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PLEKTONIK: Plasticity and Structural Textile

Abstract

The plasticity, the malleability of matter led to the evolution of application and aesthetic possibilities. Unlike timber wood, plant *filaments* such as willow and rattan are bendable, elastic, have hygromorphic behavior, and can achieve plasticity after water absorption. These *filaments* serve as design drivers for structural textiles, loop-based material systems for architectural production, yet they are not certified for construction. We assembled finite-length lignified plant fibers into (macroscopic) active structures that respond to mechanical stress and environmental humidity. Leveraging knitting techniques and traditional materials, our fabrication process challenges conventional practices. The formation of loops in textile production techniques is a negotiation between the elasticity of the material and the specific technique employed, while the properties of the yarn contribute to the textile's overall stability. These investigations are conducted within the context of interdisciplinary exhibition making. Change of intrinsic properties of material changes researchers and visitors—to adapt and explore new possibilities. Moreover, from a scientific point of view, we explore whether the loop of the preformed filament could be likened to a monomer found in polymeric materials. By bridging insights from both the nano and macro scales, we aim to transcend the limitations imposed by scale and uncover potential knowledge transfer between the realms. The exhibition provides a platform to evaluate the performance while fostering interdisciplinary innovation.

Introduction—Filaments and Droplets

In the pursuit of future architectures, this research aims to design architectural structures that operate as extensions of living systems by focusing on formable and tensioned *active yarns.*

The new culture of materials implies active individual and collective plasticity and the capacity to take form and to give form. "It is this very plasticity, the radical instability of the human, that is the basis of its massive impact," as Beatriz Colomina and Mark Wigley state, that is based on human interdependency with artifacts.[1]

1 Beatriz Colomina and Mark Wigley, *Are We Human? Notes on an Archaeology of Design* (Zurich: Lars Müller Publishers, 2016), 23.

 https://doi.org/10.1515/9783110714883-005

This metamorphic and metabolic approach reappears on several levels in the project, which develops in an interdisciplinary environment through making, exhibiting, and textiling.

During the exhibition making process, research is informed by scientific insights at the cellular level, particularly regarding structures that define the boundaries between different entities or environments. For instance, it draws from research on the topology of swelling tissue in the outer mammal skin, where dead filamentous (threadlike) cells, corneocytes, respond to changes in humidity (see fig. 1B) as studied by Myfanwy Evans.[2] The spatial, complex tissues "exhibit variable permeability properties, actively mediating between different environments." This thermodynamic model is based on morphometric method: analyzing the form in change. To prototype these entangled looping helical filaments, rattan is selected as the material (fig. 1A).

Fig. 1: Filaments and droplets: (1A) dried bacterial biofilm grown on the resilient rattan knot that can be read in its spatial state; (1B) swollen and subsequent drying states, from Myfanwy Evans and Roland Roth, "Shaping the Skin;" *Physical Review Letters* 112 (2014), 038102; (1C) knitted wood is actuated with humidity, Living Beings project, 2020; (1D) warp-knitted scaffold showing elongation with open windows due to atmospheric water, Active Curtain Project.

The *Active Curtain* project in the exhibition *After Nature* (Humboldt Lab, Berlin 2020 – 23) featured a five-by-five meter netted structure that is an experimental setting that showcases interdisciplinary research on cellulose (fig. 1D). The exhibited projects demonstrate the controlled reversable movement of cellulose when exposed to water—in the project *Living Beings*, Nelli Singer contributed to the architectural scale with knitted wooden veneer. The research on bacterial cellulose addresses the public notion of cellulose not only as plant-based but also as microbial matter. The structure bridges architecture, design, microbiology, and material science, facilitating an *exchange* of insights into different operating scales and terminology among disciplines. The constituting spatial, tubular paths (fig. 2, left) are formed by the oversized loops (radius of five millimeters) and introduce the visitor to the scale of readable textile structure. Between construction and emergence, they form a structure reminiscent of the bacterial

2 Myfawny Evans and Roland Roth, "Shaping the Skin: The Interplay of Mesoscale Geometry and Corneocyte Swelling", *Physical Review Letters* 112, no. 3 (2014): 038102, https://doi,org/ 10.1103/PhysRevLett.112.038102.

filamentation and growth stance observed in the bio-spatial extracellular matrix in bacterial biofilm research conducted by Hengge's team.[3]

Fig. 2: Textile space mediating metabolic structures: (left) warp-knitted rattan tubular paths showcasing the Living Beings project, Active Curtain Project (right) tubular willow structure accessible also in VR, Stretching Materialities exhibition at TAT.

The long branches or *filaments,* malleable upon wetting, are preformed into stable looping segments entangled by warp knitting, an industrial knitting technique. Warp knitting is a loop forming process in which separate threads are interlocked with the neighboring parallel thread along the length of the fabric. The loops (or laps) may be open or closed. We translated the open lap path for manual knitting with pre-formed resilient fibers, rattan (and later willow). The size and spacing of the pre-formed segments are varied to determine the strength and stability of the structure. Using always the same 1.8 millimeter diameter, threads with the highest density were used at the top, followed by medium density (fig. 2, left) and lowest density as we moved downward, resulting in a loosening hanging structure with a total height of five meters. The two-meter-wide void area for a video projection of structure was bridged over (fig. 1D).

Material Landscapes

Unlike thick timber wood, plant fibers like willow twigs and rattan palm are not certified for construction in Europe and they are elastic and hygromorphic, achieving plasticity for the design of structural textiles after water absorption. Working with organic material encompasses a big picture, including landscapes, ecosystems, agroforestry, and the climate. Rattan palms, mostly liana, grow on other species (fig. 3, column 1), and are defined as non-timber forest products (NTFP), referring to biological materials

3 Christiane Sauer, Natalija Miodragović, Bastian Beyer, Iva Rešetar, Daniel Suárez, Nelli Singer, Regine Hengge, Skander Hathroubi, Michaela Eder, Cécile Bidan, exhibition project "Active Curtain," Humboldt Forum Berlin, since April 29, 2021, https://www.matters-of-activity.de/en/research/laboratories/49/humboldt-lab.

derived from forests excluding timber.[4] They are bendable and formable due to their filament structure.[5] The first Forest Stewardship Council (FSC) certified rattan plantations were established in Indonesia and Borneo in 2011.[6] Small-scale producers who collect rattan do not consider plantation grown rattan an NTFP.

In the second phase of research, and for the exhibition *Stretching Materialities*, 2021–22, more stable but formable willow (fig. 3, column 2) tree branches local to Europe were used. They are also categorized as NTFP due to their small diameter. Basketry plantations are rare and small, while SRC plantations for biomass[7] are expanding also due to willow's ability to grow on and remediate polluted soil[8] or for medicine.[9] Willow exhibits controlled growth and we can envision the preforming process to occur directly on plantations or construction sites. Its bast fibers show mechanical and thermal properties suitable for reinforcement, in addition to being biodegradable and low cost.[10] The applications of small diameter willow branches grown for biomass on an architectural scale is seen as a stance in circular economy and a step toward a post-waste society. The research aims to standardize and certify organic filaments for construction. Initial measurements are conducted. Moreover, standardizing non-uniform biological "rests," such as non-timber forest products for construction, can address the emerging need for standardization of non-uniform "human-made rests" such as textiles, plastics, and debris for construction.

Structural Textiles

Freshly harvested willow twigs exhibit remarkable flexibility, due to the high water content, and can be easily shaped into any forms. However, once the wood is harvested and dried, it becomes more rigid. We used the ancient and universal technique of

4 See "FAO's Forest Resource Assessment (2015) An international journal of forestry and forest industries," *Unasylva* 198, vol. 50 (1999).

5 Hanna M. Szczepanowska, "Deconstructing Rattan: Morphology of Biogenic Silica in Rattan and Its Impact on Preservation of Southeast Asian Art and Artifacts Made of Rattan," *Studies in Conservation* 63, no. 6 (August 18, 2018): 356–74, https://doi.org/10.1080/00393630.2017.1404693.

6 John Hontelez, EU Timber Regulation / Implementation Guide for Companies Trading FSC-certified Materials in the European Union, Revised Version (February 2018), https://ic.fsc.org/file-download.eu-timber-regulation-implementation-guide.a-13.pdf.

7 Ioannis Dimitriou and Dominik Rutz, *Sustainable Short Rotation Coppice: A Handbook* (Munich: WIP Renewable Energies, 2015), https://www.srcplus.eu/images/Handbook_SRCplus.pdf.

8 Yulia Kuzovkina and Martin Quigley, "Willows Beyond Wetlands: Uses of Salix L. Species for Environmental Projects", *Water, Air, & Soil Pollution* 162 (2005): 183–204, https://doi.org/10.1007/s11270–005–6272–5.

9 Jassem G. Mahdi, "Medicinal Potential of Willow: A Chemical Perspective of Aspirin Discovery," *Journal of Saudi Chemical Society* 14, no. 3 (July 1, 2010): 317–22, https://doi.org/10.1016/j.jscs.2010.04.010.

10 Oktae et al., "Characterization of Willow Bast Fibers (Salix Spp.) from Short-Rotation Plantation as Potential Reinforcement for Polymer Composites," *BioResources* 12, no. 2 (2017): 4270–82, https://doi.org/10.15376/biores.12.2.4270-4282.

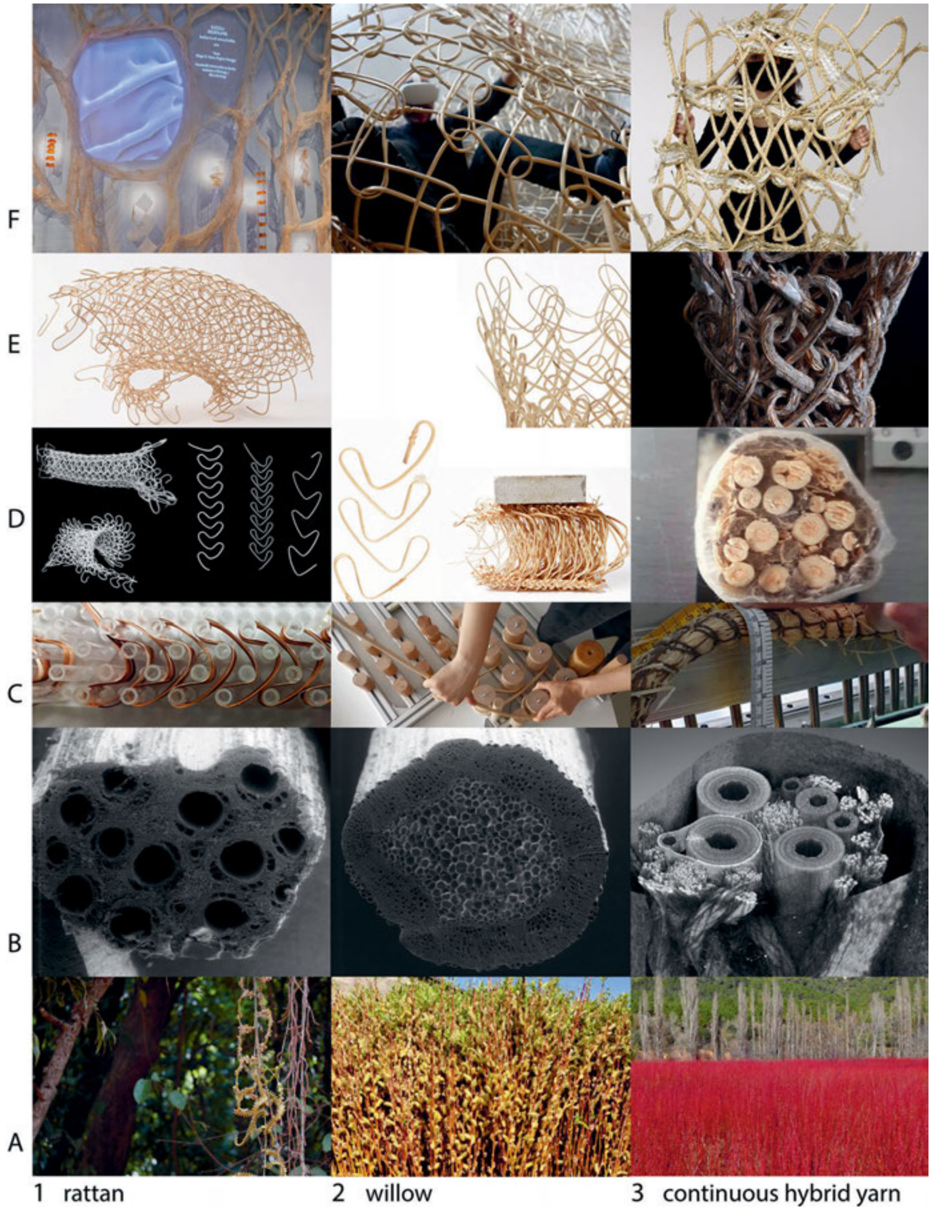

Fig. 3: Material landscapes, from agroforestry and fiber to spatial textile spatial structure: column 1, rattan; column 2, willow; and column 3, continuous hybrid yarn from finite branches.

bending dried wood[11] by applying water and for larger diameters also heat to initiate the wood plasticization. As a result, this research presents a material system for architecture production based on large-scale wood and non-wood warp-knitted structures, obtained through material plasticization and loop formation. The integration of form, active materiality, structure calibration, and bespoke fabrication methods call for a design process with a holistic approach.

Textile structures, in general, are inherently multilevel hierarchically assembled structures[12] and contain three interdependent levels at the macrolevel: fiber, yarn, and fabric. This research operates at these three levels, but we recognize the insight on the initial level of hierarchy—nano: *"Hierarchy is important because it allows materials to exhibit exceptional properties and diverse functionality through adapting structure across many different levels from nano to macro."*[13]

– At the fiber level, the project observes how moisture affects plant-based fiber. At a later stage, loop (pre-)formation, the study of the moisture conditions and hygroscopic behavior becomes a matter of particular interest and importance to this project.
– At the yarn level, the research recognized the loop as the basic building block of this material system. Thus, we explore loop formation processes based on wood bending techniques. The loop diameter (bending radius) is related to yarn thickness. Through wetting, the bending radius is reduced, and the filament "remembers" the form when dried. Hence, the wood is plasticized. In the course of our explorations, we have designed a collection of apparatuses to aid in the wetting, steaming, and bending of thin section wooden rods (fig. 3, columns 1 and 2, row C).[14] Willow stem and rattan filaments have finite lengths, therefore constraining those assemblies that demand longer threads or continuous arrangements. Here, the mono-material continuity is achieved by manually interlocking looped segments into chains (fig. 3, columns 1 and 2).

  Moreover, we present methods of manufacturing continuous wooden yarns[15] using STFI's Kemafil® technology.[16] Kemafil yarns are hybrid yarns engineered to

11 Edward W. Berry, "Notes on the History of the Willows and Poplars," *The Plant World* 20, no. 1 (1917): 16 – 28.

12 Leslie Eadie, and Tushar K. Ghosh, "Biomimicry in Textiles: Past, Present and Potential. An Overview," *Journal of The Royal Society Interface* 8, no. 59 (2011): 761 – 75, https://doi.org/10.1098/rsif.2010.0487.

13 Jane Scott, "Hierarchy in Knitted Forms: Environmentally Responsive Textiles for Architecture," *ACADIA proceedings* (2013): 361–66.

14 Robert S. Wright, Brian H. Bond and Zhangjing Chen, "Steam Bending of Wood; Embellishments to an Ancient Technique," *BioResources* 8, no. 4 (2013): 4793 – 96, https://doi.org/10.15376/biores.8.4.4793-4796.

15 Natalija Miodragović, Daniel Suárez, Nelli Singer, Regine Hengge, Michaela Eder, Christiane Sauer, "Active Yarns for Structural Textiles," poster presentation, *Bioinspired Materials Conference Proceedings* (2022).

16 R. Arnold, A. M. Bartl and E. Hufnagl, "Production of Cord and Narrow Fabric Products with Kemafil Technology," Band und Flechtindustrie 31 (1994): 48 – 52.

fulfill different performance and functional requirements.[17] The non-continuous textile and non-textile material is sheathed with selected thread, resulting in yarn with thickness up to sixty millimeters (fig. 3, column 3). Hence by programming the yarn, the coding complexity expands from geometrical to more complex behaviors and applications. These wooden yarns are also directly processed as meandering weft material on a coarse warp-knitting machine (fig. 3, column 3, row C)[18] to produce architectural surfaces.

– At the fabric level, we find the textile structure formation process. Knitting offers a multitude of tectonic arrangements. The project exploits the possibilities of warp-knitting arrangements to organize discrete programmed loops of wood material. A variety of two-dimensional warp and weft assemblies have been studied. However, the most representative one is the tricot structure.[19] After wetting, the wood and non-wood loops hold their shape while remaining partially within their elastic limit. They behave similarly to plates with out-of-plane bending resistance. As in any knitting technique, the loops interlock with their neighbors, hold their position, and create a hinged plate shell structure.

Wood and non-wood warp-knit structures lend themselves well to doubly-curved forms. The surface's positive or negative curvature is achieved through a simple hand gesture when making the textile structure. Depending on the direction in which one loop interlocks with its neighbor, i. e., from above or underneath, the loop will hinge in one order, leading to a convex or concave surface (fig. 4, right) that can be efficiently coded using a binary code, therefore programming the surface into a particular form. The spacer textile, produced also with warp-knitting technique, are part of the research (fig. 3, column 2D), the fiber properties can determine the properties of the fabric.

In fact, a broader definition that describes textiles as flexible products made primarily of polymeric (natural or human-made) fibers, is more appropriate today. However, as Julian Vincent noted, "there is a huge potential to obtain new or unusual combinations of material functions/properties by structuring a given material, rather than by changing its chemical composition."[20] In fact, textile fiber assemblies can readily provide an ideal test bed for this concept.

17 Hugh Gong, *Specialist Yarn and Fabric Structures: Developments and Applications* (Amsterdam: Elsevier, 2011).

18 Wright, Bond, and Chen, "Steam Bending of Wood," 4793–96.

19 Yordan Kyosev, *Warp Knitted Fabrics Construction* (Boca Raton, FL: CRC Press, 2019), https://doi.org/10.1201/9780429094699.

20 Julian Vincent, "Biomimetic Materials," *Journal of Materials Research* 23 (December 2008): 3140–47, https://doi.org/10.1557/JMR.2008.0380.

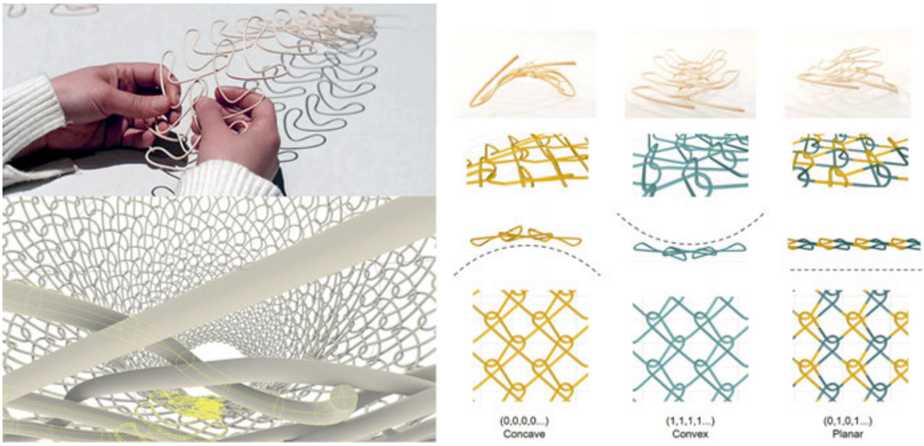

Fig. 4: Structural textile: interlocking order of loops determines the form concave and convex.

Polymeric Nature and Assembled Knitted Structures

While dealing with knitted structural textiles, we were repeatedly reminded of the other synthetic or natural structures consisting of linkage of many repeating units. An observer will notice the repeating units, as reminders of a polymeric material where chemical units known as monomers are chained together to create large chains of macromolecules.

We observed two major parameters affecting the activity of knitted wooden structures. These are, namely, the "humidity uptake" and the "actuation specific knitting design." In principle, the "humidity uptake" is a property of the matter that exists at its smallest scales. More specifically, this is in relation to the hydrophilicity of the molecular structure of the matter. In the case of wood as the subject matter here, the cellulose-based structure is the main hydrophilic structure that comprises 40 to 50 percent of the wood's fiber weight (fig. 5A). This water-friendly polymeric structure consists of repeating units of β-glucose, which are simple monosaccharides, forming polymeric chains and consequently cellulose fibers and cellular walls within plants.[21] The collective emergent activity of these hydrophilic components demonstrates a water absorption capacity that is dependent on the environmental water content (humidity).[22] The

21 Yoshiki Horikawa, "Structural Diversity of Natural Cellulose and Related Applications Using Delignified Wood," *Journal of Wood Science* 68, no. 54 (2022), https://doi.org/10.1186/s10086-022-02061-2; Jifu Wang, Daihui Zhang, and Fuxiang Chu, "Wood-Derived Functional Polymeric Materials," *Advanced Materials* 33 (2021), 2001135, https://doi.org/10.1002/adma.202001135.

22 Matthew J. Harrington et al., "Origami-like Unfolding of Hydro-actuated Ice Plant Seed Capsules," *Nature Communications* 2, no. 33 (2011), https://doi.org/10.1038/ncomms1336.

humidity uptake from the environment is then the main trigger for the process of structural expansions at cellular levels and consequently structural dynamics, or conformational changes of the structures.

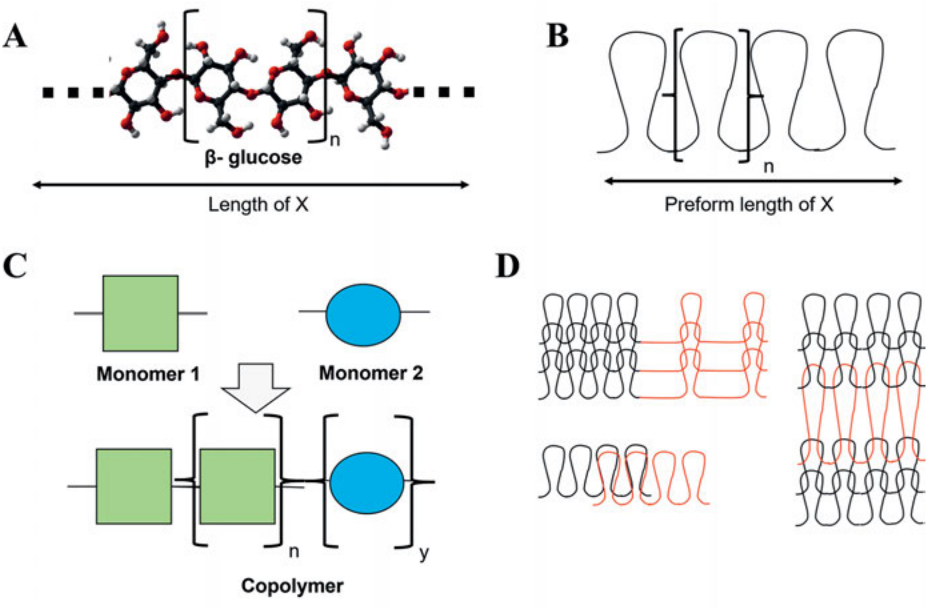

Fig. 5: (5A) the polymeric structure of the cellulose as the polymeric building block of the wood; (5B) repeating loop structure of the preformed wood before knitting and assembling into larger structures; (5C) co-polymeric structure based on two different monomers; (5D) co-knitted preforms of different geometries for specific abilities and activities.

On the other hand, the concept of "actuation specific knitting design" involves a deliberate framework of bending designed to imbue the structure with active properties. The architect or designer envisions and constructs the loops and their arrangements to control the extent and direction of the structure's response to environmental stimuli. Through the knitting/bending process, units are interconnected and chained, allowing for the incorporation of diverse geometries, sizes, and humidity uptakes, thus enabling controlled collective emergent activities, namely here "movements." This knitting process mirrors the assembly of preformed material strands and evokes the analogy of polymerization, where smaller polymer chains undergo growth to form longer chains capable of both withstanding stress and or dynamic behavior under the stimuli.

In this discussion, we highlight two key similarities between polymeric structures and knitted wooden structures that we observed to be independent of scale. These similarities are as follows: 1) Knitting process involves preforms of different geometry being combined (figs. 5C, D). 2) An activity of structures is emerged when triggered by the environmental water interaction (fig. 6). To underscore this point further, figures

5C and D exemplify the resemblance between a copolymer system comprising two different monomers and a co-knitted preform structure.

We propose that, similar to copolymer structures designed by polymer engineers, chemists, and physicists, knitted wooden structures, crafted by textile designers, also harness the amalgamation of various loop geometries, materials, and sizes to create dynamic frameworks of activity, whether it is load bearing, aesthetic, or stimuli-responsive.[23] We describe this as a "bidirectional inspiration junction". Recent experimental demonstration of the polycatenane systems as a direct demonstration of polymerization of interlocked loops of matter by Laura Hart et al. showed the possibility of achieving the interlocked assembly at nanoscale.[24] These structures indeed show multiple emerging modes of activity and vibrations as a result of stimulations and environmental changes. Furthermore, as a more classical example, the water content around a natural polymer chain, such as various proteins or DNA, is known to affect polymeric structure conformations and folding thereof, both of which are important parameters in the functionality of these molecules at their scales.[25]

The preform knitting and subsequent assembly into larger, complex structures with specific properties and functionalities captivate not only the realm of macrostructures but also serve as a source of inspiration for emerging nanostructures based on polymeric chains. A prime example lies in the field of DNA origami nanostructures, which has garnered considerable attention in the past three decades as a captivating avenue for nanoscale construction, manipulation, and the demonstration of geometrical control. This design perspective has captivated natural scientists from diverse disciplines such as chemistry, biology, and physics, empowering them to attain precise control over matter at the nanoscale. Given the existence of tools and knowledge for creating loops and self-assembly structures at the nano scale, these techniques hold significant potential for driving the synthesis of nanomaterials through a "top-down design" approach. This opens up new frontiers in material synthesis, leveraging the synergy between macrostructure and nanostructure design principles. Since the mechanical and structural investigation of the designed macrostructures such as preform knitted structure discussed here are easier and less costly, transfer of those new designs with specific emergent activities to the nano scale would be interesting and rewarding case studies.

We propose that fostering a new culture of materials involves not only the bottom-up design of materials but also the integration of "macroscale designers," such as textile designers and architects, in a collaborative, multidisciplinary environment alongside natural scientists. By adopting a top-down strategy or inspiration from structural

23 Nelli Singer, "Living Beings," master's thesis (Weißensee Kunsthoschschule Berlin, 2020 Master Studio Christiane Sauer, 2020).

24 Laura F. Hart et al., "Material Properties and Applications of Mechanically Interlocked Polymers," *Nature Reviews Materials* 6, (2021): 508 – 30, https://doi.org/10.1038/s41578-021-00278-z.

25 Marie-Claire Bellissent-Funel et al., "Water Determines the Structure and Dynamics of Proteins," *Chemical Reviews* 116, no. 13 (2016): 7673 – 97, https://doi.org/10.1021/acs.chemrev.5b00664.

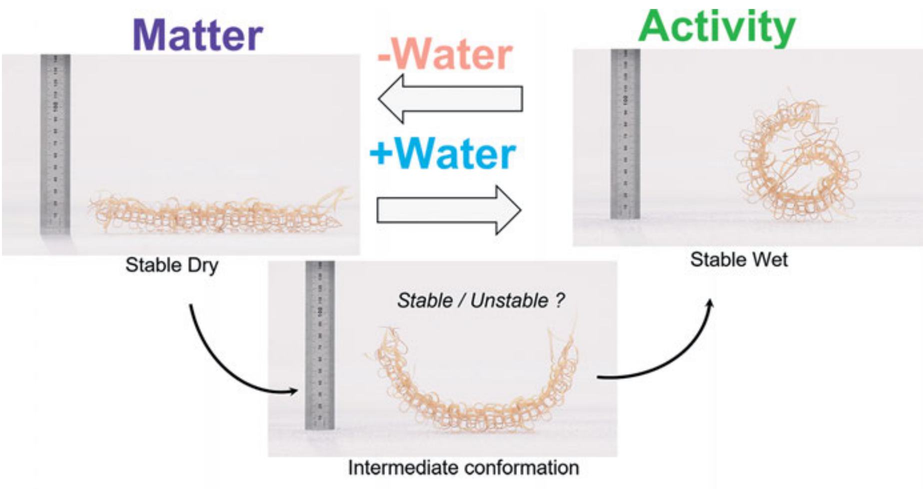

Fig. 6: Conformation balance observed in knitted wooden structures. The intermediate conformation may or may not be stable depending on the design and the humidity of the environment.

designers at macroscale, novel nanostructures can be achieved, potentially giving rise to entirely new materials and their respective emerging activities. These nanostructures will possess tangible macroscale counterparts that can be structurally modified and tested. An excellent example of this concept is the physical unification and interlocking process, which leads to the emergence of active matter, reflecting the latest rethinking in material science. Moreover, this approach encourages innovative methodologies in multidisciplinary cooperation. Additionally, morphometric-based approaches hold promise for architectural design, expanding the realm of design practices. For example, the physical unification and interlocking process creates an emergence of behavior that not only demonstrates *active matter* according to the latest rethinking, but also new methodologies in multidisciplinary cooperation that are material- and application-oriented.[26]

Whether at the building block scale of the source material or within the intricate locks and loops of knitted and assembled structures, the significance of multidisciplinary approaches cannot be disregarded. Furthermore, the plasticity of the material unveils new insights into loop-based textile techniques, where stable loops serve as initial units. Linking water molecules, environmental water, fibers, and circular economy principles to bioremediation supports the argument for a multiscale approach. Thus, this approach investigates a departure from traditional hierarchical approaches, transitioning from fiber and yarn to fabric, toward embracing multiscale modeling.

26 Mohammad Fardin Gholami et al., “Rethinking Active Matter: Current Developments in Active Materials,” in *Active Materials*, ed. Peter Fratzl, Michael Friedman, Karin Krauthausen, and Wolfgang Schäffner (Berlin: De Gruyter, 2021), 191 – 222, https://doi.org/10.1515/9783110562064-011.