sassone, M. (2015). The early design stage of a building envelope: Multi-objective search through heating, cooling and lighting energy performance analysis. *Applied Energy*, *154*, 577–591. https://doi.org/10.1016/j.apenergy.2015.04.090

Menges, A., & Reichert, S. (2012). Material Capacity: Embedded Responsiveness. *Architectural Design*, *82*(2), 52–59. https://doi.org/10.1002/AD.1379

Poppinga, S., Correa, D., Bruchmann, B., Menges, A., & Speck, T. (2020). Plant movements as concept generators for the development of biomimetic compliant mechanisms. *Integrative and Comparative Biology*, *60*(4), 886–895. https://doi.org/10.1093/icb/icaa028

Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. *Energy and Buildings*, *42*(10), 1592–1600. https://doi.org/10.1016/J.ENBUILD.2010.05.007

Tahouni, Y., Cheng, T., Lajewski, S., Benz, J., Bonten, C., Wood, D., & Menges, A. (2022). Codesign of Biobased Cellulose-Filled Filaments and Mesostructures for 4D Printing Humidity Responsive Smart Structures. *3D Printing and Additive Manufacturing*. https://doi.org/10.1089/3dp.2022.0061

Tahouni, Y., Cheng, T., Wood, D., Sachse, R., Thierer, R., Bischoff, M., & Menges, A. (2020, November 5). Self-shaping Curved Folding:: A 4D-printing method for fabrication of self-folding curved crease structures. *Proceedings - SCF 2020: ACM Symposium on Computational Fabrication*. https://doi.org/10.1145/3424630.3425416

Time, B. (1998). Hygroscopic moisture transport in wood. *Department of Building and Construction Engineering*, *PhD*(February), 1–232. http://www.ivt.ntnu.no/docs/bat/bm/phd/AvhandlingBeritTime.pdf

Wichniarek, R., Hamrol, A., Kuczko, W., Górski, F., & Rogalewicz, M. (2021). ABS filament moisture compensation possibilities in the FDM process. *CIRP Journal of Manufacturing Science and Technology*, *35*, 550–559. https://doi.org/10.1016/J.CIRPJ.2021.08.011

Zuluaga, D. C., & Menges, A. (2015). 3D printed hygroscopic programmable material systems. *Materials Research Society Symposium Proceedings*, *1800*(1), 24–31. https://doi.org/10.1557/opl.2015.644