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Simulation-based analysis methods for differentiation strategies of CNC-knitted membranes for architectural application

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Abstract

Knitting technology through its ability to steer material composition enables the making of architectural functionally graded membranes (AFGMem). During the last decades, the research into knitted textiles for architectural application has gained an increasing interest. There, knit is understood as an innovative material system that enables complex geometry and bespoke composition for a wide range of applications with variegated performances, such as structural membranes, partition screens, casting formworks, actuated structures, and solidified shell-like-canopies. The application, functionality, and performance of the knitted structures directly determine their material differentiation through stitch structure and define the methods for informing its material composition. This paper focuses on further investigation of the simulation-driven approach for material differentiation and presents the recent advancements and the evolution of the method, demonstrated through the material design of three cases of structurally employed membrane structures.

Keywords: computational membrane design, knitted heterogeneous membranes, textile material differentiation, structural analysis, architectural CNC-knitting.

1. Introduction

Knitting membrane through its inherent nature for material grading provides a promising alternative to the traditionally woven homogeneous materials in textile architecture. Membranes, made with knit can stretch to the required 3D shape by using encoded properties of material expansion. Through the strategic placement of various stitch types, numerical programming of knitting offers precise control over the local material variation. As a result, we are able to design and manufacture highly customised textile surfaces that respond to membrane performance demands and are zero waste in nature.

The conventional method of programming knitted textiles resides within the garment design, in which identical items are mass-produced, based on the prior extensive prototyping and manual tuning of the manufacturing files. The architectural field, however, has a greater demand for highly customised non-repetitive bespoke elements, that rely on their three-dimensionality and material differentiation for their structural and geometric performance. Therefore, a study of novel methods that would allow large-scale knitted membranes to be designed taking into account their structural requirements is therefore necessary.

2. Informed material variation for knitted membranes

Before the advent of numerically controlled knitting patterns, garment patterning was based on repetitive stamping of small data across the entire textile element. The emergence of computational technologies and simulation engines has made it possible to analyse the human body, leading to the development of high-performance sportswear clothing, protective and medical equipment. There the differentiation of knit patterns is informed by the body`s 3D scan input and the required properties of support, compression, stretch andbreathability of the designed item (Adidas, 2017; Mikucioniene et al., 2020, p.; Šurc et al., 2020; Tessmer et al., 2022).

In spatial design and architectural research, the inquiry towards the questions of informing the local variation and the development of design criteria, integration of analysis and feedback to the process have led to the identification of the two central approaches for knitted material differentiation, driven by *sensing* and *simulation* (Ramsgaard Thomsen et al., 2016; Ramsgaard Thomsen, Nicholas, et al., 2019).

With the *sensing* approach*,* the local sense data is collected from the site and then interfaced with the knit fabrication files. This data enables the local transformation of knit pattern structures, resulting in variegated permeability of surface light transmission properties, as seen in Sifter and Derma screens by CITA (Ramsgaard Thomsen et al., 2016) or myThreadPavilion and DataKnit by Sabin Studio (Sabin, 2013, 2021), thereby embedding an additional layer of information to the surface.

With the *simulation* approach, the material performance is digitally simulated to be interfaced with the fabrication files. In this way, the membrane's stretch and expansion behavior can be guided by placing varying stitch types across its surface. This method application is demonstrated through precedents like Isoropia and Zoirotia structures by CITA (Ramsgaard Thomsen, Sinke Baranovskaya, et al., 2019; Sinke, Ramsgaard Thomsen, Tamke, et al., 2022), or Knitted Composite Tower by Tonji University (Liu et al., 2020) and MeiTing Canopy by Southeast University of China (Liu et al., 2022).

In this publication, the authors focus on further investigation of the simulation-driven approach for knit material differentiation and present the recent advancements and the evolution of the method through the pattern design of three cases of structurally employed tensile knitted membrane structures.

Further presented membrane material designs rely on the simulation-based approach for defining their structural shape and providing the material local differentiation guidance based on the presented analysis methods. These methods differ in their evaluation of the performance criteria of each design, which is described in detail in the methods chapter and discussed through the demonstrated design cases of Zoirotia (from 2021 and 2023) and Graded Ceiling Canopy (Figure 1).

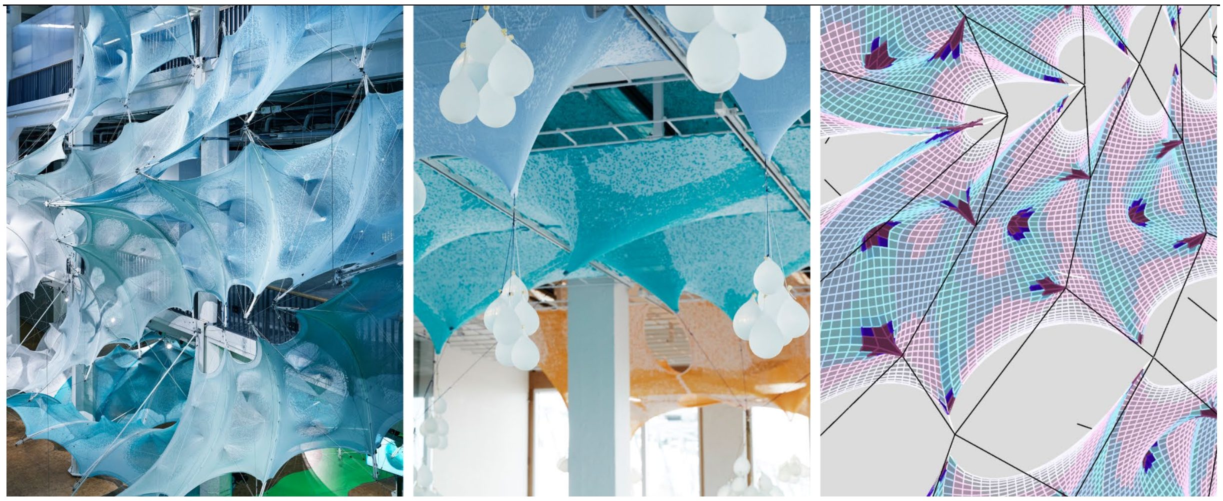

Figure 1: Three design cases, presented in the paper (left to right) - Zoirotia, Graded Ceiling and Zoirotia 2.0

In the first design case - Zoirotia - the distribution of stitches is informed by the form-finding simulation and supported by the geometrical analysis in order to achieve material differentiation allowing the membranes to expand further out from their planes. The second case - Graded Knitted Ceiling, challenges the non-perpendicular tension of the fabric and therefore explores an alternative approach towards material differentiation through the use of simulation-supported structural analysis of surface tensile utilisation. There, identifying the tension concentration on membranes enables the placement of stitches of larger and smaller dimensions to guide membrane expansion. The third case is a digital exploration of reapplying the method of structural analysis for material differentiation back to the first design case of Zoirotia.

3. Method - from form-finding to material programming

In this paper, we discuss *analysis methods* that have been recently developed as part of a comprehensive design-to-production workflow for CNC-knitted membranes, the advancement of which incrementally increased in the work of authors within research activities of CITA - Center for IT and Architecture for the past years (Deleuran et al., 2015; Ramsgaard Thomsen, Sinke Baranovskaya, et al., 2019; Sinke Baranovskaya et al., 2020; Sinke, Ramsgaard Thomsen, Albrechtsen, et al., 2022).

There are several steps in the workflow itself, including the preparation of pre-form-finding geometry (membrane boundaries, anchors, other interfacing elements), followed by the form-finding relaxation to reach the equilibrium shape. Afterward, the form-found membrane is analyzed, linking the geometrical form of the membrane design to the surface differentiation of the material. Further, the data from the analysis is translated into pixel-based maps, containing information on stitch selection and the industrial knitting machine actions. These steps are briefly described below, with the primary focus on the analysis part of the workflow.

3.1. Form-finding

Form-finding is widely used for the design of woven-based tensile structures and is crucial in determining the equilibrium shape of tensile membranes, where the forces are set in balance. For designs made up of multiple textile pieces, a well-form-found membrane model informs the cutting pattern of the membrane elements in order to ensure an optimal fiber arrangement and efficient material use. With CNC-knitted membranes, form-finding allows not only to resolve the elements cutting pattern, but also to define the stitch-based membrane composition for steering material properties.

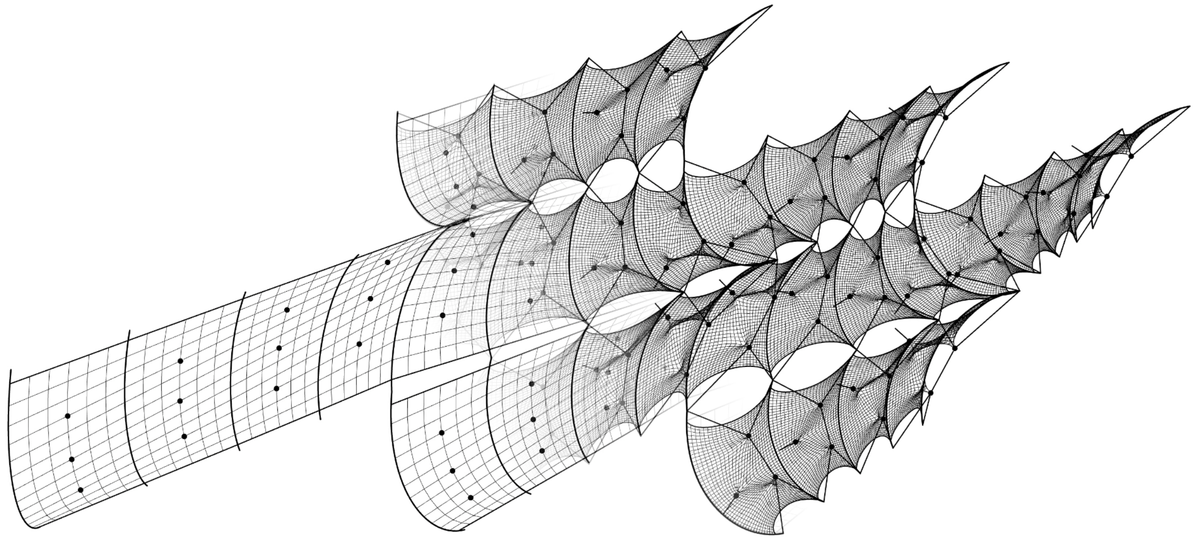

Figure 3: The form-finding set up (left side) and the corresponding equilibrium relation (right)

The form-finding setup and visualisation take place within the Grasshopper (David Rutten, 2007) environment for Rhino modeling software (Robert McNeel & Associates, 1980), where the physics simulation engines such as Kangaroo (Piker, 2013) and K2 Engineering (Brandt, 2016) plug-ins can be applied. There is a difference between the two plug-ins in terms of how the mesh properties are assigned in relation to tensile membrane form-finding. Both plug-ins are spring-based and use mesh edges (lines) as material input. Unlike Kangaroo, that requires the *spring target rest length in mm and abstract strength value as inputs, K2Engineering* operates with structural inputs of spring Young Modulus (MPa), pre-tension (Newtons) and spring cross-section area (m^2). This permits the use of the form-finding simulation in conducting further analysis of the design, based on the structure`s modifications and performance during the process of form-finding.

3.2. Analysis - geometrical and structural

In further described design examples, the priority for the membrane design is to achieve a controlled expansion of the surface by the means of strategic distribution of larger and smaller stitch types across the surface to achieve desired membrane three-dimensionality. For that, the research has developed two methods of surface evaluation - *geometric* and *structural*, where the differences lay in surface evaluation approaches (Figure 4).

The time-based digital form-finding permits the analysis of geometrical performance through the comparison of membrane state *before* and *after* applying the loads. This informs the knitting pattern and leads to an integrated membrane design with a stronger connection between the geometry and material composition, unlike in the knitted material designs, where arbitrary and manually defined surface differentiations are loosely connected to the global geometry and structural performance (Ramsgaard Thomsen, Sinke Baranovskaya, et al., 2019; Sinke Baranovskaya et al., 2020).

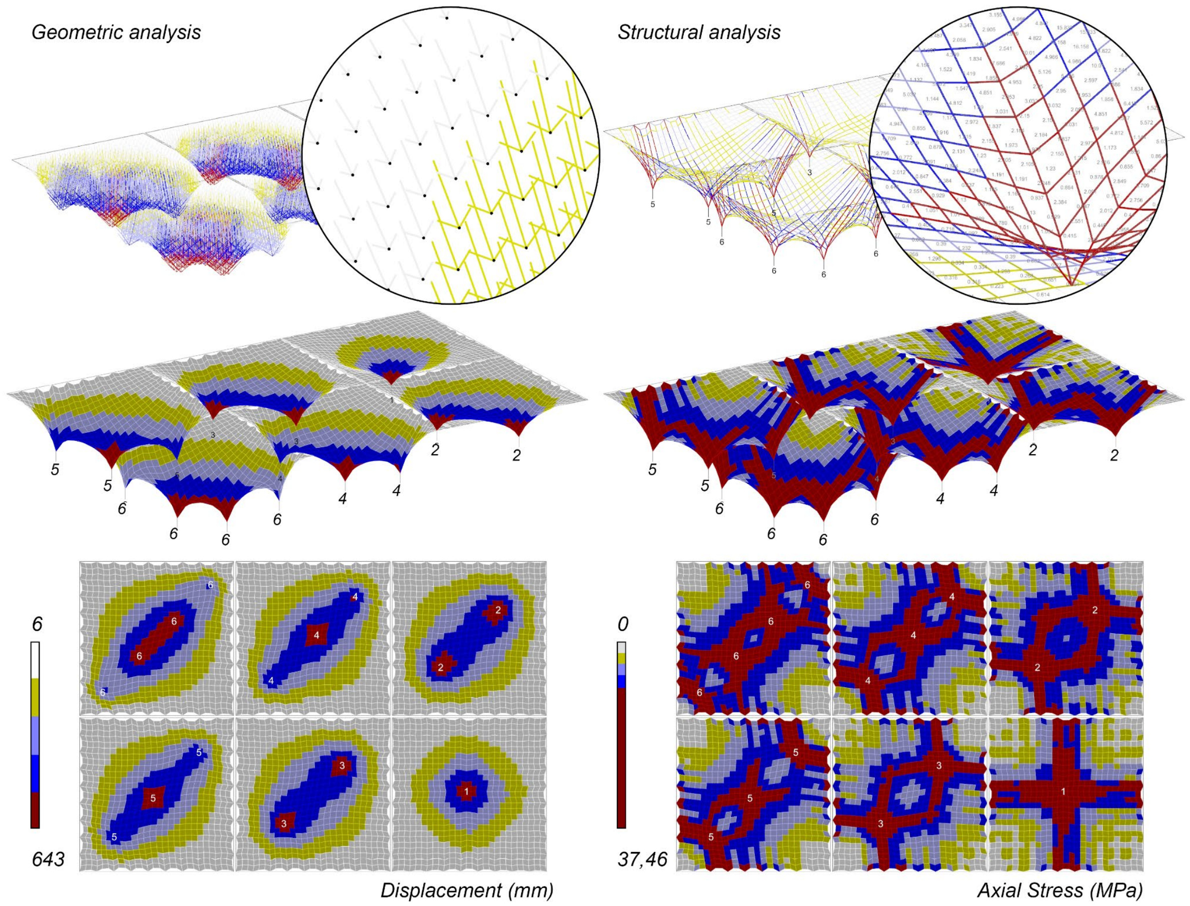

Figure 4: Diagram of geometric analysis (left) vs. structural analysis (right) approach for pattern generation

With the *geometric* analysis approach, the membrane surface is evaluated on the subject of mesh displacement over the process of form-finding. For that, the mesh face center trajectories that occur as result of form-finding are measured. The longest trajectory occurs in the point of an applied load (pull with the weight) and gradually reduces further from this point. This type of calculation can be conducted with both Kangaroo and K2Engineering plug-ins as pure geometric calculation of distance is performed.

The *structural analysis* approach relies on the forces distribution calculation in order to determine the areas of the meshes that undergo the biggest stress when under the applied loads in order to reach the final required pretension. It is crucial to use K2Engineering Solver engine for initial form-finding, as it allows to compare the axial stress (σ) within mesh before and after the loads are applied, where Bar is the simplest structural element, that transfers forces through the axial action. Here, the BarOutput component of the plug-in calculates the axial stress values *F* per each mesh edge, following the formula (Equ. 1), where F is the axial force [N], E - Young Modulus [MPa], A is the cross-section area [mm^2], L is the current length [m and x is the extension [m]The axial stress σ is calculated by dividing force F with the cross section area A (Equ. 2).

$$F = \frac{E \cdot A}{L} \cdot x \quad (1) \qquad\qquad \sigma = \frac{E}{L} \cdot x \quad (2)$$

The resulting analysis data package contains a list of numerical values, where for the geometric approach it is the distance the mesh has traveled from the initial state to the pre-tensioned state, while for structural analysis the values show the axial stress per each mesh face in MPa. These values are then used to cluster the mesh into color zones and map the values onto the geometry. Visually the mapping visually differs a lot as seen in the diagram above (Figure 4). The geometric approach projects *concentric circles* around areas of applied load, while the structural analysis maps *cross-like* propagation around the areas of membrane loading.

The membrane deformation under the single point load results in a cone-like geometry, therefore when using geometric analysis - it projects concentrically in a circular manner around the points the membrane is pulled as it follows the geometrical changes. The structural analysis shows the forces taking the shortest path from the point of applied load to the edge of membrane clamping. Therefore the mapping results in a cross-like pattern, formed by the straight lines of forces distribution from the load point to the edges. With the increase of loading points, the resulting patterns increase in complexity, as the concentric circles and cross-like areas begin to overlap. The emerging pattern corresponds to increased mesh geometrical complexity, while also providing pattern solutions that are not possible to predict manually or analytically.

3.3. Informed differentiation and material programming

The visualisation algorithm of both analysis approaches allows for freedom in tuning the color clustering. This is defined by the number of colors and the percentage threshold of color start and end. The number of cluster colors corresponds to the mesh subdivision density (Figure 5), while the percentage threshold (%) defines the connection between the color mapping and the range of numerical values within the analysed data (Figure 6).

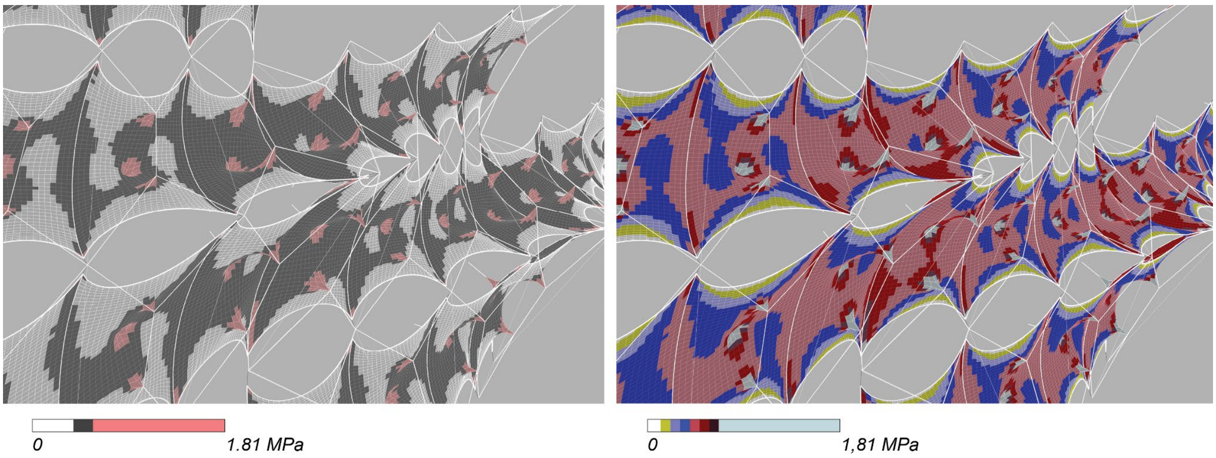

Figure 5: Color threshold diagram: 3 vs 8 colors range, shown using Zoirotia digital design case.

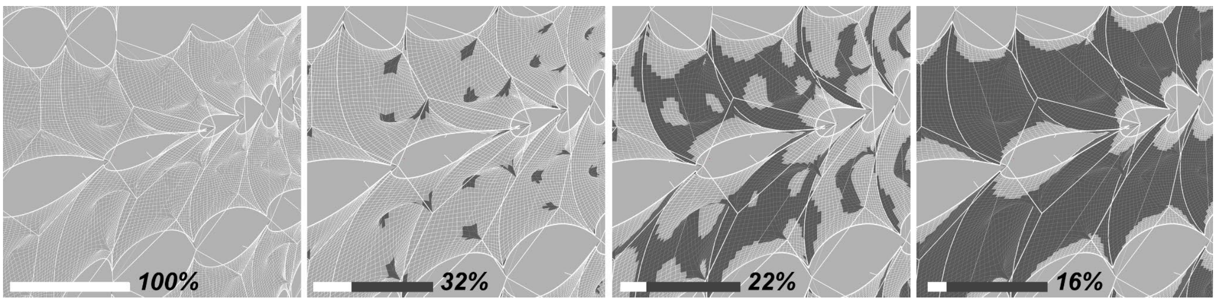

Figure 6: Gradients from 16 to 100% showing that threshold defines the part of the surface axial stress selection (here range from 0-1.56 (up to 1.81 MPa on some membranes)

The lower threshold percent involves the values at the beginning of data list, while the lower - at the end of the list. The highest (or the lowest) values are in minority within the analysed data, representing the most extreme tension or under-tensioned areas, the visualisation appears very homogeneous when taking these values. The biggest value change occurs at the range from 20-35%, therefore the pattern appears more geometry related and exciting, however this is largely dependent on the design and analysed geometry. After that, these color clusters are used to define the stitch density, informed by the percentage dithering technique, described in detail in the earlier publication by authors (Sinke, Ramsgaard Thomsen, Tamke, et al., 2022). Each color contains a certain density of larger stitch presence, in order to aid the stretch of the surface in areas of either higher displacement (geometric approach) or biggest stress (structural approach) to avoid the over-utilization of the fabric and to achieve the desired well-prestressed surface with the high degree of curvature. Dithering patterns encoded in a form of planar point clouds are then translated into color pixel-based bitmap file, that is later processed by the industrial knitting machine (Figure 7) (Sinke, Ramsgaard Thomsen, Albrechtsen, et al., 2022).

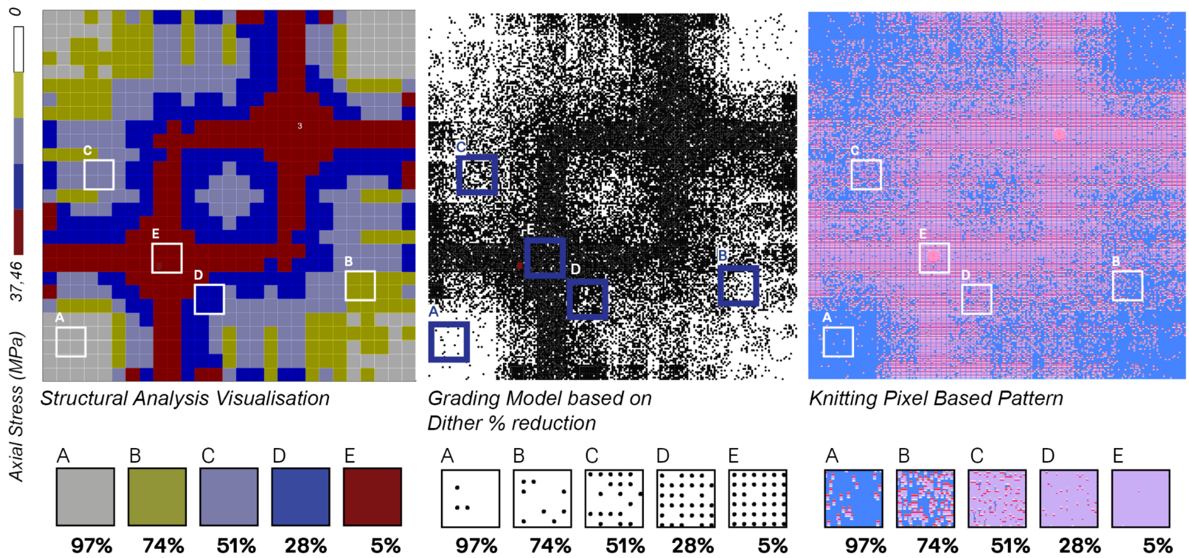

Figure 7: Translation of *structural* analysis data and surface cluster grouping into a knittable pixel-based pattern at the right resolution

4. Differentiated Knitted Membrane Design Cases

The design cases, presented below, demonstrate the application of the above-described methodological tools through differentiation patterns of membrane materials, specific to each case.

4.1 Zoirotia 2021

The first design case - Zoirotia - is a large-scale tensile installation, made of numerous bespoke knitted structural membrane units, where each is highly three-dimensional and pre-tensioned by the cablenet network. The distribution of larger and smaller stitches is informed by the form-finding simulation and supported by *geometrical* analysis, where two simulation stages are compared on the subject of displacement to identify the areas that undergo the biggest geometrical change during the simulation.

Each membrane is tensioned between the glass fiber rods from the sides and connects to the cablenet, which provides the bending for the rods and the necessary curvature for the textile surface. The cablenet interfaces with the membrane in three points, which results in the formation of cone-like tapered protrusions of the fabric when under tension. The geometric analysis leads to a material differentiation pattern of concentric circles, converged around the points of the cablenet-membrane connection (Figure 8).

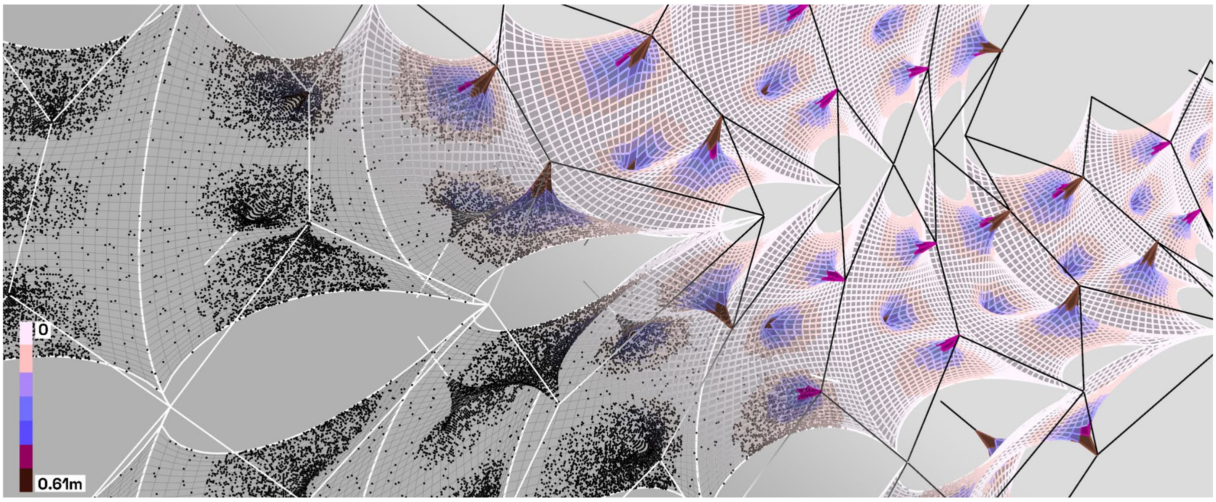

Figure 8: Clustering nature of the membrane surface (right half of image) together with informed material differentiation through dithering (left side of image), 2023.

In the initial workflow set up from the time when the installation was completed in 2021, the data from the geometric analysis was reduced to the cropped boundary of the densest color of the rich-color gradient (256 colors). The propagation of the dither pattern was then done two-dimensionally within the planarised membrane outline, rather than directly being informed by the mesh clustering derived from the analysis. This was a quick technical solution for the material differentiation part of the workflow within the given project timeline. The offset approach led to the loss of data and therefore less precise pattern definition, although close to the right one as compared in Figure 9. As described in the methods earlier, this process was later improved to maintain a more direct correspondence between form-finding and material differentiation of the membrane through the simulation-integrated mesh clustering (Figure 9, right). The zig-zag nature of the zones outlines is connected to the mesh resolution used in the simulation and post-analysis in determining these.

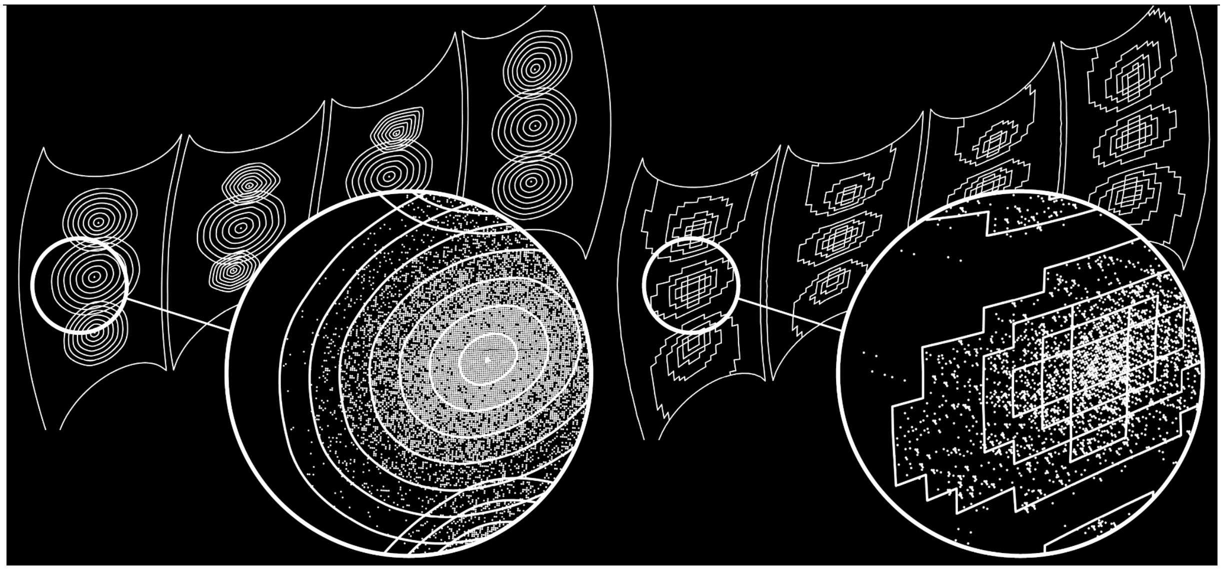

Figure 9. Material differentiation of knitting files of Zoirotia from 2021 (left) based on the planar offset vs. adjusted differentiation files from 2023 (right), based on the simulation-integrated mesh clustering, both using the geometrical analysis

4.2 Graded Knitted Ceiling Panels

The geometrical analysis is challenging to apply with the surfaces, that are not pulled perpendicular to its plane as it considers the geometrical changes rather than the structural performance of the surface. Angled loading directions create a heterogeneous distribution of membrane surface tension, leaving some surface areas in compression. This occurs due to the excessive material surface area, resulting in sagging fabrics, even with a sufficient load. (Figure 10). Insufficiently tensioned areas are preferred to be avoided within tensile membrane design as they reduce overall structural stability. For this reason, for planarly produced CNC-knitted membranes to maintain their design freedom, it is necessary to develop an alternative analysis approach that will lead to the generation of more suitable differentiation knitting patterns, thereby preventing membranes from sagging when loaded in an angled direction.

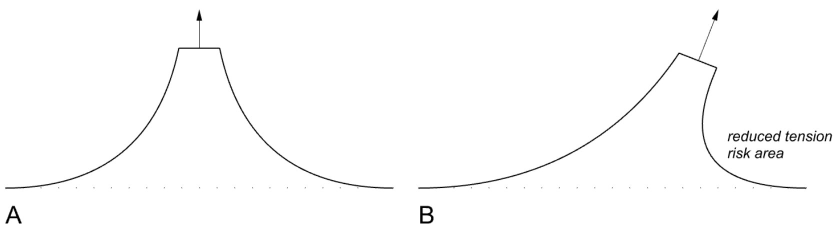

Figure 10: Perpendicular vs angled membrane loading

The second design case - Graded Knitted Ceiling Canopy, challenges and explores additional opportunities for CNC-knitted membranes material differentiation in order to permit loading direction freedom, while maintaining necessary surface tightness and expansion. This installation is a part of a workshop, held with CiA Computation in Architecture students, where the participants were testing developed by authors tools for exploring various membrane loading conditions under suspended and interconnected weights (Figure 11).

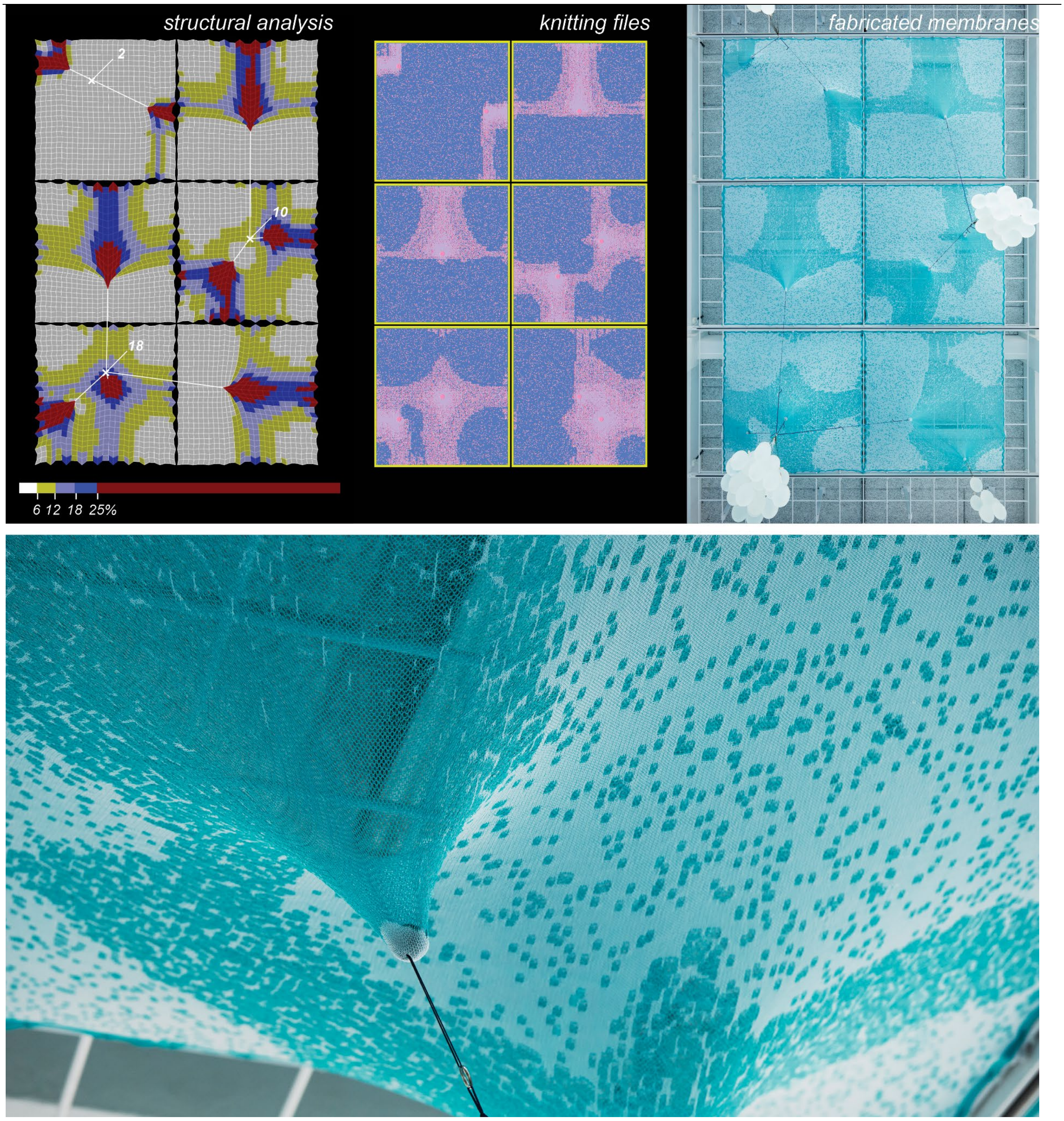

Figure 11: Structural analysis of graded panels,bitmap knitting files and the manufactured piece

The installation consists of six square textile panels made of digitally programmed CNC-knitted membranes, fixed to the ceiling. It achieves the three-dimensionality by textiles deformation under several interconnected suspended weights attached to the fabrics, thereby creating a situation where the membrane is loaded not perpendicularly, but in an angle. Consequently, this initiated the investigation into alternative patterning strategies, informed by simulation and supported by structural analysis of surface tensile utilisation. Material programming allows membrane expansion only where it is needed, by concentrating larger stitches in areas of required greater stretch, while reducing stretchiness and therefore, the presence of large stitches in the areas of reduced tension, keeping the membrane tight.

For the reasons of method evaluation, the diagram where the geometric analysis-based mesh clustering, informed by the membrane displacement under the load is overlapped with the tension analysis, highlighting in red the areas of potential compression is provided below (Figure 12). The diagram allows us to conclude that geometric analysis would create material differentiations with larger surface area in the areas where the membrane is required to be tight and therefore structural evaluation-based analysis is necessary to be used here, to achieve a better membrane performance.

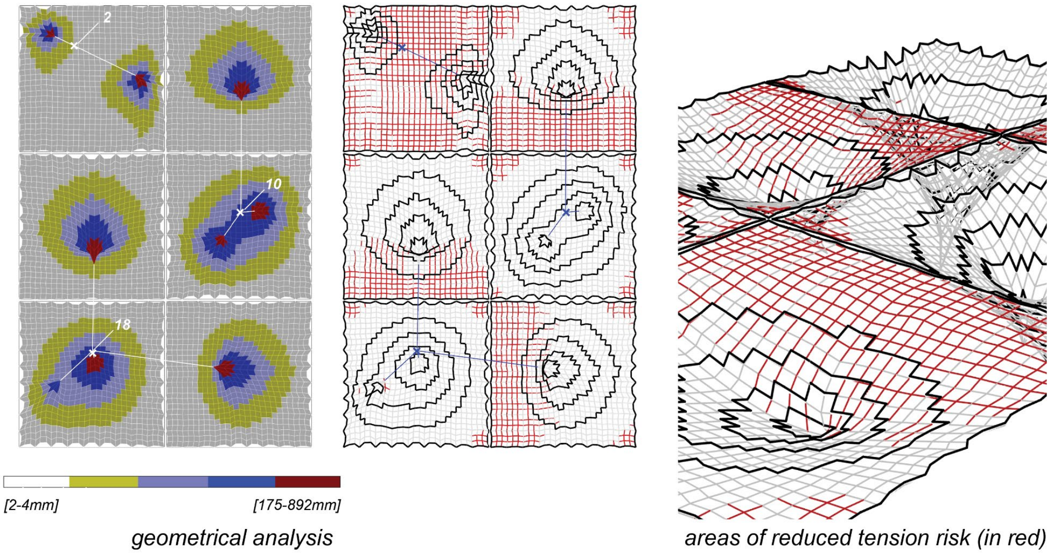

Figure 12: Diagram of material differentiation based on geometric analysis for evaluation purposes

4.3 Zoirotia 2.0 digital - 2023

The third case is a digital exploration of reapplying the method of structural analysis for material differentiation to the design case of Zoirotia. This exploration allows speculating on potential patterning outcomes of structural analysis application to a more complex design topology. The reapplication of the method results in a radically different patterning distribution in comparison to the geometrically driven approach in 4.1. In this pattern, a more sensitive approach to material differentiation is evident, as more areas of the membrane can be identified as requiring reduced or increased material density to achieve a geometrical membrane configuration as a result of stretching. A gradual change in differentiation can also be observed from the patterns once the membrane element is rotated in space or moved within the larger structure, which can be explained by the different gravity conditions applied to membranes as well as the interrelationships between membrane elements. In the diagrams below, we show potential patterning outcomes, applying a structural analysis for defining material differentiation models.

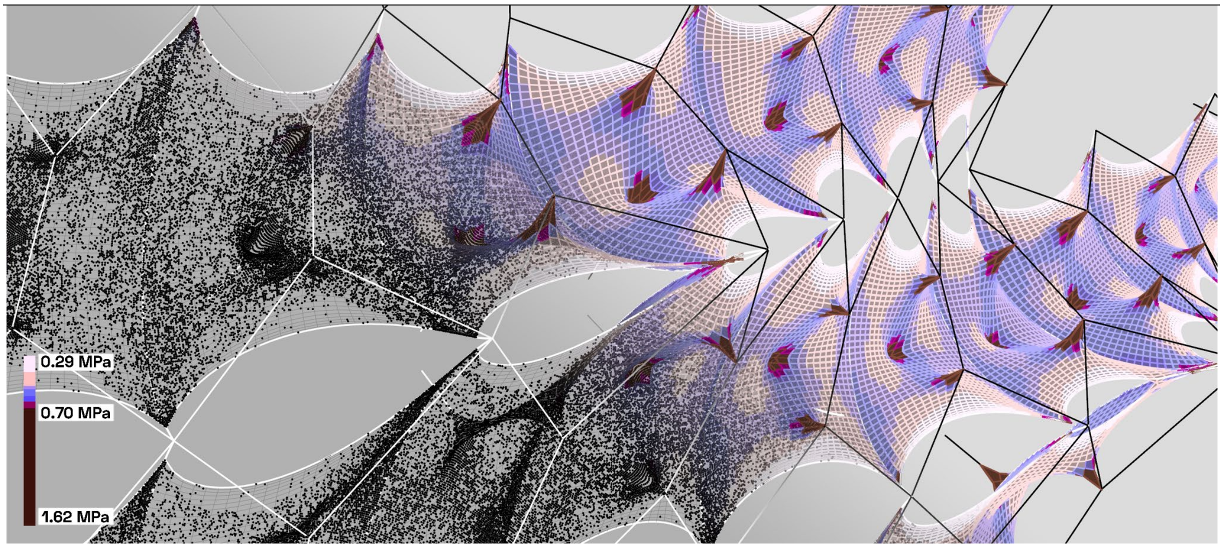

Figure 14: Zoirotia 2.0 digital exploration of structural analysis based material differentiation

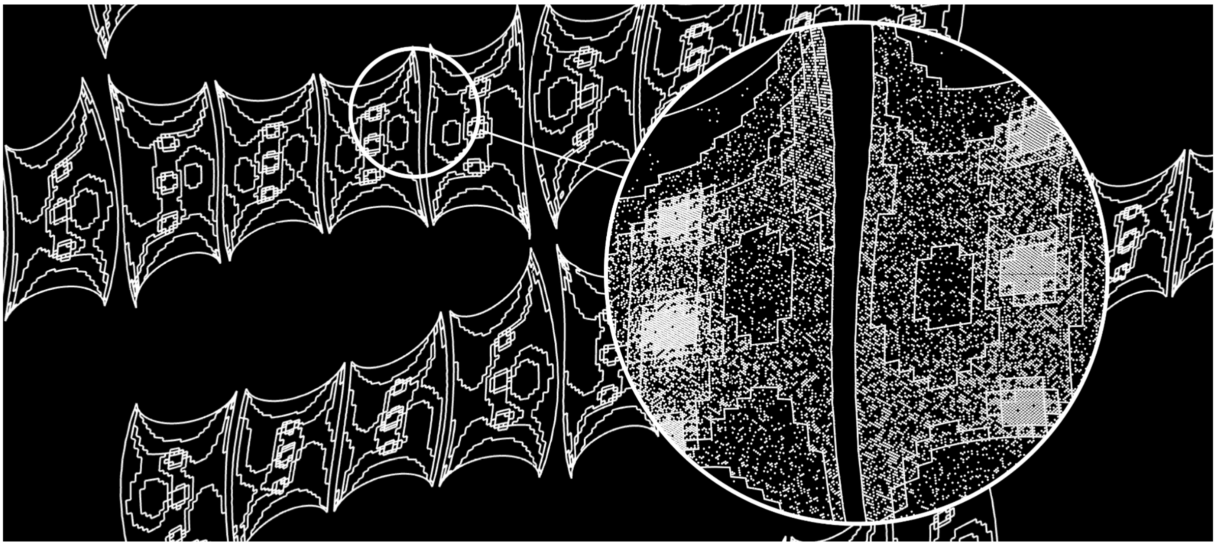

Figure 15: Diagram of material differentiation through the dithering of larger and smaller stitch types

5. Conclusion (Yuliya still to write, thinking on it)

Authors presented two methods that equally could be used for designing differentiation patterns for graded knitted membranes. The first, the *geometric* approach, operates within the membrane spatial displacement allowing the creation of clear and simple CNC-knitted patterns, concentrating the material property change mainly around the areas of applied loads. This method guarantee the efficient steer of the material property for expansion, if the load applied perpendicular to the plane of the membrane. The second method uses the structural analysis approach, which allows to take into consideration the structural performance of the surface. The resulting differentiation patterns suit better for the membrane loading conditions that are angled to the surface plane, which allows to expansion of the design space of CNC-knitted membrane structures.

The presented methods contribute to the improvement of the robustness and the capacities of the workflow chain, used for the design, analysis and manufacturing of the CNC-knitted membranes. Thus, making it more convincing the use of CNC-knitted membranes in the field of membrane architecture, bringing them closer to become more and more used membrane material, that allows for a high degree of customisation and responds to demands, that sometimes cannot be answered by traditionally used woven-based materials.

Figure 16: Materially differentiated textile ceiling canopy

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