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# CNC-knitted textiles for adaptive building envelopes: material programming and interdisciplinary design strategies

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CNC-knitted textiles present emerging opportunities for adaptive building envelopes due to their programmability at the stitch level and their capacity to generate diverse material behaviours. While knitting enables radical transformations in geometry and expression directly within the textile structure, this potential remains largely unexplored at architectural scale. This study investigates how these qualities can support environmentally responsive faades tailored to project-specific and local performance needs. Through a research-by-design methodology, the project integrates architectural, textile, and engineering expertise to develop rib-based CNC-knitted structures using sustainable mono-material yarns intended as alternatives to fossil-fuel-based elastomeric components. Iterative prototyping was employed to analyse reversible elasticity, dual-state behaviours, and fabrication strategies enabled by seamless, waste-minimal CNC-knitting. The novel architectural surfaces are implemented in an active bending structure and enable significant geometric change without conventional hinges or composite layering, supporting expressive material responses aligned with local environmental conditions. The Manta-Ray prototype exemplifies this capacity: it shows how knitted structures can function as adaptive faade elements, achieving large-scale shape change for solar shading with only minimal actuation input. The study identifies the technical, material, and collaborative frameworks necessary to transition CNC-knitted textiles from experimental prototypes toward deployable faade systems. Their inherent adaptiveness, material efficiency, and architectural expressiveness position CNC-knitted textiles as a promising strategy for responsive and sustainable building envelope design.

## KEYWORDS

adaptive architecture, CNC knit, elastic membrane material, interdisciplinary methods, material design

# 1 Introduction

The aging building stock in Europe, combined with the challenges of climate change and increasing periods of solar exposure and heat in many regions, necessitates a transformation of the built environment to improve its performance under these conditions. This transformation must occur with minimal environmental impact, reduced material consumption, and without reliance on fossil-based resources. Instead, it should prioritize renewable and sustainable materials.

Lightweight, textile-based adaptive structures offer a promising approach to dynamic sun shading. Yet, current material choices remain stagnant—dominated by rigid, fossil-based systems designed for large-scale installations. Prevailing solutions, such as roller blinds and louvers, limit both adaptability and aesthetic potential. This constraint conflicts with initiatives like the New European Bauhaus, which emphasizes beauty and cultural value in sustainable design.

While adaptive building systems have advanced through new material systems and fabrication technologies, most research focuses on woven textiles or rigid components, which constrain form, adaptability, and integration. The potential of CNC-knitted textiles—with their inherent programmability at the stitch level, elasticity, and seamless fabrication—in membrane architecture is an emerging field of research, where realised demonstrators show the potential to achieve architectural scale. These build structures focus so far on fundamental questions of knit structure and programming aiming at structurally stable and high-performance systems. Further questions, that link to core textile considerations are rarely addressed:

- Integration of mechanical adaptability and aesthetic variability (e.g., color, transparency, porosity) within a single textile system.
- Material innovation using renewable fibers and mono-material systems without fossil-based elastomers.

This research positions CNC-knitted textiles as a novel strategy for adaptive architectural structures, aiming to:

- Develop programmable knitted systems with reversible elasticity and dual-state behavior for dynamic sun shading.
- Explore material efficiency and sustainability through mono-material natural fiber-based solutions.
- Establish interdisciplinary design and fabrication methods combining textile and architectural design, and material science.
- Demonstrate the architectural potential of knitted systems through prototyping and performance evaluation, highlighting their capacity for environmental responsiveness and expressive design.

## 1.1 Architectural adaptive membrane design

Textile elements have long played a pivotal role in both traditional and contemporary adaptive building components. Their inherent lightweight nature, flexibility, and capacity for

shape transformation make them particularly suited for dynamic architectural applications. These properties enable textiles to modulate environmental conditions—such as solar radiation and thermal gain—by transitioning between different states, thereby offering varying degrees of solar shading and regulating the influx of light and heat into buildings.

The adaptive behavior of textiles typically operates between two primary states: relaxed and tensioned. This principle is exemplified in large-scale shading and weather protection systems, particularly in stadium architecture. Historical precedents include the adjustable solar shades used in Roman amphitheaters (Montilla, 1969), while contemporary examples range from the membrane structures of the Montreal Olympic Stadium (Lazzari et al., 2009) to modern football arenas where centrally stored textile masses are tensioned via pulley systems to cover expansive areas (Göppert et al., 2013).

Beyond iconic structures, adaptive textile systems are widely applied in urban solar screens, temporary enclosures, and everyday shading devices such as louvers and blinds. These systems span both permanent and temporary installations, and are employed in indoor and outdoor contexts, including façades and spatial partitions (Barozzi et al., 2016).

The predominant material class used in these systems is woven textiles, often derived from fossil-based polymers. Polyester and ePTFE Expanded Polytetrafluoroethylene) yarns are both favored for their durability and resistance to environmental stressors. Furthermore, composite membranes such as PVC coated/polyester or PTFE coated/glass offer effective protection against water, UV radiation, and pollutants, while an increasing innovation of top coatings and finishing layers applied over the woven fabric is recently prolonging the service life of these membranes around 25–30 years (McKeen and Ebnesajjad, 2023).

On the other hand, these materials are scrutinized due to their environmental impact. Along with their production processes, the composite chemical nature makes both recycling and disposal problematic. Also, the manufacturing process is a very specialized and complex, which limits the wide-spread application of this architectural technology. It is often resource-intensive and generates significant waste, particularly during cutting, welding and sewing stages (European Commission. Joint Research Centre, 2023; Monticelli and Zanelli, 2021). However their very low material consumption justifies makes the use of lightweight membrane structures and textiles facades, still more sustainable than other material and structural options (Procaccini, 2025), while the use of membranes for short-term and temporary installation can be generally considered unsustainable (Monticelli and Zanelli, 2021).

### 1.1.1 Bending active systems

Mechanically, adaptive textile systems rely heavily on complex hinge and pulley mechanisms, which introduce vulnerabilities. These systems are maintenance-intensive, prone to mechanical failure, and typically require specialized repair and servicing, adding to their operational costs and limiting their long-term viability (Attia et al., 2018).

In contrast bending-active systems exploit the intrinsic material behavior—specifically the elastic bending of rods or profiles—to achieve complex geometric (Lienhard, 2014). Rather than requiring pre-formed curved elements, which are typically expensive and environmentally costly to produce, bending-active structures can



FIGURE 1  
Large scale CNC knitted structures (from left (A) Hybrid Tower 2016, (B) Isoropia 2018, (C) Zoirotia 2022).

be assembled from straight, flat-packed elements that are bent into shape during installation. In many cases, the necessary deformation forces can be applied manually. These systems have been extensively theorized and explored in architectural research, often in conjunction with glass-fiber reinforced elements. Notable examples include adaptive façade systems such as Flectofin (Lienhard et al., 2011), where bending-active components interact with layered glassfibre materials to create responsive shading mechanisms.

When combined with textiles, these systems form hybrid textile-bending-active structures (Lienhard and Knippers, 2015), in which the membrane constrains the movement of the bending elements while simultaneously inducing the required prestress within the system. Large-scale applications of these principles have been realized in academic contexts, including projects such as the Hybrid Tower (Thomsen et al., 2015), BeTA Pavillion (Davis-Sikora et al., 2020) and the work of Sean Ahlquist (Ahlquist et al., 2013) or in the TemporActive project (Mazzola et al., 2021), where a hybridization of bending-active arches with restraining cable and a transparent elastic membrane has been explored. The use of hybrid textile-bending-active structures in deployable and retractable shading structures has been explored to a lesser extent, e.g., in the Marrakech Umbrella system (Lienhard and Knippers, 2015). Here bending-active systems offer an alternative to mechanically intensive adaptive architectures, which presents a pathway toward lightweight, low-energy, and material-efficient adaptive structures.

### 1.1.2 CNC knitted architectural membranes

The fabrication of complex patterned bending-active structures presents significant production inefficiencies, particularly when complex textile shapes require many patches to be joint and equipped with details. Recent large-scale explorations have investigated CNC-knitted textiles as an alternative to conventional membrane surfaces. Unlike woven textiles—which necessitate cutting and seaming, resulting in increased cost and material waste proportional to the number and size of elements—CNC knitting offers a zero-waste, highly adaptable fabrication method (Sinke et al., 2022). Projects such as Isoropia (Ramsgaard Thomsen et al., 2019) and Zoirotia (Ramsgaard Thomsen and Tamke, 2023) (Figures 1A–C) demonstrate the potential of knitted membranes to be produced as seamless, form-fitting components with integrated

detailing. In these workflows digital design workflows design, simulation and fabrication are integrated and allow CNC knit fully fashioned textile pieces, that are shaped to required geometry, with bespoke knit structure and integrated details, that allow to interface these large textile patches with other building elements. This not only reduces material waste but also enhances structural and aesthetic performance. However, in these applications, knitted membranes are employed in a fully tensioned state, adhering to the traditional principles of membrane architecture, where structural stability is achieved through globally distributed, ideally homogeneous tension across doubly curved surfaces. Consequently, the membranes remain static in shape and replace woven membrane.

Knitted structures, possess a unique potential: they can be programmed at the stitch level to exhibit tailored mechanical and aesthetic properties (Tamke et al., 2020). This capability enables the integration of form and detail directly into the fabrication process. This has been used to achieve gradient colors and transparencies (Sinke, 2025). Here the inherent three-dimensionality, texture, and porosity of knitted structures provide opportunities that transcend the typically monochromatic aesthetic of architectural membranes and can incorporate patterns, gradients, and multicolor expressions, opening new avenues for design and architectural articulation.

However in architectural design the elasticity inherent to knit has so far been viewed as a limitation—due to challenges in simulation and predictability (Sinke et al., 2023). In this paper we will explore how this inherent characteristic of knitted materials may instead serve as a strategic asset for adaptive architectural systems.

Current membrane designs and the related methods for formfinding and simulation are optimized for their stretched state (Gengnagel et al., 2018). Upon relaxation, woven materials tend to fold in uncontrolled ways, posing significant challenges for fold management, as seen in stadium roof membrane systems (Göppert et al., 2013). Knitted textiles, by contrast, have the potential to introduce controlled elasticity and elongation, offering new possibilities for dynamic behavior.

## 1.2 Elastic knit pattern design

Knitted structures are created by programming on loop level. The way individual loops are combined determines the behaviour,



FIGURE 2 Example from fashion how ribs can shape garment (A) Proenza Schouler RTW Fall-Winter 2019. (B,C) Alexander Wang RTW Fall-Winter 2015.

appearance and expression of a textile. Approaching knitting from a textile design perspective means to technically know the mechanical characteristic of the single loops and to have the ability to anticipate the behavior of a textile generated by the combination of loops in rows and columns.

When designing fashion products, the fit of the garment to the three-dimensionality of the human body and its movement is of key concern (Wolff et al., 2023). Here, elasticity is distributed on a garment according to the structural influence it brings to the whole piece (Liu et al., 2019; 2021). Elasticity in knitted textiles depends on the combination of diverse elements like material selection, structural design, and fabrication techniques. Key assets include:

- Yarn choice: incorporating elastomeric fibers such as spandex, Lycra, or rubber into the yarn blend provides the best stretch and recovery. Among natural fibers, the elasticity depends on the fiber itself (e.g., wool is more elastic than cotton, linen is the more rigid one) but also on the structure of the yarn itself, its twisting, its construction on multiple plies rather than single.
- Stitch structure: some stitches, based on the rhythmic alternation of knit and purl loops, naturally allow reversible extensibility, while others make the fabric loose and soft allowing extension but with no return. Others still, like woven knits or multi-color jacquards, give the fabric more structural stability due to the density and regularity of the loops.
- Gauge and tension control: adjusting machine settings optimizes loop size and density, influencing elasticity and drape. In this case, elasticity is a matter of balance between the fabric compactness and its softness.

These combined elements allow designers to produce knit fabrics with tailored stretch, resilience, and functional behavior for apparel, performance textiles, and industrial applications, and

demonstrates that elasticity in knitted materials is not merely an inherent property of the fiber, but an emergent characteristic arising from the *interaction* of yarn properties, stitch structure, and fabrication parameters (Singal et al., 2024). Among the possible structures, ribbing is one of the foundations of knitting. Rib knit fabric is renowned for its natural elasticity, which allows it to stretch and recover without losing shape (Figures 2A–C). This characteristic is primarily due to the alternating knit and purl stitches that create a textured surface, enhancing flexibility. The comfort and ease of movement provided by rib knits make them ideal for trims on garments (wrists, collars, hems, etc.), but also for the adaptive architectural structures object of this article. In these applications, the fabric's inherent stretchiness contributes to its durability, ensuring it retains its form over time.

While conventional elastic textiles often rely on fossil-based elastomers (Bolaji and Dolez, 2024; Eichhorn et al., 2009) the natural elasticity of rib-knit structures could serve as a sustainable alternative. Capable of achieving reversible elasticity through structural design alone, rib-based knitted fabrics maintain their elasticity even when produced from mono-material natural fibers, without the need for spandex or other synthetic elastomeric components. This approach suggests that careful selection of fiber type, yarn construction, and rib geometry can replicate the stretch-and-recovery behavior traditionally achieved with synthetic elastic blends, potentially reducing the environmental footprint of elastic textiles while maintaining functional performance.

Whether it be in fashion production or in architecture, the integration of CNC (computer numerical control) knitting technology represents a key enabler for precise, repeatable production of complex rib-based structures. CNC knitting allows designers to program loop formation at a highly detailed level, controlling stitch type, loop density, and pattern variation across the textile (Tamke et al., 2020). This level of control makes it possible to explore advanced functional properties—such as localized elasticity,

structural stability, and adaptive fit—that would be time-consuming with standard knitting machines, while minimizing material waste and enabling rapid prototyping.

Together with the structural behaviour, what is common in the design development of any fashion product is its aesthetic. A lot of this is made by the colour story, which with knitting can be very versatile and offers to designers a wide space for experimentation (Black, 2002; Gitelson-Kahn et al., 2023). One particularly effective method is plating, which uses two different yarns—typically one for the front and another for the back—allowing for unique colour combinations and visual effects. This technique enables the fabric to subtly shift color across knit and purl sequences, highlighting the construction and movement of the textile. Because the two yarns are juxtaposed rather than separated, the colors blend seamlessly, producing dynamic shades that can appear concealed or revealed depending on the fabric's structure and motion.

## 2 Materials and methods

The integration of CNC-knitted structures into architectural design can offer new possibilities for controlling membrane surface properties—such as elasticity, color, and texture—in response to local environmental and spatial conditions. This potential for responsive and expressive façades depends on the ability to align architectural design intentions with the specific material behaviors and fabrication logics inherent to knitted textiles.

To enhance architectural performance through material behavior, it is necessary to reconcile two distinct design paradigms: the bottom-up approach characteristic of textile and knit design, and the top-down methodology typical of architectural practice. While knit design often begins at the material and stitch level, emphasizing local performance and fabrication constraints, architectural design tends to operate from abstract concepts and large-scale spatial strategies, refining these iteratively toward material resolution.

This methodological tension raises a central question for our research: *How can design methods be combined to enable interdisciplinary integration of knitted textiles into architectural systems?*

Architectural design is typically driven by scaleless abstraction, where ideas are developed through conceptual representations and later translated into material form. In this process, material behavior is often encoded or abstracted (Ramsgaard Thomsen and Tamke, 2009) to remain effective across different scales and design stages. Designers rely on (computational) simulation tools to verify assumptions about material performance, which allows to handle physical properties until later phases of development.

Textile architecture occupies a unique position within this framework. The form of membrane structures is inherently shaped by force interactions (Koch and Habermann, 2004; Otto and Rasch, 1992). Shaping a textile architecture is therefore requiring simulation-based form-finding methods—from early analog models with soap films and elastic textiles (Goldsmith, 2016), to contemporary design-integrated computational

simulations (Deleuran et al., 2016; Quinn et al., 2016). While this process is often described as bottom-up due to its reliance on physical behavior, it typically excludes the actual material properties of the membrane. Most membrane designs assume stiff, non-elastic behavior, omitting elongation and deformation from the design equation. The integration of elastic materials such as knit is therefore a topic of ongoing research, that investigates methods to design integrate computational design methods on knit level in the architectural design processes (Sinke et al., 2023).

In contrast Textile Design, and particularly knit design, follows a bottom-up process. The process begins with experimentation at the most fundamental level—the individual loop and stitch—where designers explore how variations in yarn type, twist, ply, and stitch structure influence the mechanical, visual, and tactile properties of the fabric. This initial experimentation often takes the form of 1:1 samples, maybe smaller in dimensions but with stitches and structures in real scale, enabling designers to directly observe elasticity, drape, stability, and aesthetic effects in a real-scale context.

From these initial explorations, patterns and structures are iteratively refined. Adjustments to tension, loop configuration, and stitch combinations are tested to optimize performance and expression. Because the process is material-led, unexpected behaviours often emerge, which can inspire entirely new directions for texture, colour, or structural innovation. Once the desired properties are achieved, the design can be scaled up, combining multiple 1:1 units into larger textile surfaces suitable for garments, architectural membranes, or functional textile systems.

This bottom-up methodology emphasizes emergent behaviour, iterative prototyping, and direct material interaction, allowing the textile to inform and shape the final outcome. At its core it requires at all stages a testing of the knit in 1:1 scale. Starting from samples and swatches to larger parts, The development of the knit structure is the center of design and it cannot be scaled, but need to be explored 1:1. This sets as well a limitation of the scale that can be reached in design, as a building scale or even building element scale resist to 1:1 scale iterations. In our process the two methods have been combined, articulated in two distinct phases where the interdisciplinary expertise of researchers allowed the combination of the two methods in a flexible, collaborative and iterative cycle.

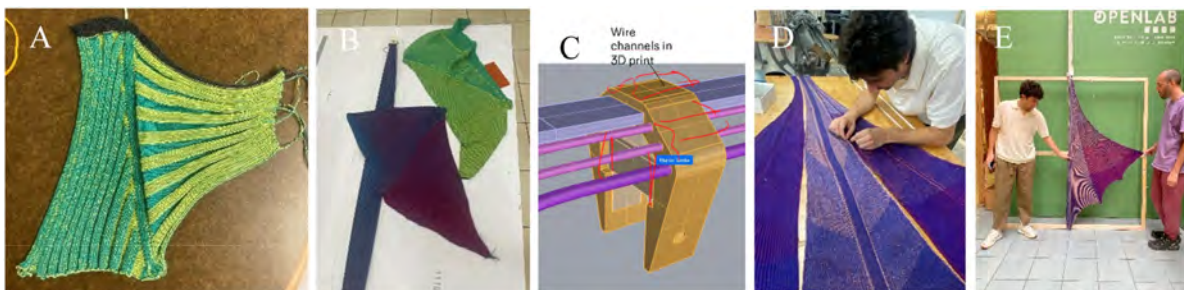
### 2.1 Design research phase

The design research phase of the Manta Ray project was conducted primarily by architects and followed the logic of an architectural design process. Its objective was to define the overarching goals and requirements of the system, particularly in relation to solar shading, façade integration, and underlying structural conditions. A review of the state of the art in adaptive façades and textile-based systems helped contextualize the project and led to the formulation of key design criteria.

Central to the approach was the integration of bending-active elements and knitted textiles as primary strategies for actuation and



**FIGURE 3** Small scale models exploring actuation concepts (A), knitting strategies (B,C), environmental and material simulation and analysis (D, E), knit samples leading to a working prototype (F).



**FIGURE 4** Samples (A,B), detail design (C) and prototypes (D,E) from the development research phase.

surface articulation. These principles were selected for their potential to reduce mechanical complexity while enabling expressive, responsive movement. In this phase, the design process benefited from a loose connection between scales and components, allowing individual aspects to be explored independently. This separation enabled progress without being hindered by unresolved dependencies, fostering a flexible and iterative development environment.

The hands-on exploration was conducted using proxy materials, such as woven mesh textiles, in place of actual knitted fabrics (Figures 3A–F). These materials allow rapid prototyping and intuitive testing of actuation principles through small-scale hand models. The process was embedded within a design studio setting, involving architecture students in a semester-long investigation. The studio introduced the fundamentals of bending-active systems and encouraged experimentation through conceptual development, physical probes, and working prototypes. While inspiration was drawn from stretchable knit patterns, the complexity of integrating CNC-knitted textiles exceeded the scope of this phase. Collaboration with knit designers focused instead on testing feasibility through simplified samples.

The design process operated across multiple scales and levels of abstraction. Scale-less hand models were used to explore compositional strategies, while digital simulations incorporated precise geometries, environmental data, and site-specific

conditions. The workflow alternated between conceptual abstraction—examining how elements could be composed on a façade—and detailed 1:1 prototyping to resolve technical challenges.

The outcomes of this phase included a set of design requirements, a scaled working prototype, and a deeper understanding of the actuation and bending-active systems. Performance testing focused on the behavior of joints, the dynamics of textile movement, and the interaction between structure and gravity. These insights informed the system’s responsiveness, speed, and shading performance. Digital tools supported the process throughout, enabling sketching, simulation, spatial arrangement, and the development of 3D-printed components. While the results remained exploratory, they established a robust foundation for the next phase.

## 2.2 Development research phase

Building on the design parameters and performance benchmarks established in the first phase, the development research phase shifted focus toward material innovation, technical integration, and fabrication feasibility. Unlike the conceptual and macro-scale orientation of the design research, this phase concentrated on detail-level problem solving, scaling up, and cross-disciplinary integration.

Here, hypotheses introduced during the design research—particularly those concerning the interaction between



FIGURE 5 Politecnico di Milano, Campus Leonardo da Vinci - Building 11, Façade and entrance on Ampère street.

knitted textiles and bending-active structures—were subjected to realization and testing. The development phase required the system to function cohesively across scales, moving beyond isolated component studies to integrated assemblies (Figures 4A–E). This included the refinement of actuation mechanisms, the scaling of textile surfaces, and the transition from cut-and-sewn mesh to CNC-knitted materials.

A technically demanding aspect of this phase was the development of CNC-knitted components. Extensive sampling was necessary to translate the specifications derived from mesh-based prototypes into stitch-level fabrication logic. This involved testing yarn behavior, stitch density, and pattern geometry to ensure compatibility with the actuation system and structural performance requirements.

The development research phase also addressed the integration of mechanical and textile elements, requiring precise coordination between material properties, fabrication techniques, and spatial configuration. The goal was to validate the system’s performance not only in terms of movement and shading but also in terms of durability, manufacturability, and architectural applicability.

This phase marked a transition from speculative design to technical exploration, where the system’s feasibility was tested through full-scale components and refined prototypes.

### 3 Results

#### 3.1 Case study: building 11, politecnico di milano

To ground the development of the adaptive shading system based on CNC-knitted textiles, we chose a real-world architectural testbed. The choice was an existing building, reflecting the ambition to explore transformative interventions that improve the performance of current building stock. While the design approach remains applicable to new constructions, the focus on retrofit scenarios allowed the research to engage with real constraints, existing façade systems, and urgent performance challenges.

The chosen Building 11 (Figure 5) is located on the Leonardo da Vinci Campus. Designed by Vittoriano Viganò and constructed between 1970 and 1983, the four-story steel-and-glass building features a radial layout of classrooms organized around a central circulation core. This configuration ensures that most classrooms are surrounded by extensive glazing, which—while architecturally expressive—has led to persistent issues of overheating, excessive solar gain, and visual discomfort, particularly during spring and summer months (Figures 6A,B).

Given the building’s structural and technological characteristics, the most viable strategy was to introduce an external shading layer. This intervention leverages the existing 90 × 90 cm mullion grid of the façade, which provides a modular framework for mounting adaptive shading elements. The proposed system was conceived as a versatile and low-maintenance solution, capable of addressing both thermal performance and daylight modulation.

The façade system was treated as representative of typical post-war curtain wall constructions, making the findings broadly applicable to similar retrofit scenarios. This case study thus

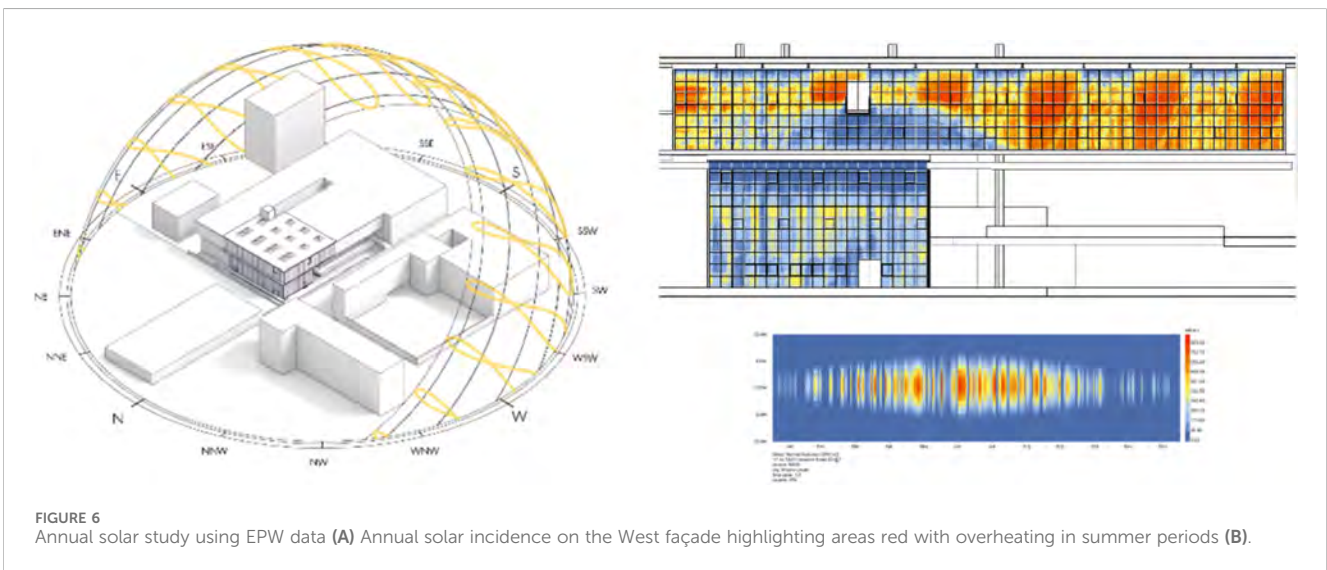
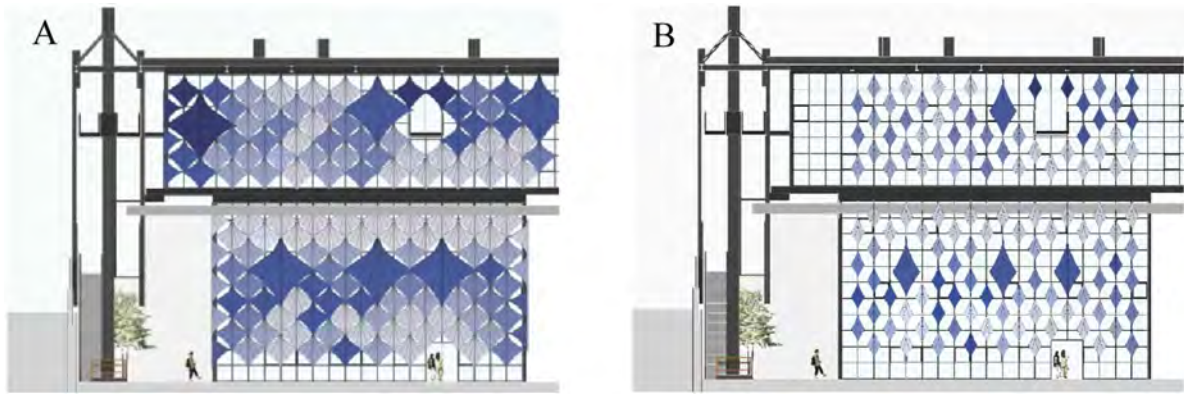
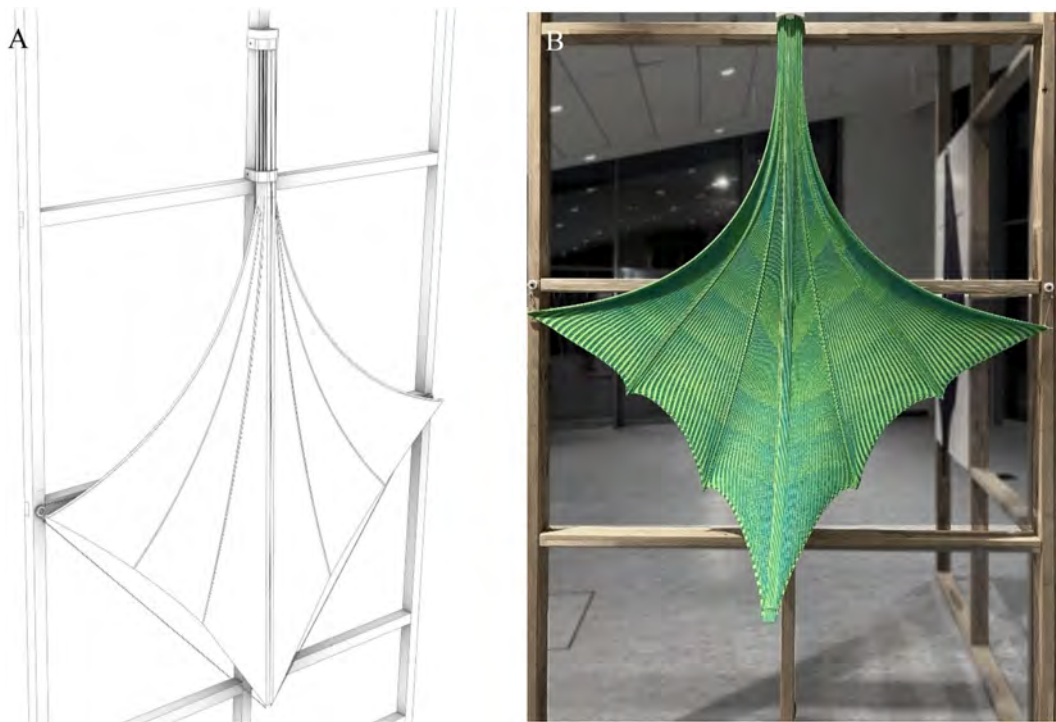


FIGURE 6 Annual solar study using EPW data (A) Annual solar incidence on the West façade highlighting areas red with overheating in summer periods (B).



**FIGURE 7**  
Pattern of the system featuring different sizes of modules in fully opened (A) and half-closed state (B).



**FIGURE 8**  
The bending active system of the Manta mounted on the square façade system of the Building 11 in drawing (A) and as a 1:1 scale Prototype (B). 3D printed elements at the top holding the gfr elements.

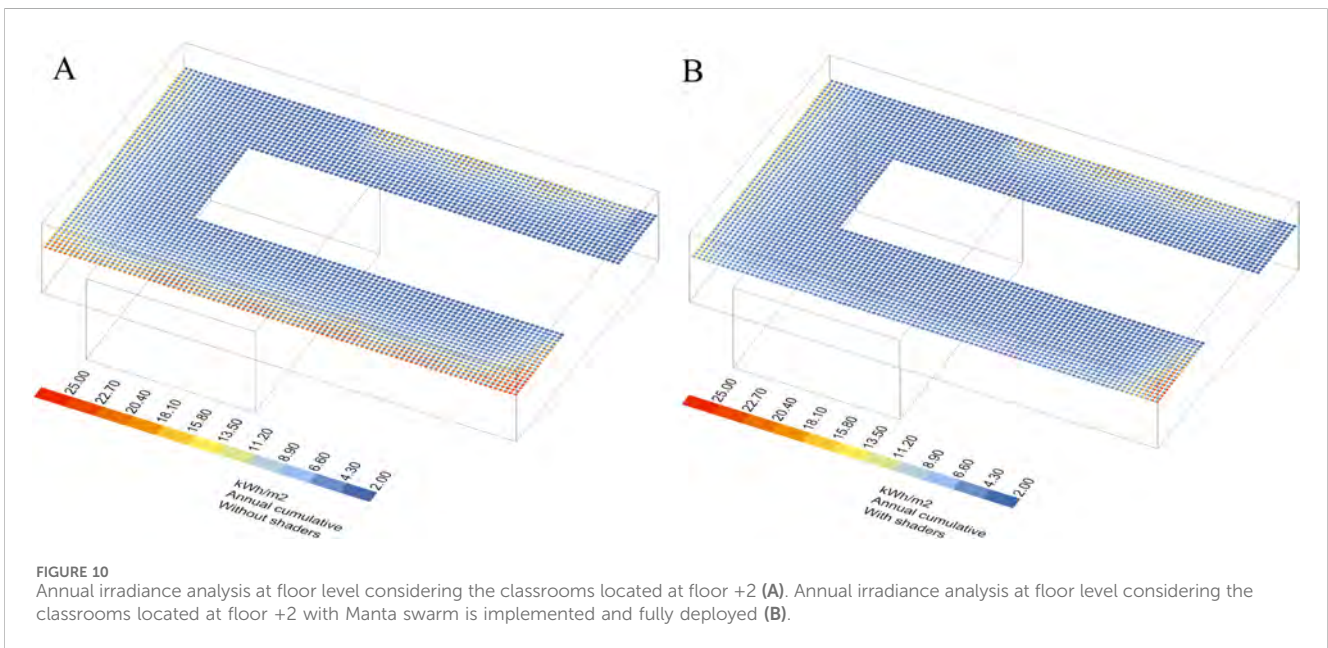
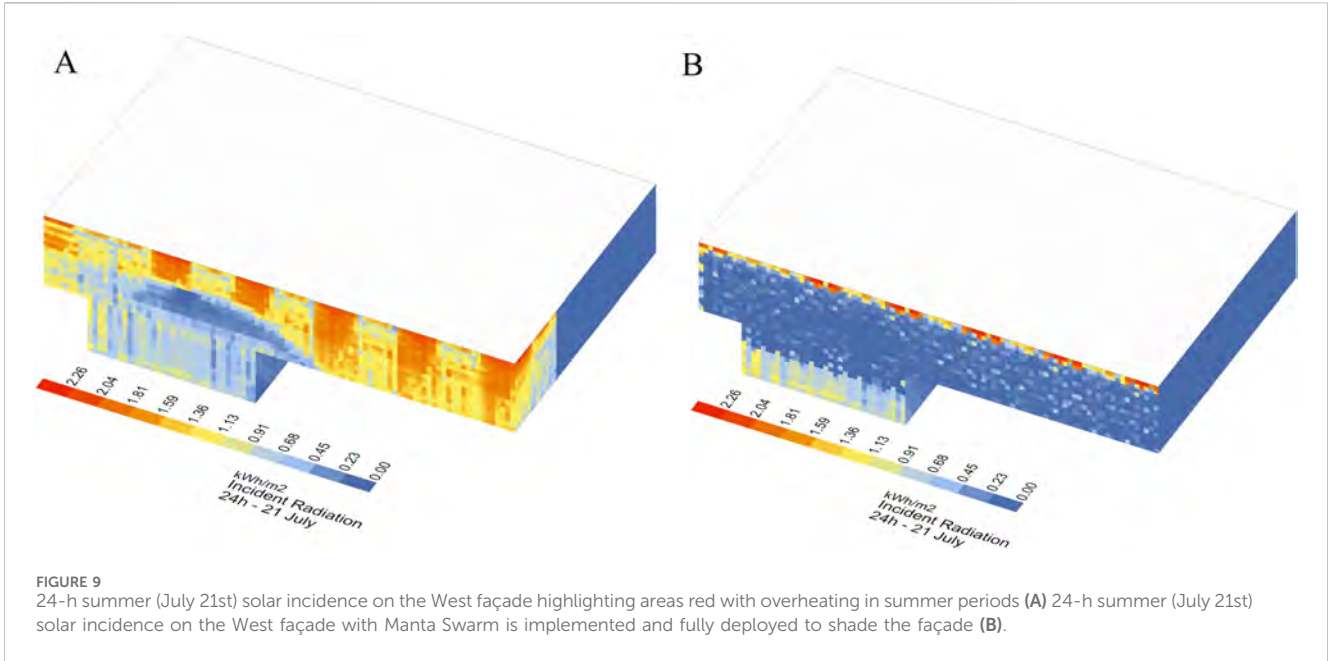
serves as a strategic platform for testing the integration of knitted materials, bending-active structures, and adaptive control systems within a real architectural context. It enables the evaluation of both technical feasibility and architectural impact, bridging the gap between material innovation and spatial performance.

The solar gain and shading simulation were run using publicly available weather data from Milano Linate Weather Station (WML: 16,080/ICAO: LIML) using Rhinoceros Grasshopper’s Ladybug and HB Radiance plugins. The model took in consideration the glazed façade facing west. Although an exact light transmission coefficient

was not measured at this stage of development, an assumed value of 20% was used.

### 3.2 Manta knit: responsive façade system

The proposed design features a modular shading array composed of diamond-shaped CNC-knitted textile screens, each capable of transitioning between two distinct states (Figures 7A,B). In their fully tensioned configuration, the knitted membranes



provide effective solar shading and contribute to the visual articulation of the façade. When retracted, the modules align in a linear arrangement with the vertical elements of the existing façade system, remaining visually unobtrusive and minimizing their impact on daylight access and the architectural expression of the building envelope. The design minimizes the interface between the shading system and the façade system to a few screws, that position compact 3D printed units of the Manta system on the vertical metal elements of the existing façade (Figure 8).

The Manta system’s three-dimensional movement enables control over both azimuthal and zenithal solar radiation, offering nuanced modulation of light and heat. This is achieved while minimizing the number of mechanical components, leveraging

the elasticity of the knitted membrane and the bending-active behavior of the GFRP (glass fibre reinforced polymer) structure. The synergy between textile flexibility and structural responsiveness allows for a lightweight, low-maintenance solution with high adaptability.

Each module is equipped with an individual actuation mechanism, enabling localized responsiveness to environmental conditions. Actuation is governed by sensor inputs, allowing the system to dynamically respond to variations in solar intensity, temperature, or user-defined parameters. This modular and responsive configuration supports both functional performance and architectural integration, making it suitable for retrofit applications as well as new constructions.

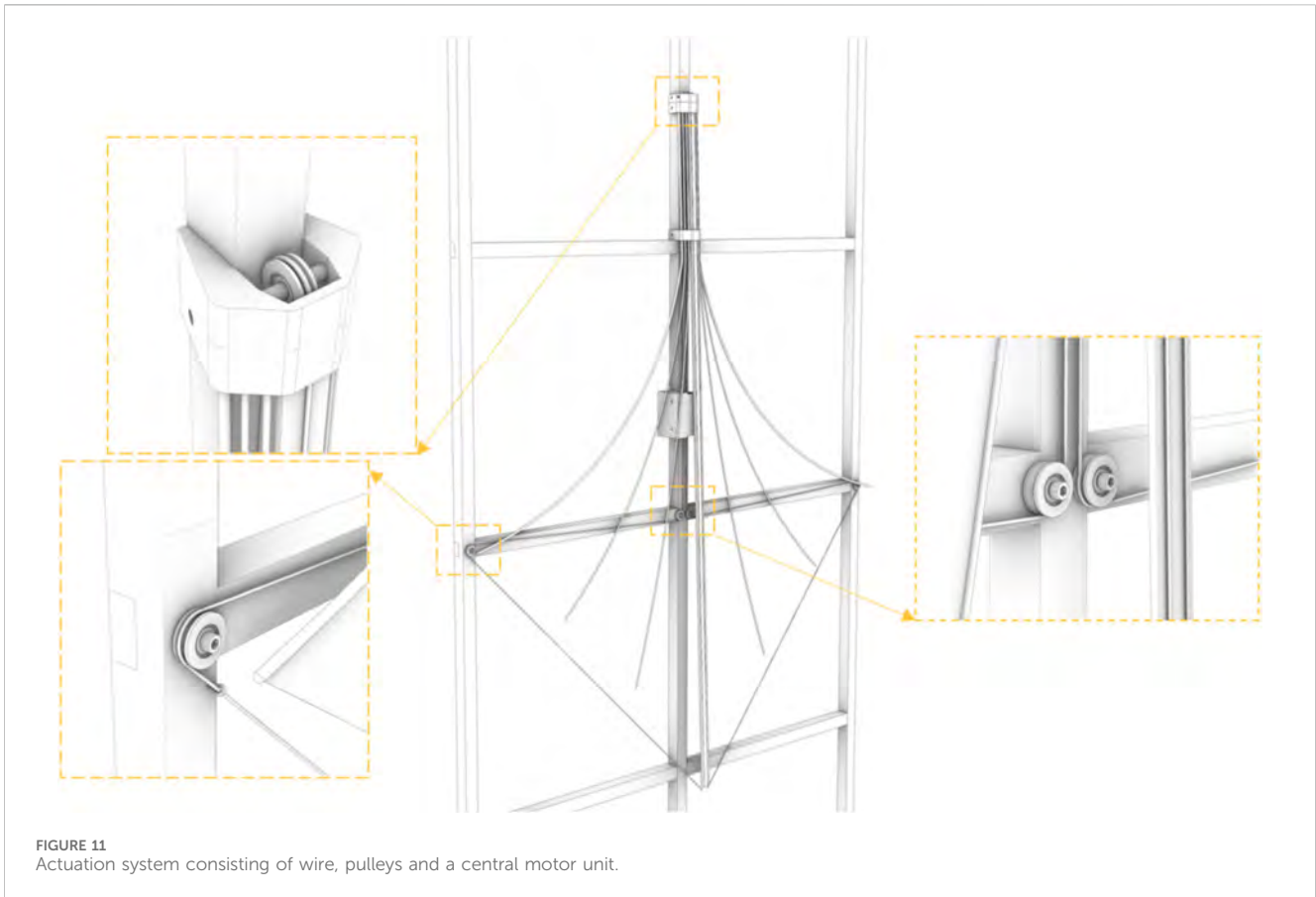


FIGURE 11  
Actuation system consisting of wire, pulleys and a central motor unit.

### 3.3 Solar performance: context and assessment

The system was designed with energy performance as a major consideration. The design was optimized to maximize the covered area when the manta knit elements were fully opened, as well as to enable regulation across different stages of opening. To evaluate these design objectives on the façade, we considered a scenario in which a complete set of manta knits—referred to as a “manta swarm”—was deployed (Figure 7).

Our analysis focused on the rooms located on the second floor of Building 11, as these spaces are the most critical in terms of exposure to direct incident sunlight. Given the exploratory nature of this development and to maintain computational efficiency, we assumed that the knitted material would block 100% of incoming sunlight. The results, visualised in Figures 9, 10, revealed that a swarm of fully-deployed modules can bring down direct incident radiation on the envelope from an average of 1.32 kWh/m<sup>2</sup> to 0.04 kWh/m<sup>2</sup> on a typical summer day (July 21st, 24-h simulation, cumulative incident radiation).

In terms of internal solar gains, the overall solar irradiance at floor level of the second floor rooms was brought down from an average of 12.24 kWh/m<sup>2</sup> (with hotspots of 24.98 kWh/m<sup>2</sup>) to an average of 3.21 kWh/m<sup>2</sup>.

A more accurate investigation will be needed to limit the observation to cumulative irradiance over single days and single months, as during winter days the system would not

be deployed as solar thermal and illuminance gains would be desirable.

Further development is necessary to analyse the knitted fabric through spectrophotometric measurements at different stages of module deployment and fabric stretch to define an accurate material model for the energy simulation.

### 3.4 Bending active system for actuated façades

The actuation strategy for the Manta Knit prioritizes a reduction in mechanical components. Instead of conventional hinges or joints, the system employs bending-active elements, made of GFRP (glass fibre reinforced polymer), to achieve motion and structural transformation. These rods enable the textile to spread in a manner reminiscent of a manta ray’s wing movement. The knitted textile has channels in which the rods are placed providing stable interface of the material systems (Figure 8).

The actuation framework consists of 6 mm and 3 mm diameter GFRP rods, complemented by a 30 × 3 mm GFRP stabilizing profile. These elements are secured using 3D-printed clamps, which are mounted on vertical beams—similar to those found in the ABC building and other façade systems. The use of additive manufacturing enabled rapid prototyping and iterative refinement, allowing for the integration of multiple functions into a single component. This approach facilitated precise spatial

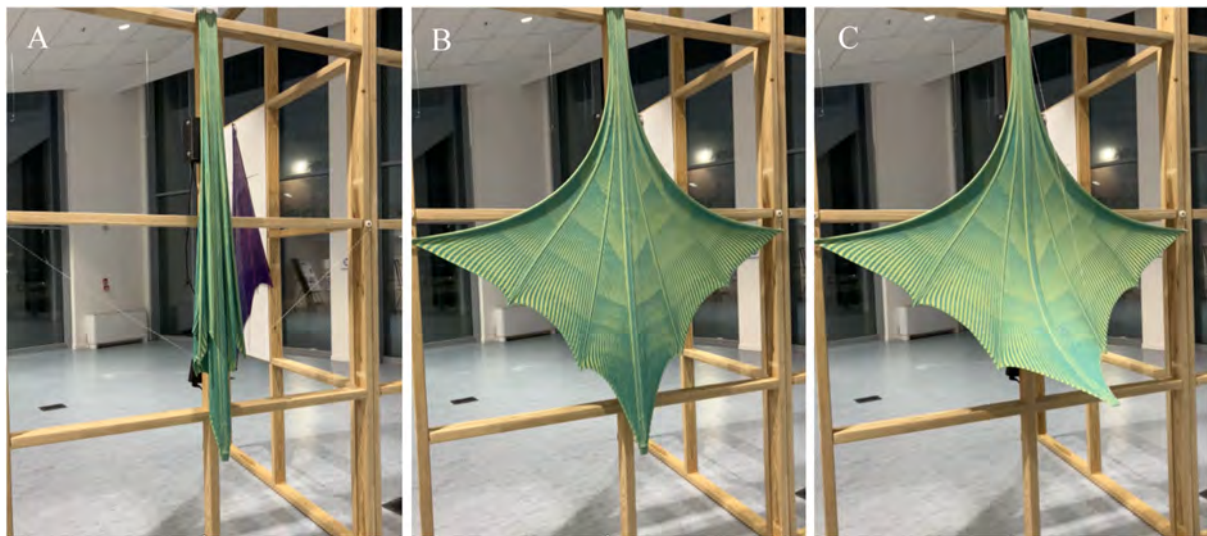


FIGURE 12

The three different actuation states of the manta: closed ((A): 0s), wings open ((B): after 50 s), Tip lifted ((C): after 62 s). The return to the initial state is equally timed.

arrangements and the development of intricate joints that would be difficult to fabricate using traditional subtractive methods.

The 3D-printed components serve multiple roles:

- They secure the rods and clamp the knitted textile.
- They guide the actuation cables through a mortised pulley system.
- They provide resting points for the manta structure in its façade-mounted configuration.

While the current components are printed in PLA, this material is considered a placeholder for more durable alternatives. Nonetheless, the process demonstrates the potential of additive manufacturing for producing complex, multifunctional parts with short lead times.

The GFRP rods fulfill two primary functions:

- They act as interfaces between the textile and the actuation system.
- They define the geometry of the textile surface. The characteristic curvature of the manta's upper surface is governed by the bending radius of the outermost 6 mm rods, while two inner 3 mm rods provide tension and guide the fabric during actuation cycles.

### 3.5 Movement and actuation mechanism

To explore actuation strategies for knitted textiles, the Manta Knit prototype employs a simple yet effective pulley system (Figure 11). The actuation cables follow the force trajectories required for movement and are routed to a centralized actuation unit. This configuration minimizes cable length and consolidates mechanical components, simplifying maintenance and enhancing accessibility.

The central actuation unit is mounted atop the central vertical beam, a location intentionally chosen to remain concealed beneath the textile surface, thereby protecting it from environmental exposure and visual distraction. The direct transmission of force from the cables to the rods is facilitated by openings integrated into the knit, allowing 3D-printed connectors to interface with the rods and secure the actuation strings.

The cable routing follows the movement paths of the textile:

- Cables run to corner pulleys, which define the outer limits of the wing's motion.
- From there, they are redirected via additional pulleys to the central actuation unit.

The cable controlling the manta's tip is routed vertically to the end of the GFRP profile, then redirected beneath the profile back to the central unit.

The actuation system comprises:

- Two motors, each driving a 3D-printed spool via gears and chains. The spools feature grooves dimensioned to wind the precise length of cable required for actuation.
- An Arduino-based control unit with motor drivers, powered by an external 12V supply.
- A 3D-printed casing, with a second iteration incorporating bent metal brackets to support the motor and spool axes. These metal elements enhance structural stiffness and provide thermal decoupling, mitigating deformation of the PLA due to motor heat during extended operation.

The motors are independently controlled, enabling differentiated movement of the wings. This allows for adaptive shading and controlled transparency, such as lifting the manta's tip to open views through the façade. The independent control also



**FIGURE 13**  
Detail of the tubular channels in between the rib portions of fabric.



**FIGURE 14**  
Detail of one of the tubular channels hosting the glass-fiber rods in the maximum tensioned state.



**FIGURE 15**  
Detail of the vertical striped pattern created by the plating technique when applied to a rib knit structure.

facilitates choreographed motion sequences, where the wings initiate movement followed by the tip (Figures 12A–C).

Earlier experiments with asymmetric wing movement revealed that lateral forces on the central profile caused undesirable skewing. A previous design iteration employed a round rod as a central spine to allow for such movement, but maintaining balance in the central structure proved more critical. The current configuration ensures a stable and predictable motion pattern, minimizing structural strain and preserving the integrity of the overall system.

### 3.6 Knit structures for adaptive structures

#### 3.6.1 Development process

The development process focused on exploring bio-based, particularly cotton, as a primary material, to maintain a mono-material approach and avoid synthetic fibers. Given the complexity of the intended shapes and the structural features to be incorporated—such as holes, tubular sections (Figure 13), and small pockets for integration of the GFRP elements with the

TABLE 1 Uniaxial hand-made empirical testing of the knitted samples.

Picture	Module	Stitch	Needles	Rows	FB stitch size	BB stitch size	Relaxed dimation	Horizontal elongation with uniaxial pull on X-axis		Vertical elongation with uniaxial pull on X-axis	
								cm	%	cm	%
		Plain knit	420	462	45	—	67 × 47 cm	10 => 24 cm	140%	10 => 3.5 cm	-65%
		1/1 rib	420	462	40	40	43 × 64 cm	10 => 27 cm	170%	10 => 6.5 cm	-35%
		2/2 rib	420	462	40	40	45,5 × 55 cm	10 => 25,5 cm	155%	10 => 7 cm	-30%
		3/3 rib	420	462	40	40	35 × 55 cm	10 => 30 cm	200%	10 => 8 cm	-20%
		4/4 rib	420	462	40	40	28 × 52 cm	10 => 33 cm	230%	10 => 8.5 cm	-15%
		5/5 rib	420	462	40	40	26 × 51 cm	10 => 35 cm	250%	10 => 9 cm	-10%

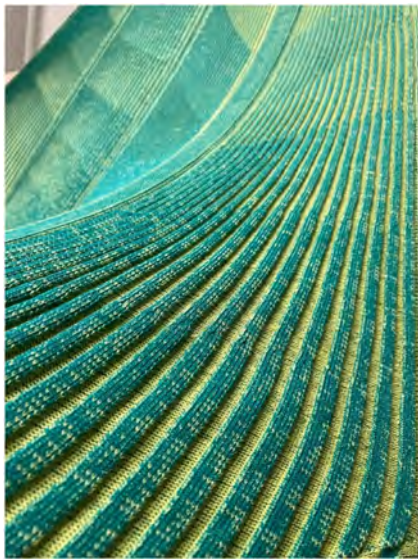


FIGURE 16  
Detail of the graphical effect obtained.

tensile structure (Figure 14), the selection of yarns prioritized a strong, flexible, easy to work with option. This choice ensured reliable machine operation, which can otherwise stress loops and cause stitch loss or yarn breakage.

Initial activities involved producing knitted samples and probes, experimenting with different colors and yarn combinations to assess their aesthetic potential and chromatic interaction. Different types of rib structures were then tested to explore the design space, evaluate their feasibility, and understand how structural variations affect stretch, drape, and overall performance. This iterative approach allowed the team to refine both the material selection and the knitted structures before moving on to broader textile applications.

Once defined the rib structure and the color combination for plating, the process went on with the adaptation of the measurement to the real-size structure and with the consequent programming of the CNC knitting machine.

### 3.6.2 Yarn selection

The yarn selected is the 100%-cotton “Zero” yarn supplied by Filmar®, a sustainably grown and certified 3-ply yarn for knitting which is implemented to be highly resistant to mechanical stress and to be “zero-pilling”, thanks to a selection of long cotton fibers and the implementation of the twisting system, making it optimal for this kind of application. The yarn count selected was a 3/100 NM, to be used in four endings (two for each colour) on a 12-gauge Shima Seiki SSR machine.

### 3.6.3 Plating technique

Manta Knit employs a colour-combining technique known as plating, which integrates two yarns of different colours within each loop through the simultaneous use of two feeders. The second feeder runs slightly behind the first, positioning its yarn at the back of the needle hook so that the front shows the first colour and the reverse the second.

In rib structures—alternating vertical knit and purl columns—this produces a vertically striped pattern that accentuates both the rib’s texture and its dynamic opening and closing (Figure 15). The resulting optical variations, influenced by rib ratio, fabric tension, and viewing distance, are particularly relevant for architectural applications.

Multiple rib samples were developed to optimize stitch density, balancing elasticity and color clarity. Achieving a clean separation between the two colors is challenging, as yarn behavior depends on several parameters, including yarn type, number and count of ends, stitch density, and the pulling force applied during knitting.

### 3.6.4 Material Characterization using empirical uniaxial tests

With the aim of investigating the mechanical behavior of different types of knit structures, an empirical uniaxial tensile test was performed. Since there are no standardized testing systems in use, this type of testing was selected with the intention of informing the early stage of design and orientate the choice of the knitting pattern. The aim, indeed, was not to generate universally valid data, but to obtain specific answers related to the project to direct the next steps of design.

Being aware that the final elasticity of the knitted fabric strongly depends on several variants, including the type of fiber, the yarn typology, and its twisting, the tests samples were made in a way, so that only the type of rib ratio used varied, while the yarn, plating combination and geometry were kept consistent. The later was achieved by casting on the same number of stitches, knitting for the same number of rows and keeping the same average stitch density (also referred to as “loop size” or “stitch size”). Five types of ribs (1/1, 2/2, 3/3, 4/4 and 5/5) were selected and compared with a plain knit.

A square of 10 × 10 cm was traced at the centre of each of the five knit samples, to easily visualize and measure the elongation of the fabric in an area which - when the fabric is pulled - is not influenced by the casting-on and casting-off of the sample, as well as by the hands pulling it.

The elasticity was measured with a uniaxial pulling only on the X-axis, since knit is intrinsically more elastic on this direction and such property was used in the development of the Manta Knit itself, which is elongated mainly horizontally. The results of such measurements are visible in Table 1.

The measurements show clearly the correlation in elongation: the higher is the ratio of the rib, the higher is the elasticity obtained. A 5/5 rib, in fact, arrives at a percentage of elongation of 250% of its relaxed dimension, while the 1/1 rib stops at 170%.

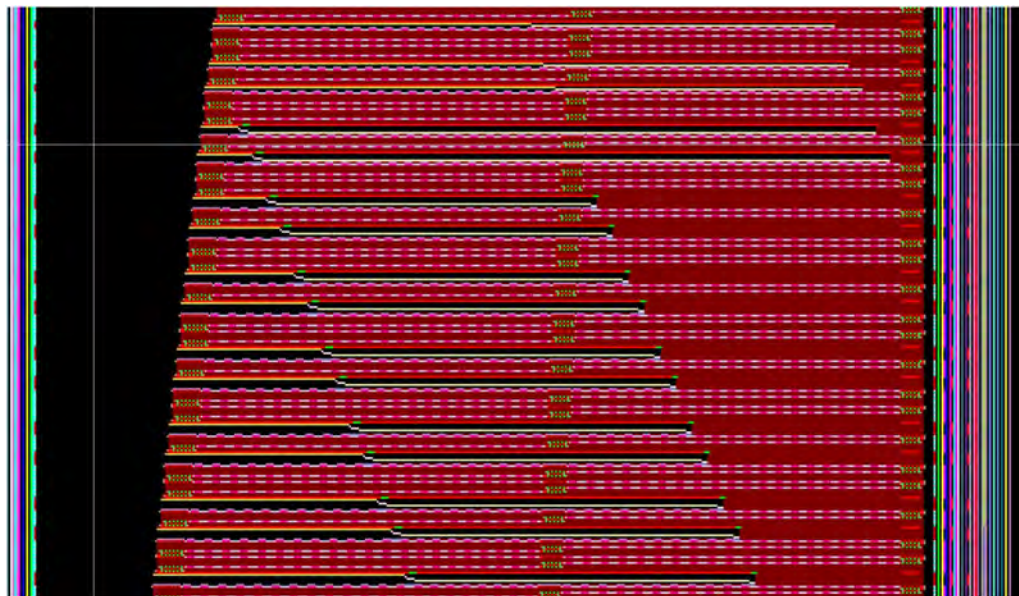
These findings were valuable in confirming the intended sizing and distribution of the rib knit structure; however, the tests cannot be regarded as a standardized protocol for assessing the structural performance of the entire system. Loading conditions were not quantified, as the pulling tests were conducted manually and empirically. Therefore, these tests should be understood as part of a qualitative design process within a research-by-design framework rather than as rigorous structural evaluation.

### 3.6.5 Placement of ribs into the elements

Taking into consideration the behavior of the samples emerged from the uniaxial testing, the Manta Knit was developed using the



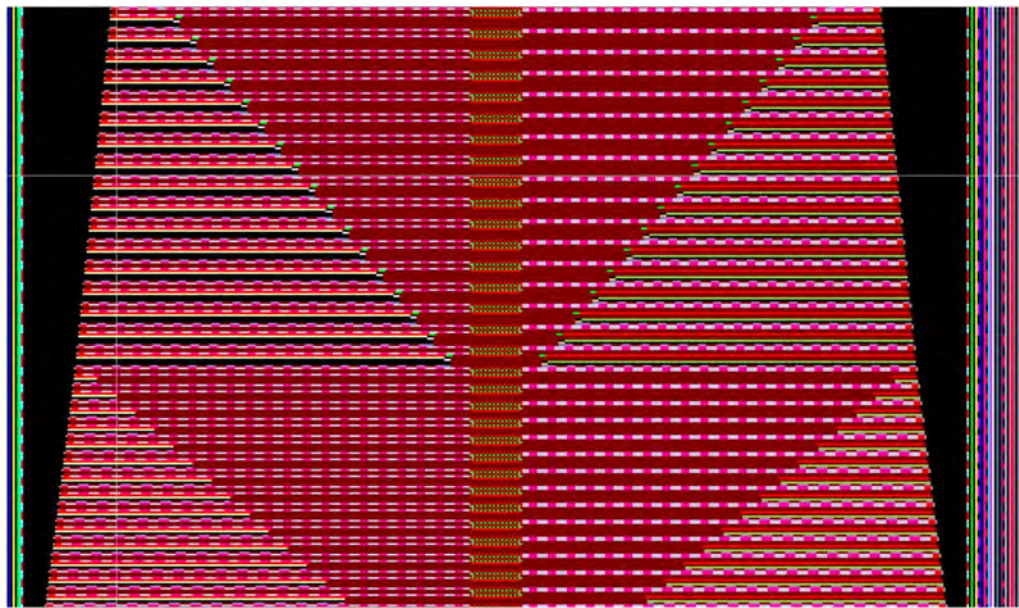
**FIGURE 17**  
The Manta Knit in an almost fully closed (left) and open state (right).



**FIGURE 18**  
Detail screenshot of the program of a lateral panel made on the APEX software of Shima Seiki.

largest ribs at the bottom of the structure, which is the most tensioned area, gradually decreasing the dimension of the ribs until obtaining a 1/1 rib at the top of the piece, which needs almost no elongation.

Such distribution also creates a strong and impactful graphical effect (Figure 16), which dramatically emphasizes the open state of the Manta, since ribs with a higher ratio placed at the bottom open widely when the piece is fully tensioned.



**FIGURE 19**  
Detail screenshot of the program of the central panel made on the APEX software of Shima Seiki.



**FIGURE 20**  
The Shima Seiki SSR112 knitting machine used to prototype the Manta.

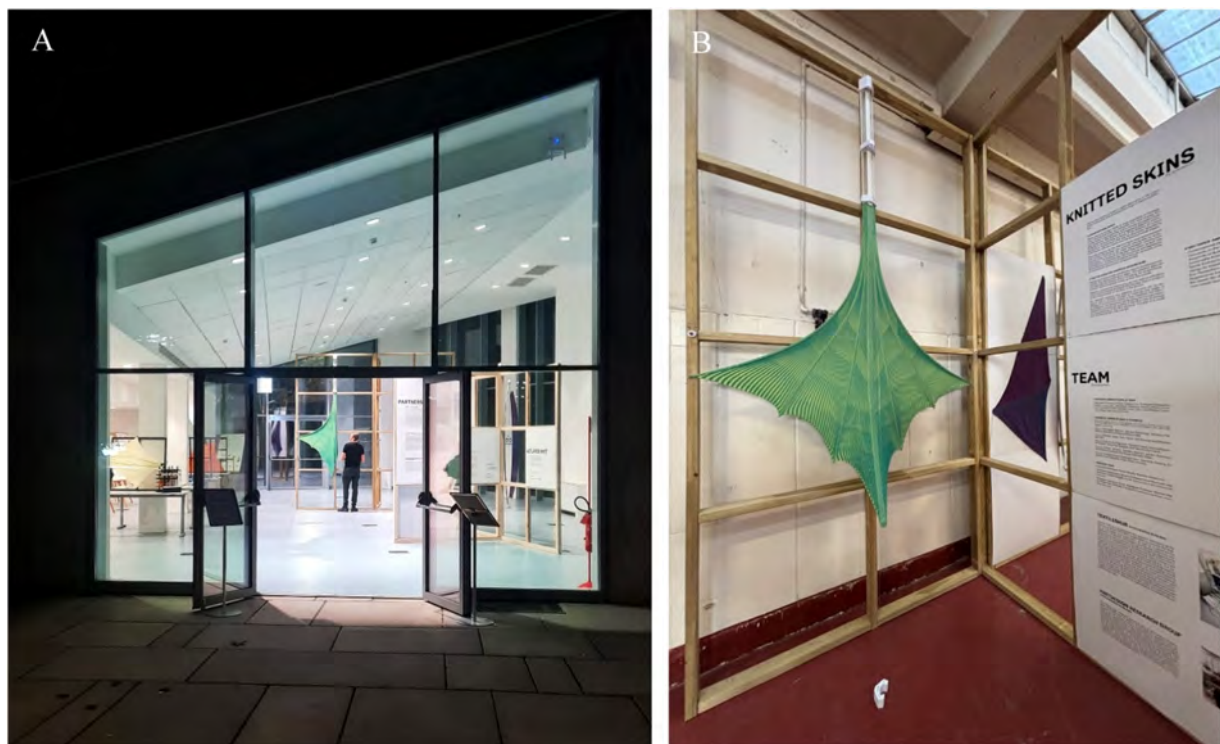


**FIGURE 21**  
Work in progress picture of the three panels before the assembly through linking.

At the very end, a small portion of plain knit - which is the less elastic of the knit structures explored - was used to create a functional piece of fabric to be wrapped around the 3days-printed joint and sewn into its parts.

The different structures also present a significantly different behavior when the tension is released. Larger ribs have less return

and tend to drape once closed, while the 1/1 rib has more return and remains flat and compact once back to a relaxed state. This behaviour was also strategically implemented to enhance a



**FIGURE 22**  
Display of the Manta Prototype at Polimi in the frame of the Actuated Knit exhibition ((A): October 2024) and during the Milano Design week in the frame of the “Actuated Knit//Textilemorphosis” exhibition ((B): April 2025).

draped effect of the Manta once returned to the closed position (Figure 17).

### 3.6.6 Programming of shape

Manta Knit is obtained through a fully-fashioned knitting process, that, through increases and decreases in the number of stitches allows to obtain shaped pieces with no cuts, resulting in a zero-waste technique which can be considered as the additive manufacturing of textiles.

Manta is made of three triangular pieces knitted starting from larger bottom parts which are gradually decreased to become smaller on the top.

To combine the fully-fashioning process of the shape with the gradual change of the rib module along the length of the piece, a complex type of internal decreasing was involved. In garment knitting, typically the number of stitches moved in each decrease is constant, while in this specific use of a rib structure, prior trials proved that the same system would compromise the elasticity. Decreases were thus positioned in varied customized cycles, always performed from the centre of each fully-fashioned piece towards the side, and alternating them on knit and purl stitches, going from 5/5 ribs to a 4/5 rib decreasing on the knits, then to a 4/4 by decreasing on the purls, repeating the process to get a 3/4, 3/3, 2/3, 2/2, 1/2, and finally a 1/1. This type of iteration creates a scale effect which is even more emphasized by the plating technique, which—creating contrast between knits and purls - visually stresses the transition from one rib ratio to the other (Figures 18, 19).

The knitted components of the Manta were conceived to integrate glass fibre rods. Fully-fashioned knitting enables the inclusion of multiple structural configurations within a single fabric, minimizing post-processing and optimizing energy, time, and material efficiency. The Manta structure comprises six rib-knit segments (three mirrored per side) separated by channels of variable width. These channels are open at the top and closed at the bottom, allowing rod insertion from above. A vertical slit, positioned 5 cm from the base on the reverse side, permits full insertion to the channel ends.

### 3.6.7 Production and assembly

The Manta consists of six rib sections alternated with seven channels. Although a single-piece construction would be theoretically feasible, the Shima Seiki SSR112 (gauge 12) used for production had needle-beds too narrow to accommodate the full width of the tensile structure (Figure 20). The Manta had to be divided into three parts: a central panel (one wide central channel and two lateral ribs, 320 needles) and two mirrored lateral panels (two rib portions divided by a central tubular channel and bordered by two outer channels, 340 needles each) (Figure 21).

The Manta’s geometry can be simplified as two mirrored triangles, with knitting oriented along the central axis dividing them. As knitting progresses bottom-up, the process follows this direction. Producing such shapes is complex due to the difficulty of sharply increasing the number of active loops over a few rows. To achieve the triangular formation, knitting began from a wider cast-on and employed partial knitting, that introduces excess fabric and

reorients the stitch direction, to gradually shape the angle. This unbalanced technique increases the risk of loop drop due to uneven tension, requiring precise control of the take-down system.

Once knitted, the three panels are assembled using a circular linking machine specific for knitwear, to control the elasticity of the seam and obtain an adaptable joint that perfectly follows the movements that the whole fabric needs to be able to perform. The linking machine can be also set up using the same yarns used to knit the fabric, resulting in a mono-material textile component which has the exact same colour, has the same reaction to steaming and washing phases and which is also potentially easy to disassemble and recycle at the end of the life of the product.

### 3.7 Manta ray development and prototype

The Manta Ray prototype was developed over a 6-month period, culminating in its exhibition at the Politecnico di Milano in September 2024 and later at Milan Design Week in spring 2025. The initial *design research phase* was conducted in collaboration with a dedicated group of students. Beginning from first principles, the team explored actuation strategies and developed a 1:3 scale working prototype. This early version featured a woven mesh textile surface and was manually actuated, serving as a proof of concept.

The subsequent *development research phase* focused on two parallel tracks: the refinement of the knitted textile system and the engineering of the bending-active structure with integrated 3D-printed joints.

The development of the knitting programs required 2 months of work, but represents a solid and reasonably adaptable foundation in case Manta production is scaled up in the future. The pieces each take 50 min to be knitted off stably, for a total of 2 h and 30 min of total knitting time. The weight of the waste produced is approximately 20 g in total. The significant amount of time for development was due to the unprecedented needs of tensile structures, not common in the usual development of knitted garments. Starting from the present iteration, future research could focus on defining a programming framework more specifically tailored to the generation of tensile structures.

For prototyping and exhibition purposes, timber frames were employed as temporary scaffolds. These were later adapted into self-supporting structures for the installation at Politecnico di Milano (Figures 22A,B). The frames were dimensioned to reflect the scale of the ABC building's façade, though simplified through the use of half-lap timber joints. The Manta Ray system was mounted directly onto these frames using screws, while pulleys were embedded into the timber using hex nuts. This assembly strategy could alternatively be executed with 3D-printed joints, offering a more seamless simulation of a façade transformation on an existing building.

The assembly process was intentionally designed for speed and simplicity. The Manta Ray structure, including the 3D-printed joints and actuation system, was affixed to the timber façade at a limited number of predefined points. The frame itself provided precise positioning for all components, eliminating the need for on-site measurements and significantly reducing installation time.

Disassembly was equally efficient. The system's linear, flat-packable design facilitated straightforward transport and storage. This modularity enabled a rapid reinstallation of the prototype at

Milan Design Week, where it operated continuously for three weeks—10 h per day—without any mechanical failures or interruptions.

## 4 Discussion

We investigated the architectural potential of CNC-knitted systems by focusing on programmable elasticity, interdisciplinary design processes, and full-scale prototyping. The results demonstrate both the strengths and limitations of integrating knitted textiles into adaptive architectural systems.

### 4.1 Material behavior and elasticity

A key outcome was the demonstration that rib knit structures can achieve reversible elasticity through geometry rather than synthetic elastic yarns. This approach allowed us to use natural fibers—typically not associated with elasticity—in adaptive systems. The shift from material-based to geometry-based elasticity is significant, as it opens new pathways for sustainable design by reducing reliance on fossil-based materials.

CNC knitting enabled precise control over the knit structure, allowing elasticity to be embedded at the stitch level. This capability was validated through both small-scale samples and a full-scale prototype exhibited two times in Milan. Over the 4-week exhibition at Milan Design Week, the rib knit fabric and embedded GFRP rods showed no signs of fatigue or deformation, indicating promising durability. However, the resulting textile was relatively thick and heavy, which may limit its responsiveness and scalability. Future iterations will need to explore lighter yarns and optimized knit densities to improve performance without compromising structural integrity.

### 4.2 Testing and evaluation

To assess the elasticity of the knitted samples, we developed a rapid, low-tech testing method. Each sample could be produced and evaluated within minutes, providing a practical tool for early-stage design decisions. While the method lacks full repeatability due to manual execution, it proved sufficient for comparative analysis during prototyping.

However, scaling up testing remains a challenge. Existing bi-axial testing machines and protocols are not well-suited to the anisotropic and highly elastic nature of knitted textiles. This points to a broader issue: current testing standards and tools are not yet adapted to the unique behaviors of textile-architectural hybrids (Christidi et al., 2025; Tamke et al., 2015). Developing new testing protocols that account for the dynamic and directional properties of knits will be essential for advancing this field.

### 4.3 Visual behavior and surface expression

The rib knit structure also enabled a dual-state visual effect by embedding two yarn colors. In the relaxed state, one color

TABLE 2 Two-phase research-by-design workflow for adaptive façade development.

Phase	Objective	Steps	Feedback loop
Phase 1 – Design research	Establish conceptual and functional goals for the adaptive façade system, focusing on solar shading, actuation principles, and architectural integration	<ul style="list-style-type: none"> <li>- State-of-the-art review to define performance benchmarks and design criteria</li> <li>- Exploratory prototyping using proxy materials and small-scale models to test bending-active principles and spatial configurations</li> <li>- Digital simulation for environmental analysis and geometric feasibility</li> </ul>	Insights from physical models and simulations informed design iterations, refining actuation strategies and structural logic before scaling up
Phase 2 – Development research	Translate conceptual strategies into technically viable solutions through material innovation and fabrication integration	<ul style="list-style-type: none"> <li>- Material sampling to define knit structures and yarn behavior at stitch level</li> <li>- CNC programming and fabrication of full-scale components based on performance criteria from phase 1</li> <li>- Integration testing of knitted textiles with bending-active elements and actuation systems</li> </ul>	Empirical tests on elasticity, assembly feasibility, and actuation performance guided adjustments to knit geometry, rib ratios, and structural interfaces

dominates; under tension, the second color becomes visible. This creates a dynamic surface that responds visually to movement and deformation.

In small-scale samples, the color shift was clear and striking. However, in the full-scale manta ray prototype, the effect was more subdued. The complexity of the CNC knit pattern and the shaping of the textile surface diluted the visual contrast. This highlights a trade-off between logics on knit level and visual clarity. Achieving a strong visual effect at scale may require simpler knit patterns or more strategic color placement. Additionally, the interaction of yarns within the knit structure affects color blending, necessitating careful sampling and testing during the design phase.

#### 4.4 Actuation and mechanical integration

The integration of elastic knit with a bending-active system using GFRP rods allowed for a reduction in mechanical complexity. The movement achieved through this hybrid system would be difficult to replicate with rigid components alone. The rods showed no fatigue during the exhibition, and the overall actuation was stable and reliable.

Despite these successes, the actuation system presented some limitations. The pulley-based mechanism was easy to implement and control, the necessary motor unit became in its final iteration however quite bulky, compromising the goal of fully integrating the system behind the textile wings. The mechanisms exposed nature also raises concerns about long-term durability and weather resistance in real-world applications. Moreover, the complexity of the system increases with the number of motors required. Future designs should explore more compact and integrated solutions, such as single-motor systems with staggered spools or wireless. Mesh-networked control systems could simplify wiring and allow to manage multiple units simultaneously.

#### 4.5 Architectural performance and spatial dynamics

At the architectural scale, the manta ray prototype demonstrated how knitted textiles can enable dynamic spatial transformations. The structure transitions between two archetypal states: a taut

membrane and a draped curtain. These states reflect the dual heritage of textile architecture—the tent and curtain (Ramsgaard Thomsen and Bech, 2011) — balancing functional performance with expressive potential.

The transitions between these states are not merely mechanical but choreographed spatial events. Gravity, material behavior, and timing all contribute to the experience of movement. The inclusion of GFRP rods helped stabilize and guide the folding process, ensuring smooth transitions. The speed and sequencing of wing movement and membrane lifting were also critical in shaping the spatial and environmental performance, particularly in terms of shading and light modulation.

However, current digital design tools are limited in their ability to simulate these transitional states. Most membrane design software focuses on fully tensioned geometries, neglecting the intermediate configurations that are central to the expressive and performative qualities of knitted structures. This gap in simulation capabilities presents a significant barrier to the broader adoption of knitted systems in architecture.

#### 4.6 Methodological reflections

The research employed a two-phase research-by-design methodology, structured to integrate architectural form-finding and textile material design through iterative prototyping and evaluation. This approach was organized into a reproducible workflow comprising (1) Design Research and (2) Development Research phases, each with defined steps, criteria, and feedback loops (Table 2).

Reflecting on the implementation of this approach, it can be stated that it in our case effectively facilitated a dynamic exchange between top-down design intent and bottom-up material behavior. In our case, early and sustained interdisciplinary collaboration was crucial. Textile designers contributed deep material expertise, while architects translated spatial and performative ambitions into a coherent concept and set of specifications. The success of the project relied on mutual respect, openness, and a willingness to iterate.

Prototyping played a central role throughout the process. Physical samples, hand models, and digital simulations were employed in tandem to test hypotheses and refine designs. This iterative, evidence-based approach proved essential for addressing the complexities of textile-architectural integration. However, it also demanded significant time,

resources, and expertise, underscoring the need for dedicated frameworks to support such interdisciplinary work.

## 4.7 Conclusion

The exploratory research presented here positions CNC-knitted textiles as a viable and innovative material system for the next-generation of adaptive building envelopes. By shifting from conventional woven materials to programmable knits, the project introduces a new design paradigm—one in which material behavior is not a constraint but a driver of architectural form and function.

The Manta Ray prototype illustrates the feasibility of this approach. Through the integration of knitted textiles and bending-active GFRP rods, the system achieves responsive movement with minimal mechanical complexity. The result is a lightweight shading system that aligns with demands for sustainable and adaptable architecture. The durability and reliability of the prototype during the two exhibitions indicates its potential for real-world application.

Looking ahead, several key areas for future development emerge:

- **Simulation and Design Tools:** To move forward future projects would strongly benefit from digital tools that can simulate the initial and transitional states of knitted textiles. Especially the intermediate configurations are critical to both the performance and expression of textile-based systems, yet they remain poorly supported by current software. Here simulation environments such as Kangaroo or animation-based textile solvers can visualize such transitions, they remain of limited use for fabrication purposes. Advancing simulation environments that bridge this gap will be essential for integrating knitted systems into mainstream architectural workflows.
- **Material Optimization:** The current prototype used relatively thick and heavy yarns, which limited responsiveness. Future iterations should explore lighter materials and optimized knit structures to enhance performance while maintaining durability. Balancing elasticity, visual clarity, and structural integrity will be key to tailoring knitted systems for diverse architectural contexts. While overall bending limitation in curvature of the beams is easily done, wind-load analysis in different states as well as outdoor tests of yarn and structure would provide indications of further avenues for development. Testing of the yarns hydrophilicity would provide indicators of eventual weight gain from rain and the implication on the structure could e.g., be countered with larger diameter stiffer rods.
- **Scalability and Integration:** While the prototype demonstrated the feasibility of knitted actuation systems, further work is needed to refine and miniaturize the mechanical components. Wireless control systems, modular actuation strategies, and more compact integration methods could make these systems more viable for large-scale deployment.
- **Sustainable Fabrication:** CNC knitting offers significant advantages in terms of material efficiency and customization. Because knitted fabrics can be produced seamlessly and without waste, they support sustainable fabrication practices. Moreover, the ability to vary pattern, color, and elasticity at no additional production cost allows for site-specific adaptation and expressive versatility. The

industrial production process and near product state of the Mantas would allow for a LCA analysis.

- **Interdisciplinary Practice:** Finally, the project underscores the importance of research-by-design and interdisciplinary collaboration. The integration of textile and architectural expertise enabled a holistic approach to design, where material, structure, and space were developed in concert. Scaling this approach will require new educational models, collaborative platforms, and institutional support.

In conclusion, CNC-knitted textiles offer a compelling framework for rethinking adaptive architecture. Their programmable elasticity, responsiveness to environmental forces, and seamless fabrication unlock new possibilities for building skins that are not only performative and sustainable but also richly expressive. This research lays the groundwork for future explorations where material intelligence and architectural design converge.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

MT: Writing – original draft, Supervision, Funding acquisition, Investigation, Conceptualization, Writing – review and editing, Resources, Validation, Project administration, Formal Analysis, Methodology, Data curation, Visualization. DD: Formal Analysis, Conceptualization, Methodology, Resources, Visualization, Writing – original draft, Writing – review and editing, Investigation, Validation, Data curation. MF: Investigation, Visualization, Data curation, Formal Analysis, Conceptualization, Validation, Methodology, Writing – original draft, Writing – review and editing. CE: Formal Analysis, Validation, Data curation, Writing – review and editing, Methodology, Investigation, Visualization. LM: Visualization, Writing – original draft, Writing – review and editing, Investigation, Data curation, Methodology, Conceptualization. SA: Visualization, Writing – review and editing, Validation, Investigation, Conceptualization, Data curation. MM: Data curation, Writing – original draft, Visualization, Methodology, Validation, Investigation, Formal Analysis, Writing – review and editing, Conceptualization, Supervision. AZ: Data curation, Investigation, Resources, Conceptualization, Funding acquisition, Writing – review and editing, Methodology, Validation, Project administration, Formal Analysis.

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## Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## References

- Ahlquist, S., Lienhard, J., Knippers, J., and Menges, A. (2013). Physical and numerical prototyping for integrated bending and form-active textile hybrid structures. 1–14. Available online at: [https://www.researchgate.net/profile/Sean\\_Ahlquist/publication/301551388\\_Physical\\_and\\_Numerical\\_Prototyping\\_for\\_Integrated\\_Bending\\_and\\_Form-Active\\_Textile\\_Hybrid\\_Structures/links/5718ea9108aed43f63234b95/Physical-and-Numerical-Prototyping-for-Integrated-Bending-and-Form-Active-Textile-Hybrid-Structures.pdf](https://www.researchgate.net/profile/Sean_Ahlquist/publication/301551388_Physical_and_Numerical_Prototyping_for_Integrated_Bending_and_Form-Active_Textile_Hybrid_Structures/links/5718ea9108aed43f63234b95/Physical-and-Numerical-Prototyping-for-Integrated-Bending-and-Form-Active-Textile-Hybrid-Structures.pdf).
- Attia, S., Bilir, S., Safy, T., Struck, C., Loonen, R., and Goia, F. (2018). Current trends and future challenges in the performance assessment of adaptive façade systems. *Energy Build.* 179, 165–182. doi:10.1016/j.enbuild.2018.09.017
- Barozzi, M., Lienhard, J., Zanelli, A., and Monticelli, C. (2016). The sustainability of adaptive envelopes: developments of kinetic architecture. *Procedia Eng.* 155, 275–284. doi:10.1016/j.proeng.2016.08.029
- Black, S. (2002). *Knitwear in fashion*. London, United Kingdom: Thames & Hudson. Available online at: <https://www.abebooks.com/9780500510841/Knitwear-Fashion-Black-Sandy-0500510849/plp> (Accessed October 19, 2025).
- Bolaji, J. T., and Dolez, P. I. (2024). Mechanical properties of woven fabrics containing elastane fibers. *Fibers* 12, 30. doi:10.3390/fib12040030
- Christidi, N., Louter, C., and Popescu, M. (2025). Planar biaxial tensile testing of weft-knitted textiles with varying knit architectures. doi:10.2139/ssrn.5233494
- Davis-Sikora, D., Liu, R., and Ohrn-McDaniel, L. (2020). Form-finding and fabrication of BeTA pavilion: a bending-active biotensegrity textile assembly. *SN Appl. Sci.* 2, 2011. doi:10.1007/s42452-020-03363-0
- Deleuran, A. H., Pauly, M., Tamke, M., Tinning, I. F., and Thomsen, M. R. (2016). Exploratory topology modelling of form-active hybrid structures. *Procedia Eng.* 155, 71–80. doi:10.1016/j.proeng.2016.08.008
- Eichhorn, S. J., Hearle, J. W. S., Jaffe, M., and Kikutani, T. (2009). *Handbook of textile fibre structure*. Cambridge, United Kingdom: Woodhead Publishing Limited. doi:10.1533/9781845696504
- European Commission. Joint Research Centre (2023). *Prospect for European guidance for the structural design of tensile membrane structures: support to the implementation, harmonisation and further development of the eurocodes*. Luxembourg: Publications Office of the European Union. Available online at: <https://data.europa.eu/doi/10.2760/24763> (Accessed October 20, 2025).
- Gengnagel, C., La Magna, R., Ramsgaard Thomsen, M., and Tamke, M. (2018). Shaping hybrids-form finding of new material systems. *Int. J. Arch. Comput.* 16, 91–103. doi:10.1177/1478077118778587
- Gitelson-Kahn, A., Hartmann, J., and Missoni, L. (2023). Color in knitting: by designers, for designers.
- Goldsmith, N. (2016). The physical modeling legacy of frei Otto. *Int. J. Space Struct.* 31, 25–30. doi:10.1177/0266351116642071
- Göppert, K., Paech, C., and Stein, M. (2013). Design of a new landmark for Vancouver - BC Place Stadium. *Proc. IASS Annu. Symp.* 2013, 1–5.
- Koch, K.-M., and Habermann, K. J. (2004). *Membrane structures: innovative building with film and fabric*. Germany: Prestel. Available online at: <https://www.abebooks.co.uk/9783791330495/Membrane-Structures-Innovative-Building-Film-3791330497/plp>.
- Lazzari, M., Majowiecki, M., Vitaliani, R. V., and Saetta, A. V. (2009). Nonlinear F.E. analysis of Montreal Olympic stadium roof under natural loading conditions. *Eng. Struct.* 31, 16–31. doi:10.1016/j.engstruct.2008.07.010
- Lienhard, J. (2014). Bending-active structures: form-finding strategies using elastic deformation in static and kinetic systems and the structural potentials therein. Available online at: <http://nbn-resolving.de/urn:nbn:de:bsz:93-opus-94838> (Accessed October 20, 2025).
- Lienhard, J., and Knippers, J. (2015). Bending-Active Textile hybrids. *J. Int. Assoc. Shell Spat. Struct.* 56, 37–48.
- Lienhard, J., Schleicher, S., Poppinga, S., Masselter, T., Milwich, M., Speck, T., et al. (2011). Flectofin: a hingeless flapping mechanism inspired by nature. *Bioinspir. Biomim.* 6, 045001. doi:10.1088/1748-3182/6/4/045001
- Liu, Z., He, Q., Zou, F., Ding, Y., and Xu, B. (2019). Apparel ease distribution analysis using three-dimensional motion capture. *Text. Res. J.* 89, 4323–4335. doi:10.1177/0040517519832842
- Liu, Z., Han, X., Zhang, Y., Chen, X., Lai, Y.-K., Doubrovski, E. L., et al. (2021). Knitting 4D garments with elasticity controlled for body motion. *ACM Trans. Graph.* 40, 1–16. doi:10.1145/3450626.3459868
- Mazzola, C., Zanelli, A., Stimpfle, B., and Canobbio, R. (2021). Temporactive pavilion: second design-to-construction loop of an ultra-lightweight temporary architecture. *Archit. Eng. Des. Manag.* 17, 216–228. doi:10.1080/17452007.2020.1769545
- McKeen, L., and Ebnesajjad, S. (2023). “Chapter 8 - expanded polytetrafluoroethylene: basic properties, characteristics and microstructure,” in *Handbook of thermoplastic fluoropolymers*. Editors L. McKeen, and S. Ebnesajjad (Boston, MA: William Andrew Publishing), 41–45. doi:10.1016/B978-0-323-91627-1.00015-3
- Monticelli, C., and Zanelli, A. (2021). Material saving and building component efficiency as main eco-design principles for membrane architecture: case - studies of ETFE enclosures. *Archit. Eng. Des. Manag.* 17, 264–280. doi:10.1080/17452007.2020.1768507
- Montilla, R. B. (1969). The awnings of roman theatres and amphitheatres. *Theatre Surv.* 10, 75–88. doi:10.1017/S0040557400007419
- Otto, F., and Rasch, B. (1992). Finding form: towards an architecture of the minimal. Germany. Available online at: [http://archive.org/details/isbn\\_3930698668](http://archive.org/details/isbn_3930698668) (Accessed October 20, 2025).
- Procaccini, G. (2025). Textile materials and retrofit strategies. New frontiers for energy efficiency. *TECHNE - J. Technol. Archit. Environ.* 29, 299–308. doi:10.36253/techne-16600
- Quinn, G., Deleuran, A. H., Piker, D., Brandt-Olsen, C., Tamke, M., Thomsen, M. R., et al. (2016). Calibrated and interactive modelling of form-active hybrid structures. *Proc. IASS Annu. Symp.* 2016, 1–9.

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Ramsgaard Thomsen, M., and Bech, K. (2011). *Textile logic for a soft space. København: the royal danish academy of fine arts, schools of architecture, design and conservation, school of architecture. Copenhagen, DK: Arkitektens Forlag.*

Ramsgaard Thomsen, M., and Tamke, M. (2009). in *Narratives of making: thinking practice led research in architecture*. Editor J. Verbeke, 1–8. Available online at: [https://www.researchgate.net/publication/313768586\\_Narratives\\_of\\_making\\_thinking\\_practice\\_led\\_research\\_in\\_architecture](https://www.researchgate.net/publication/313768586_Narratives_of_making_thinking_practice_led_research_in_architecture) (Accessed April 24, 2017).

Ramsgaard Thomsen, M., and Tamke, M. (2023). “Zoirotia,” in *BioMedia - the Age of media with life-like behavior*, Available online at: <https://zkm.de/en/publication/biomed> (Accessed January 18, 2024).

Ramsgaard Thomsen, M., Sinke, Y., Montero, F., Lienhard, J., La Magna, R., and Tamke, M. (2019). in *Systems for transformative structure in CNC knitted fabrics - isoropia*. Editors A. Zanelli, C. Monticelli, M. Mollaert, and B. Stimpfl, 95–110.

Singal, K., Dimitriyev, M. S., Gonzalez, S. E., Cachine, A. P., Quinn, S., and Matsumoto, E. A. (2024). Programming mechanics in knitted materials, stitch by stitch. *Nat. Commun.* 15, 2622. doi:10.1038/s41467-024-46498-z

Sinke, Y. (2025). *Differentiated Knit Materiality: simulation for discovery of novel material gradings for CNC-knitted architectural membranes*. Copenhagen Denmark: The Royal Danish Academy - Architecture, Design, Conservation.

Sinke, Y., Ramsgaard Thomsen, M., Albrechtsen, D. S. S., and Tamke, M. (2022). “Design-to-production workflows for CNC-knitted membranes: ACADIA 2022,” in *Hybrids & Haecceities: proceedings of the 2022 Acadia conference* (Philadelphia,

United States: ACADIA: University of Pennsylvania). Available online at: [http://acadia.org/content/conferences#past\\_conferences](http://acadia.org/content/conferences#past_conferences).

Sinke, Y., Thomsen, M. R., Tamke, M., and Seskas, M. (2023). “Strategies for encoding multi-dimensional grading of architectural knitted membranes,” in *Towards radical regeneration*. Editors C. Gengnagel, O. Baverel, G. Betti, M. Popescu, M. R. Thomsen, and J. Wurm (Cham: Springer International Publishing), 528–542. doi:10.1007/978-3-031-13249-0\_42

Tamke, M., Deleuran, A., Gengnagel, C., Schmeck, M., Cavalho, R., Figueiro, R., et al. (2015). in *Designing CNC knit for hybrid membrane and bending active structures*. Available online at: [https://upcommons.upc.edu/bitstream/handle/2117/109359/Designing\\_cnc\\_knit\\_281\\_295.pdf](https://upcommons.upc.edu/bitstream/handle/2117/109359/Designing_cnc_knit_281_295.pdf).

Tamke, M., Sinke, Y., Monteiro, F., Lienhard, J., La Magna, R., and Ramsgaard Thomsen, M. (2020). Computational Knit - design and Fabrication Systems for Textile structures with customised and graded knitted fabrics. *Archit. Eng. Des. Manuf.* doi:10.1080/17452007.2020.1747386

Thomsen, M. R., Tamke, M., Deleuran, A. H., Tinning, I. K. F., Evers, H. L., Gengnagel, C., et al. (2015). in *Hybrid tower, designing soft structures*. Editors M. R. Thomsen, M. Tamke, C. Gengnagel, B. Faircloth, and F. Scheurer (Cham: Springer), 87–99. doi:10.1007/978-3-319-24208-8\_8

Wolff, K., Herholz, P., Ziegler, V., Link, F., Brügel, N., and Sorkine-Hornung, O. (2023). Designing personalized garments with body movement. *Comput. Graph. Forum* 42, 180–194. doi:10.1111/cgf.14728