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HempHalo: Designing Lightweight CNC-Knitted Architectural Canopy System with Hemp

Yuliya SINKE*, Valentine TROI[b], Avinash MANIAN[c], Lena FRITSCH[a] [a]
Zelma BALODE[d], Ilze BALTIŅA[d], Mette RAMSGAARD THOMSEN[a], Martin TAMKE[a]

* ,[a] CITA – Center for IT and Architecture, Institute of Architecture and Technology, The Royal Danish Academy,
Philip de Langes Alle 10, Copenhagen 1435, Denmark, ybar@kglakademi.dk

[b] GROWNLab, Institute of Engineering Design and Materials Science, University of Innsbruck,
Technikerstrasse 13, 6020 Innsbruck, Austria.

[c] Research Institute for Textile Chemistry and Textile Physics, University of Innsbruck.
Hoechsterstrasse 73 6850 Dornbirn, Austria

[d] IAD Institute of Architecture and Design, Riga Technical University. Ķīpsalas iela 6, Riga LV-1048, Latvia.

Abstract

This paper presents *HempHalo*, an umbrella-like canopy prototype, exploring hemp as a sustainable alternative for membrane tensile structures. The proposed system is made of CNC-knitted membranes from hemp yarn and hemp-based pultruded rods. Both materials are additively manufactured: the membrane production employs advanced CNC-knit technology with multi-resolution material strategies to accommodate the challenging properties of hemp yarn, while the rods advance the profile pultrusion processes established in the industry. This hybrid coupling enables the canopy to achieve structural performance and spatial definition with minimal material mass and waste. The system operates through an active-bending rod–membrane interaction, eliminating hinges and mechanical fastening. The interplay between bio-based knitted textiles and hemp rod mechanics presents a novel hybrid system for tensile membranes and is informed by natural material characterisation through mechanical testing of yarn and knitted textiles and the pultruded rods coupled with digital design and fabrication techniques.

Keywords: hemp, CNC-knitting, tensile membranes, active-bending hemp rods, architectural canopy, shading

Figure 1: HempHalo Prototype for Bio-Based Architectural Canopy System, made from hemp 100% fibers

1. Introduction

Recent research in novel material systems, spatial structures and textile architecture has increasingly turned toward bio-based materials as viable alternatives to carbon intensive composites and synthetic materials [1]. Within this context, natural fibres, specifically hemp, offer a balance between ecological and structural performance. Hemp fibres are distinguished by the possibility of extracting long fibres, which contribute to improved mechanical properties and higher material strength. In comparison to other widely used natural fibres, such as flax and cotton, hemp presents several environmental advantages, including low agricultural maintenance requirements, reduced CO_2 footprint, rapid growth cycles, and high fibre yield per unit of land. Hemp cultivation requires little to no pesticides, is naturally resistant to many weeds and pests, and additionally contributes to soil regeneration while functioning as a carbon sink. Hemp fibres have long been recognised for their low density, strength, durability, and environmental resistance, indicating strong potential for architectural applications requiring lightweight yet structurally active material systems.

Figure 2: Vision of the double-layer canopy system using 100% hemp-based CNC-knitted differentiated membrane and hemp pultruded rods

Despite these advantages, hemp remains underutilised in architectural and construction applications, particularly in design-driven contexts. This is partly due to its lower mechanical performance compared to fossil-based materials, but also the lack of mature infrastructures for long-fibre processing suitable for yarn and textile production. This gap is linked to the historical loss of industrial knowledge following prolonged regulatory restrictions on hemp cultivation. Although industrial interest is re-emerging, processing and spinning industries remain less developed than for flax, requiring further advancements to enable stable long-fibre processing and scalable high-performance yarn production. Nevertheless, ongoing investigations aim to stimulate innovation, technological refinement, and supply-chain development.

Hemp is also perceived as coarse and aesthetically inconsistent, contributing to its marginalisation in textile and architectural design contexts where precision and uniformity are prioritised. Rather than framing these characteristics as limitations, this research reconsiders hemp as both a design and structural material through a canopy system case study.

The investigation focuses on identifying appropriate scales, tectonic strategies, and application contexts that align with hemp's intrinsic properties, rather than replicating synthetic material performance. The aim is to explore how hemp can be meaningfully integrated into architectural systems through controlled processing and fabrication, contributing to new spatial and design possibilities. For that the *HempHalo* prototype combines a CNC-knitted hemp membrane with a supporting structure of hemp-based composite rods, forming a coherent tensile system for lightweight shading applications (Figure 1, Figure 2).

2. State of the Art

Figure 3: State of the art in short hemp fiber applications as fillers, insulation jacket lining (Salewa/Imbotex), stitched fibre mats for composite applications (FUSE, SPURart), needle punched felt for geotextiles (Seidemann), hemp blended yarns for garment (Candiani, Lenzing)

Only a small number of producers in Europe currently manufacture consistent long hemp yarns, and these yarns are predominantly classified for weaving rather than knitting due to their high stiffness and variability. Consequently, hemp long fiber yarns remain largely excluded from CNC-knitting, that rely on yarn uniformity and controlled behaviour. This exclusion is significant because knitting offers a fundamentally different approach to material performance. Unlike woven systems, where the elastic and form-active behaviour can solely be achieved through fibre flexibility, knitting can generate this through loop geometry by redistributing stiffness *parameters on the surface.* This creates the possibility of using stiff long-fibre hemp yarns within spatial and structurally active textile systems. At the same time, recent developments in digital design and fabrication research, with CNC-knitting and robotic fibre placement, have demonstrated how *long*-fibre orientation and *digital* fabrication logic can be integrated into high-performance architectural systems (Figure 4). These novel tectonic structural and hybrid systems demonstrate how renewable natural materials can meet increasingly demanding architectural performance criteria [2], [3], [4]. However, these developments involve *flax*, while hemp has received far lower attention.

While flax established long-fibre processing routes enable high-performance yarns, rovings, and structural reinforcement products and have already undergone substantially technological development in both textile and composite applications, however the dominant part of the annual flax production is reserved for fashion. This complicates the sourcing and the using of flax for architectural purposes. While flax-based processing concepts provide an important technological reference framework for the further development of comparable hemp-based reinforcement systems, the hemp fibres are ultimately longer than hemp and provide therefore space for development of even more performative applications.

Figure 4: State of the art in flax-fiber based architectural investigations with the focus on fiber performance, aesthetics and exposure. Left to right: ICD-ITKE Research Pavilion 2024, livMats Pavilion 2024, Necto 2025.

Current tensile membrane architecture practice relies predominantly on synthetic materials such as PVC-coated fabrics and glass-fibre reinforced membranes. While earlier lightweight constructions, e.g. cotton-based tents, demonstrate the historical use of natural fibres in tensile systems, these applications have not been translated into contemporary high-performance architectural membranes. As a result, hemp remains largely absent from the market of structurally active, spatially expressive and aesthetically pleasing textile systems in architecture. By combining material investigation, computational design, and digital fabrication strategies, *HempHalo* aims to expand the design space of hemp-based products and to position hemp as viable material for design of architectural textile systems.

3. HempHalo – Design and Prototyping

3.1. HempHalo as a Hybrid System for Bio-Based Shading Canopies

HempHalo is a prototype that investigates a bio-based architectural system for CNC-knitted shading canopies. The design is conceived as an umbrella-like structural element composed of three interdependent components (Figure 5): (a) CNC-knitted textile membrane made from 100% hemp yarn, (b) hemp-based composite rods acting as primary structural and bending elements, and (c) localised 3D-printed connection details that ensure controlled interaction between textile and rod system.

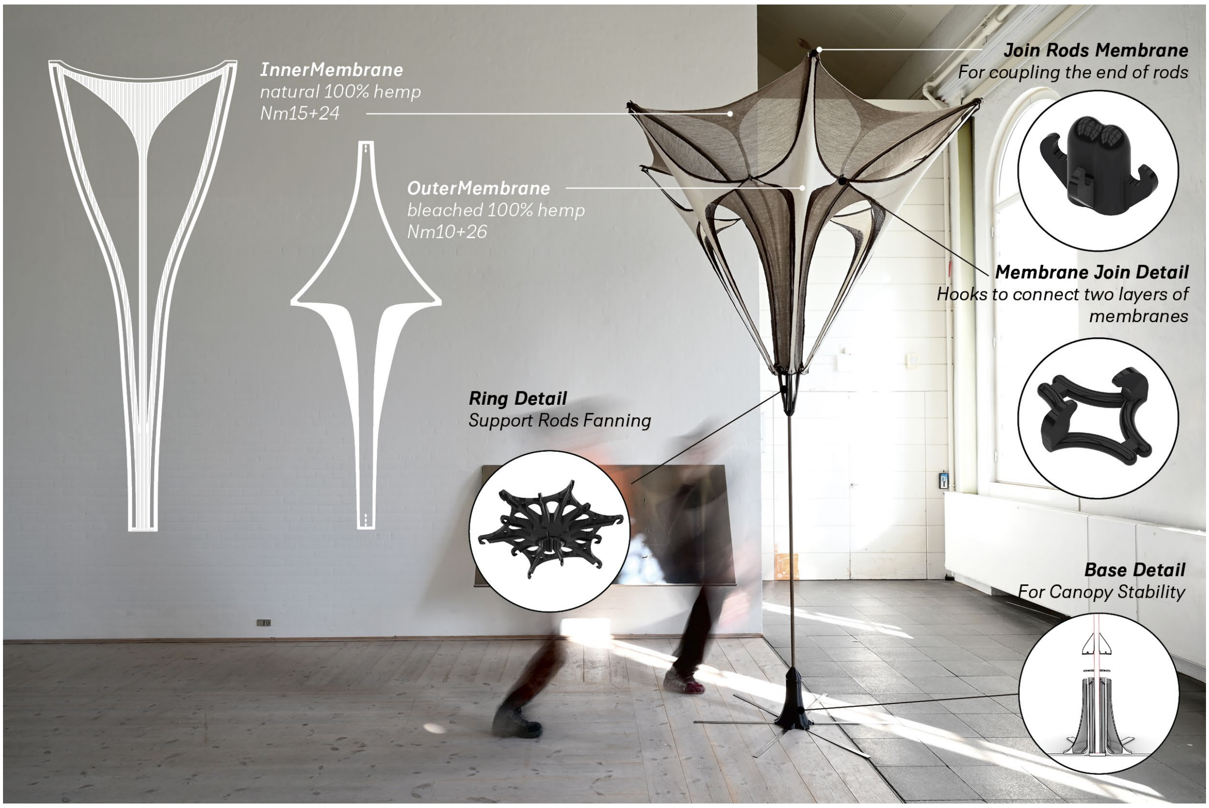

Figure 5: HempHalo components

The composite rods are elastically bent and structurally stabilised through the pre-tensioned textile membrane. In this system, the textile and rod components operate in mutual dependency: the rods together with textile skin generate form and curvature, while the membrane provides restraint, tension, and covering spatial solution. The design therefore explores a hybrid equilibrium system in which material behaviour, geometry, and fabrication constraints are co-developed. Instead of treating the textile and rod as separate subsystems, *HempHalo* investigates their integration into a structural hybrid as system for form-active, lightweight, bio-based canopy applications.

3.2 Hemp Halo Textile Membrane. Design, Prototyping and Yarn Selection

3.2.1 Structural Organisation of the Tensile System

The textile component of HempHalo system consists of two CNC-knitted membranes: the *InnerMembrane* and the *OuterMembrane* (Figure 6). Both are produced using 100% hemp wet spun long fiber yarn but are differentiated through geometry, knit structure, and yarn composition to fulfil distinct structural roles within the canopy system.

Figure 6: Two Textile Membrane Layers of the HempHalo

The *InnerMembrane* forms the overhanging geometry in interaction with the bent hemp rods, integrated into edge channels within the textile. This membrane contributes to spatial enclosure and controlled shading while maintaining a relatively lower stress regime due to its structural support from the rod system. The *OuterMembrane* functions as a tensioning and form-activating belt-like element and generate the primary pre-tension forces that control rod deformation and global system stability. It is also structurally and visually coupled to the *InnerMembrane* through arm-like connections, reinforcing both mechanical interaction and a layered architectural expression.

3.2.2 Yarn Selection and Material Composition

Both membranes are knitted from custom combinations of 100% hemp yarns with varying linear densities provided by leading European spinning companies of Safilin and Linificio di Canapificio. The aim for yarn combination is to tune the stiffness, structural capacity, and processability and fabrication, while maintaining full bio-based material consistency.

The *InnerMembrane*, operates under lower stress conditions and uses a combined yarn system resulting in yarn count of 9.2 Nm (2-ply configuration of 15Nm + 24Nm). The *OuterMembrane*, subjected to higher tensile forces due to its role in rod actuation, and therefore uses a thicker yarn combination with a yarn count of 7.2 Nm (2-ply configuration of 10Nm + 26Nm). Both membranes incorporate a high-contrast dark brown 2-ply hemp yarn (24/2 Nm equivalent) for the edge definition. The dark brown edges serve both structural and manufacturing functions, ensuring stability during shaping operations and facilitating controlled narrowing and widening during knitting process on a gauge 12 (E6.2 needles

E10) STOLL CNC-knitting machine. The body of both membranes is knitted using a 1×1 needle selection strategy (half-gauge of 12), which increases loop spacing and accommodates the high stiffness of the hemp yarns. This configuration is essential to ensure manufacturability – for forming the loops during the production and structural reliability during the deployment.

3.2.3 Yarn Preparation and Knittability of Hemp

Hemp yarn presents challenges in loop formation during knitting, as confirmed through experimental prototyping and reported in literature [5]. While cottonisation and fibre blending can improve processability, these approaches reduce the mechanical advantages of long-fibre hemp. In contrast, *HempHalo* exclusively employs long-fibre hemp yarns in order to preserve structural performance. To improve knittability, the yarn is pre-conditioned through controlled moisture treatment prior to fabrication. This involves heat-assisted humidification of the yarn bobbin followed by rewinding with simultaneous waxing to stabilise moisture content of the yarn. This process significantly improves loop formation and reduces breakage and undesired holes during CNC-knitting (Figure 7).

Figure 7: Hemp yarn preparation activities to ensure knit quality

3.2.4 Form-Finding, Knit Direction and CNC-Knit Fabrication Logic

Both membranes are directly shaped through CNC-knitting informed by a form-found geometry and further refined through iterative 1:1 scale prototyping. Due to the anisotropic and nonlinear behaviour of knitted hemp textiles, precise planarisation remains non-trivial and requires empirical adjustment. The *InnerMembrane* is knitted from its widest section toward the narrow edge to optimise material usage and ensure controlled take-down during the production. The *OuterMembrane* adopts a cruciform geometry, minimising waste material in non-structural regions while maintaining stable production conditions and uniform tension distribution during knitting.

3.2.5 Knit Structure and Mechanical Behaviour

Knit structure plays a critical role in defining the mechanical response of the textile membrane, as loop geometry directly influences stiffness, contraction, and load distribution. The *InnerMembrane* is knitted in a piqué lacoste structure (Knit D, F in Table 1), selected for its near-isotropic behaviour and reduced contraction forces. This is essential to avoid counteracting the pre-tension introduced by the rod system. Early prototyping with homogeneous lacoste structures revealed insufficient contraction in the upper membrane zones, leading to sagging. Consequently, a locally differentiated interlock structure (Knit B, E) is introduced in the central region to increase tension and stabilise geometry. In contrast, the *OuterMembrane* is fully knitted in interlock structure using the higher-strength yarn combination (Knit A, C). This configuration provides low elongation along the primary force direction, ensuring resistance to tensile loads generated by rod deformation. At the same time, the perpendicular flexibility of the interlock structure allows controlled adaptation at connection points with the *InnerMembrane*.

		Load @ Break (N)	Std Dev	Elongation @ Break (%)	Stdev
Knit A	K_**wale**_interlock _Y_H100_**10Nm+26Nm**_bleached	**842.04**	51.97	97.58	4.97
Knit B	K_wale_interlock _Y_H100_15Nm+24Nm_natural	643.99	91.94	86.80	4.28
Knit C	K_course_interlock _Y_H100_10Nm+26Nm_bleached	585.14	32.44	253.81	4.77
Knit D	K_wale_**piquet** _Y_H100_15Nm+24 Nm_natural	264.13	38.51	**74.21**	6.83
Knit E	K_course_interlock _Y_H100_15Nm+24Nm_natural	469.21	48.73	225.12	10.82
Knit F	K_course_**piquet** _Y_H100_15Nm+24Nm_natural	382.81	31.12	**74.86**	4.61

Table 1: Uniaxial tensile test results of knit structures in wale and course direction (interlock, piquet lacoste) utilized in *HempHalo* Prototype

	Nm10+26 *(interlock)*	**Nm15+24** *(interlock)*	**Nm15+25** *(piquet lacoste)*
Mean burst strength (N)	735	630	315
Burst strength SD	295	95	45
Burst strength CV (%)	40.5	14.8	14.8
Mean jaw displacement at rupture (mm)	39	27	20

Table 2: Three-dimensional Burst tensile test results of the knit structures, utilized in *HempHalo* prototype

3.3 *HempHalo* Composite Active Bending Rods

As a structural complement to the CNC-knitted hemp textile components, the *Hemp Halo* demonstrator is realized using hemp-based pultruded composite profiles, forming the load-bearing framework of the lightweight canopy structure. The design required 12 x 8 mm solid rods of the round profile for the radial umbrella members and a 20 mm hollow tube, serving as the central support element. The rods are created in a unique development of hemp fiber pultrusion process, created within research project.

3.3.1. Production and performance of pilot pultruded hemp-based rods

Pultrusion method is able to produce continuous fibre-reinforced profiles with highly aligned reinforcement, constant cross-sections, and high fibre volume fractions. In the pultrusion process, continuous fibre rovings are guided through a resin bath to ensure complete impregnation and subsequently pulled through a heated forming die, where the final profile geometry is defined and the thermoset matrix is cured under the controlled thermal conditions. This continuous manufacturing approach enables the production of endless composite profiles with high geometric precision, low geometric variability, and consequently highly reproducible mechanical performance (Figure 8).

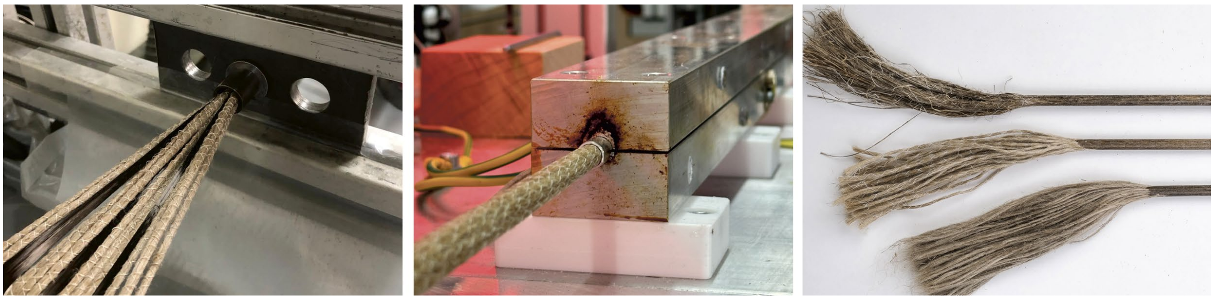

Figure 8: Hemp-fiber based pultruded rods: Fiber selection, process of making and assembled skeleton with restraining ropes

To investigate hemp-based pultrusion under different production conditions, the profiles were intentionally manufactured with two complementary industrial partners. The pilot production route involved the large-scale pultrusion manufacturer CG Tec, enabling the validation of industrial processability while addressing the inherent material variability of plant-based reinforcements under industrial manufacturing conditions. In parallel, a second route was pursued with Manaomea, specialized in small-batch composite prototyping using a 98% plant-based polyester resin system, enabling the investigation of profiles with significantly increased renewable material content.

Manufacturer	Mat.	Ø	V^f	ρ	E^{flex}	E^{spec}	σ^{flex}	σ^{spec}
		mm	vol.-%	g cm⁻³	Gpa	GPa cm³ g⁻¹	Mpa	MPa cm³ g⁻¹
Manaomea	Hemp	8	38.7 ± 3.3	1.19 ± 0.01	16.96 ± 0.43	14.2 ± 0.4	180 ± 8	151 ± 7
CG TEC	Hemp	8	55.5 ± 0.4	1.32 ± 0.01	26.73 ± 0.84	20.3 ± 0.5	339 ± 13	257 ± 9
CG TEC	Glass	8	62.1 ± 0.7	2.04 ± 0.01	43.93 ± 0.65	21.5 ± 0.3	840 ± 24	410 ± 10

Table 3: Results of the three-point bending test on pultruded rods

For both manufacturing routes, Terre de Lin hemp rovings in two linear densities (2400 tex, 1000 tex) were used. A primary objective was achieving the highest possible fiber volume fraction V^f in order to maximize the stiffness while simultaneously improving environmental performance. Mechanical performance of 8mm rods was evaluated by three-point bending tests according to an adapted DIN EN ISO 14125, with six specimens per configuration. Commercial glass-fiber pultruded rods manufactured by CG Tec were additionally tested as a benchmark and compared in Table 3.

3.4 HempHalo Prototyping the System in 1:1

3.4.1. Design of the support 3d printed elements for the rods

The interconnection of the hemp rods is secured by custom developed 3d printed PLA elements, which are designed to maximise the canopy overhang within the length limitations of the pultruded hemp rods (2m). To achieve this, 4 types of custom connector details were developed and continuously refined throughout the prototyping process in response to structural behaviour, assembly requirements, and material performance (Figure 5). The overarching design goal, was an ease of assembly, resulting in friction based joints of PLA to PLA, pultruded rod to PLA and hooks as mechanism that connects to the membrane. The *Base Detail* stabilises the HempHalo structure through a hollow foot designed to accommodate 10kg of small lead pellet balls, as ballast, that acts as counterweight to the cantilever of the umbrella. The base can be filled and emptied of these allowing for easy transport. The *Ring Detail*, positioned at the top of the central rod, accommodates twelve thinner hemp rods arranged radially. Each pair of rods, integrated into the membrane edge, is coupled at the top through integrated hooks that maintain the tensioning of the textile membrane. In addition, custom 3D printed PLA hooks are sewn onto specific areas of the membrane to connect the textile layers.

3.4.2 Incremental Prototyping of Textiles

Textiles were also incrementally prototyped for tuning the dimensions of the *InnerMembrane*. The Cut-and-sew strategy, widely used in fashion industry for garment construction from homogeneous textile, supported rapid, cost-effective, full-scale prototyping, while the CNC-knitted membranes were under development. Pinning the neoprene panels on to the rod structure demonstrated mutual dependency between the textile and the rods: increasing the panel width produced a lower and wider structure with greater overhang, while reducing the width generated a higher, more contracted radial configuration, limiting the desired overhang of the *HempHalo* structure. This exercise helped to approximate the panel width, despite the method being not fully suitable for prototyping the overall balance of forces, as the weight of the neoprene panels exceeded that of the hemp-knitted panels and affected the behaviour of the rods by altering the structural response. The final tuning was done with CNC knitted panels. The length of the belt-like *OuterMembrane* is defined by measurements from the prototype, linked to the required bending and pretension of the inner membrane layer (Figure 9).

3.4.3 Assembly Design and Process

The *HempHalo* canopy is configured for rapid deployment through its active-bending rod–membrane interaction, eliminating hinges and mechanical fastening. The system relies on the pre-tensioned *InnerMembrane* and belt-like *OuterMembrane* to induce and stabilise the form-active geometry.

Assembly is performed at ground level and begins with erecting the central rod and positioning the integrated membrane–rod package onto the Ring Detail. By engaging the *OuterMembrane* with the ring hooks, pre-stress is introduced, activating rod bending and tensioning both membrane layers into a stable configuration. The lightweight, compact system can be transported in a ski bag and assembled in under 10 minutes by mostly a single person.

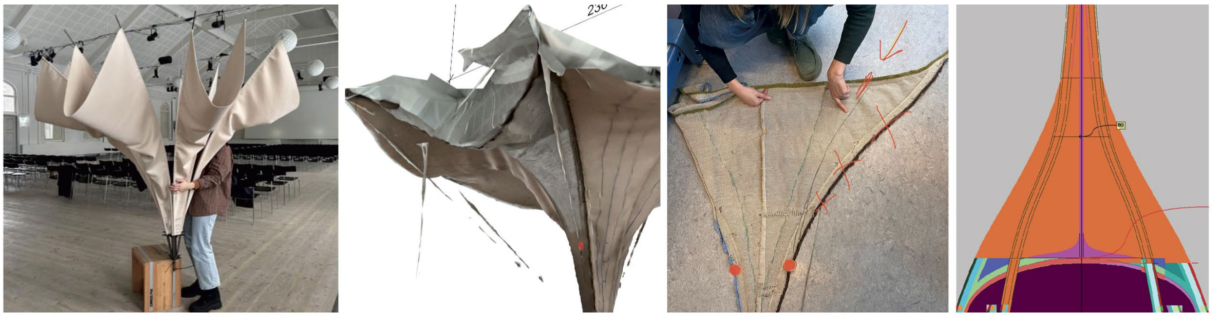

Figure 9: Incremental prototyping method for the CNC-knit textiles and the hybrid system of HempHalo with active bending rods

4. Conclusion

HempHalo demonstrates the potential of hemp as a bio-based material system for lightweight architectural membranes through the integration of CNC-knitted hemp textiles and hemp-based pultruded active-bending rods. The project contributes a hybrid structural approach in which textile membranes and bending-active composite elements operate as an interdependent system for form generation, pre-tensioning, and spatial lightweight enclosure weighing 6,5kg. The prototype demonstrates a distinct architectural expression achieved through the interplay of material behaviour, knit structure, and colour choices. The strategic use of contrasting yarns and differentiated knit patterns contributes to a visually legible and aesthetically expressive system.

A key contribution of this research lies in demonstrating the feasibility of CNC-knitting with 100% long-fibre hemp yarn and novel fiber based pultrusions. Through moisture pre-treatment and knit process adaptation, hemp yarn, traditionally considered unsuitable for knitting was successfully integrated into a digitally controlled knit fabrication workflow. This expands the applicability of CNC-knitting technologies to stiffer currently available yarns, enabling new possibilities for complex, high-resolution textile tensile structures.

The developed CNC-knitted textile system follows a differentiated material logic, where higher-strength yarns and higher strength knit structures are allocated to high-tension regions, while the thinner and isotropic surface configurations are assigned to non-structural regions of the canopy. This material allocation aligns with the canopy structural demand, demonstrating the potential of CNC-knitting as a tool for functionally graded textile systems. However, the textile membrane part of HempHalo in its next iterations would greatly benefit from the potentials of integrating the structural analysis into the knit patterning to even further tune the material allocation strategies and reinforce the empirical assumptions used in HempHalo for material distributions.

At the same time, the prototype revealed current limitations of hemp-based systems, particularly regarding rod stiffness, creep behaviour, and the achievable level of membrane pre-tension. Future development would benefit from integrating structural analysis more directly into knit pattern generation, increasing rod stiffness for ensuring greater canopy overhang, and refining the tectonic organisation of the restraining membrane system to improve spatial efficiency and structural performance.

Beyond its technical contributions, *HempHalo* positions hemp not only as a sustainable substitute for synthetic materials, but as a material with distinct structural, aesthetic, and tectonic potentials when engaged through appropriate computational design and fabrication strategies. By combining renewable fibres, digital fabrication, and lightweight structural principles, the project proposes a new direction for breathable, translucent, and structurally active bio-based architectural membrane systems, while contributing to the broader reactivation of hemp as a regional material resource within European manufacturing and construction contexts.

Figure 10: 3D Scanning documentation of the Final Prototype Assembly of *HempHalo* for further evaluation of the tolerances

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