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SIMULATION CALIBRATION OF DIFFERENTIATED KNITTED MEMBRANES WITH EVOLUTIONARY OPTIMISATION TOOLS

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Summary. Knit, with its inherent flexibility and ability to integrate bespoke material performance, creates a promising alternative to traditionally woven membranes in architectural textile applications. The CNC-knitting technology allows for the manufacturing of membranes with gradient expansion properties by numerically controlling the distribution of varied stitches. In architectural knitted structures, material programming is used to achieve complex bespoke three-dimensional surfaces at a large scale, with a minimum residual waste during continuous digital manufacturing[2–4]. This permits to depart from the cut-pattern-based strategy commonly used for woven non-expandable membranes while allowing for the integration of multiple material properties in a single production process.

In our research, we strategically guide the material expansion of knitted membranes in order to achieve non-developable textile surfaces by combining various stitch types informed by digital form-finding and structural analysis. As a result, membranes obtain their gradient stretch capacities under tension through the distributed material density. However, the heterogeneous irregularity of the distributed material density of CNC-knitted membranes makes it difficult to establish reliable digital simulations due to material complexity, novelty of the topic, and associated knowledge gaps. The success of simulation models relies on a thorough understanding of material properties, including their representation and translation between digital and physical environments. In particular, it is important to consider abstraction strategies to maintain computational feasibility of these models and accuracy of representation in order to reflect complex material composition.

In this paper we investigate these questions through prototyping of simulation models and their calibration, in order to achieve geometrically more accurate results, when designing with the differentiated CNC-knitted membranes. Here we present the extension of the method for simulation and calibration of graded textiles, published earlier by the authors[5,6]. The experiments are conducted on several CNC-knitted ceiling panels of varied three-dimensional geometry, where each is materially graded, and therefore stretch differently under the suspended weights. The digital simulation is calibrated towards the reduction of geometric deviation between the digital and physical artifacts of the textile panels by tuning the differentiated stiffness values and mesh representation alternations through the use of evolutionary optimisation algorithms (Fig. 1).

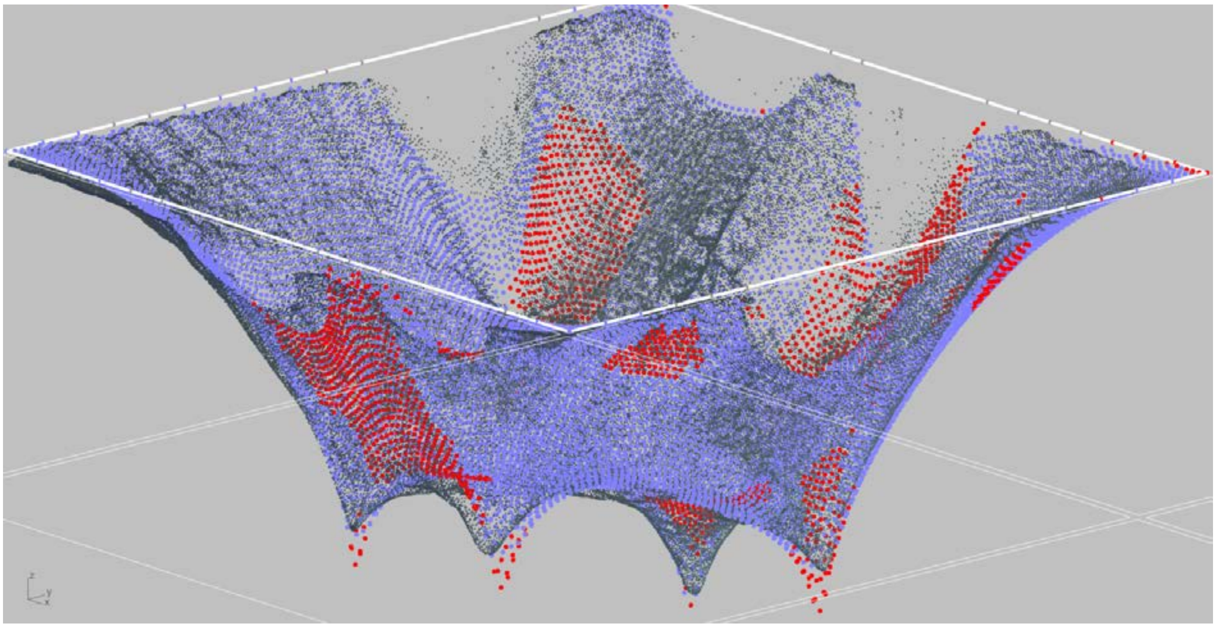

Figure 1: Evolutionary algorithm aiding the search of membrane stiffness value

1. INTRODUCTION

1.1 Conventional tensile membrane simulation

Simulation plays a crucial role in the field of membrane structures as it enables the accurate determination of their shape. In conventional membrane structures made of homogeneous woven textiles, form-finding process leads to the structure attaining an equilibrium shape based on its initial configuration and applied initial prestress[7]. To digitally represent the membrane, a network of dynamic springs is utilized, where all the springs are treated as one type with homogeneous prestress settings. As result, they expand and contract, ensuring a balanced distribution of forces and facilitating the desired equilibrium geometry. Typically, these membranes tend to adopt a minimal surface configuration, which limits the design possibilities available with such materials.

1.2 Differentiated membranes require other methods for simulation

Knitted structural membranes, on the other hand, represent a distinct branch within the field of membrane architecture, offering unique capabilities through their graded properties, compared to conventional homogeneous membranes Their graded properties allow for variations in material characteristics throughout the structure, providing enhanced versatility and performance. They enable architects and designers to create membranes that can adapt to specific functional and aesthetic requirements. For example, different areas of the membrane can exhibit different degrees of stiffness to support varying loads or achieve desired three-dimensional shapes under stretch. This effect is achieved by allocation of loops with different expansion rates. Due to their loop structure they have a large geometric stretch without a significant increase of stress and a very high Poisson's ratio and a strong anisotropic behavior[8]. This capacity defines the behavior of the material and shall be taken into account early on during the design process, form-finding and simulation[6].

While the interest in simulating knitted structures has been present in the field of material science and computer graphics, their realistic models of detailed loop simulation are currently feasible only at the scale of garments and not applicable to large-scale architecture[9,10]. Furthermore, off-the-shelf digital tools used for form-finding in the architectural and engineering domains, while scalable, often lack the integration of graded properties across the modeled surface. This limitation leads to a uniform material behavior throughout the structure, neglecting the potential of knitted membranes for varying material properties that could enhance its performance and functionality.

1.3 Phylosophical questions within the context of simulation

Alongside the technical aspects, simulation raises philosophical questions related to its nature as a knowledge-generating tool[11]. These include:

- Simulation vs. experimentation: How does simulation relate to traditional physical experimentation? Can it fully replace or replicate experimental outcomes?
- Reliability of simulations: Assessing the trustworthiness and credibility of simulation results, considering the simplifications inherent in mathematical models and algorithms.
- Sparse data evaluation: Can simulations accurately capture complex systems' behavior with limited or incomplete data? How meaningful are the results under such conditions?
- Role of assumptions: Understanding the impact of assumptions and simplifications on simulation results, and their implications for critical evaluation.

Exploring these philosophical questions deepens our understanding of simulation's strengths, limitations, and epistemological aspects. It prompts critical examination of assumptions, uncertainties, and interpretations in simulation-based research, enhancing methodology across domains. Particularly, when dealing with novel material systems, where understanding is incomplete, these questions become more challenging.

1.4 Demand for abstracted but accurate models for graded knitted structures

In order to address above mentioned technical and philosophical challenges, simulation models for graded architectural knitted structures require a certain level of abstraction to maintain computational feasibility while accurately representing differentiated properties of such membranes. The success of simulation models relies on a comprehensive understanding of material properties, particularly their representation and translation between digital and physical environments. However, finding the balance between *abstraction* and *accuracy* poses difficulties in terms of implementation, due to uncertainties surrounding the choice of abstraction resolution scales to maintain computational feasibility and determining appropriate methods for arranging and assigning material properties to represent the material's complexity within abstracted simplified system.

1.5 Abstraction and accuracy when building simulation for differentiated knits

When simulating knitted membranes at larger scale, an *abstraction* technique is commonly used, wherein the knitted structures are represented as grid-like meshes. This approach disregards the lower-scale loop-based structure of the knitted material and simplifies the computational modeling process. By using grid-like meshes, the simulation focuses on the overall behavior and properties of the knitted membrane rather than intricately modeling each individual loop. In order to accurately represent the heterogeneous nature of the knitted membrane, the simulation model must reflect differentiated properties. This is achieved by assigning varied stiffness values to the mesh springs, leading to the differentiated behavior of the membrane during simulation.

Building upon this technique, we extend previously published method for simulating and calibrating graded textiles[5,6]. Our current study explores these inquiries by creating simulation models and calibrating them to achieve more accurate geometric results when designing with differentiated CNC-knitted membranes. For that we conduct digital experiments using various CNC-knitted ceiling panels with diverse three-dimensional geometries as physical counterparts. These panels possess material gradation, causing them to stretch differently under distributed weights. To reduce geometric discrepancies between the digital representation and physical artifacts of the ceiling panels, the digital simulation is fine-tuned using evolutionary optimization algorithms. This calibration process involves adjusting stiffness values and modifying mesh representations to improve the accuracy of the simulation results.

2. STATE OF ART IN KNITTED MATERIAL DIGITAL CALIBRATION

2.1 Adoption of knitting technology for structural membrane design

An increasing adoption of knitting technology in experimental design, coupled with the development of user-friendly programming platforms and accessibility of digital scanning technology, has sparked custom digital tools development leading to the emergence of workflows and integrated design models for architectural knitted structures[6]. These tools can be specifically tailored to address the unique requirements and challenges posed by the knitting technology for architectural applications. as they provide flexibility to customize digital functions. They enable researchers and practitioners to efficiently generate and assess various design options, simulate the behavior of knitted structures under different conditions with variegated material differentiation, optimize structural performance, and generate fabrication data specifically catered to industrial knitting machines[3,12–16]. However, the heterogeneous and irregular distribution of material density in CNC-knitted membranes presents challenges for reliable digital simulations. The novelty of this topic and existing knowledge gaps contribute to its complexity, requiring further research and development. Advancements in simulation techniques and material representation will improve the accuracy and reliability of digital simulations for CNC-knitted membranes, enabling their broader application.

2.2 Research outputs in simulation calibration of differentiated knitted structures for architectural application

Research studies in simulation and form-finding of knitted structures for architectural applications have covered several key aspects. These include abstraction and adaptation of knitted structures for simulation, exploring possibilities for mesh topology in knitted structures, determining the appropriate resolution of the mesh for simulations, assigning properties to the mesh for accurate representation as well as utilizing evolutionary algorithms for value search and optimization.

2.2.1 Knit Abstraction

Within the architectural domain, two approaches to knit abstraction can be observed in the reviewed research outputs. The first approach involves detailed modeling of knitted structures using a high-resolution loop representation with straight springs, resulting in complex mesh topology[17–19]. Another approach adopts a strategy of a larger abstraction and utilizes quad-based meshes with lower complexity at sparser resolutions[16,20–24]. This allows for simulations of larger structures compared to the first approach. Additionally several mesh topologies such as quad-, triangle-, hexagon- and non-uniform ones are explored[12,13,25–28].

2.2.2 Abstracted Mesh properties - rest lengh vs. stiffness values

Before the availability of plug-ins specifically designed for the structural evaluation of membrane designs, the assignment of mesh properties in simulations was often based on arbitrary cable stiffness values with target rest lengths[17,18,20,21,29]. With the introduction of plug-ins like K2Engineering, Karamba and Kiwi3D, a more standardized approach became possible. These plug-ins allow for the utilization of the E-modulus stiffness value (Young's modulus) to describe the material properties of the membrane. By using the E-modulus stiffness value, the simulation can be linked to existing engineering standards, making it easier to evaluate force distribution within the simulated structure and assess its strength and reliability[4,5,24,30].

2.2.3 Difficulty in finding the stiffness value

However, assigning stiffness values to the mesh in simulation poses challenges due to the complex translation from dense loop-based knitted structures to sparse abstracted grid-based meshes. A reliable approach to evaluating the correctness of stiffness values involves comparing the simulated structure with its physical counterpart manufactured digitally. This comparison ensures that the simulated structure exhibits behavior consistent with its real-world manifestation, validating the effectiveness of the assigned stiffness values.

2.2.4 Methods for simulation evaluation

Currently, two common methods are used for evaluating simulations: material sampling and 1:1 scale prototyping. Material sampling is suitable for structures made of homogeneous knitted membranes, as the uniformity of the pattern allows for easier extraction of representative samples for axial tensile testing. Stiffness values obtained from these samples are then assumed to hold true and applied to larger structures, assuming the same behavior when scaled up[15,16,25,26,31,32].

However, for heterogeneous knitted membranes, it is more challenging to extract samples for material testing due to complex patterns and the influence of pattern distribution on overall behavior[5]. In such cases, 1:1 scale prototyping has proven to be a valuable method for understanding the behavior of the structure. By comparing the produced physical artifact with the digital design through a digitally scanned model of point cloud, researchers gain insights and refine the simulation accordingly[2,5,6,33,34]. Although, theprocess of prototyping can be tedious and time-consuming, especially when searching for suitable stiffness values. To expedite the calibration process and automate the search for stiffness values, evolutionary algorithms can be used. These algorithms aid in efficiently fine-tuning the simulation and finding appropriate stiffness values, leading to quicker and more automated calibration[35–37].

2.2.5 Evolutionary algorithms as aiding tool for design and calibration

Evolutionary algorithms have found integration into the architectural domain through various plug-ins that enable single and multi-objective optimizations for generating and evaluating alternative optimal or near-to optimal design solutions, based on specific objectives or criteria[38–42]. Additionally, evolutionary algorithms can be used to calibrate simulations and minimize geometric discrepancies between digital and physical artifacts. This approach proves particularly useful when dealing with complex knitted textiles and their digital representations. Here the stiffness values can be searched and discovered with the fitness value reduction, applied for both homogeneous and heterogeneos knit structures [5,30]. Building upon mentioned research outcomes, a further improvement and alternations of the method is described in this paper through testing some alternative approaches in value search and mesh clustering.

3. METHOD EXTENSION OF SIMULATION CALIBRATION OF DIFFERENTIATED KNITTED MEMBRANES

This chapter presents the extended methods used to construct a digital simulation for differentiated knitted membranes and their subsequent calibration using evolutionary algorythms to reduce discrepancies between physical and digital counterparts. Diagram in Figure 2 shows various representations of the panel used in this study.

3.1. Physical set up, knit structure and analysis based differentiation

The simulation and calibration experiments described here are closely linked to the production of physically fabricated graded knitted membranes. These membranes achieve material differentiation by combining two stitch types: tight and loose. Both stitch types are based on the double jacquard loop structure. The tight stitch is formed by coupling loops from the front and back needle beds, while the loose stitch is created by unraveling this loop structure. This combination allows the membranes to have controlled expansion properties, offering versatile and adaptable solutions for material grading (Fig. 2, A). Each panel within the membrane structure is designed in a square shape, featuring either continuous or selective clamping of the perimeter to the solid support frame. Selective clamping creates larger openings in the membrane structure, and redistributed tension across the panel surface, reflected in their material grading. More detailed explanation of the grading strategies, informed by form-finding and structural analysis can be found in previously published papers by the authors[43].

3.2 Digital simulation set up

In the digital realm of the experiment, the membranes are digitally represented using lower-resolution grid-like meshes, where the mesh springs are clustered to reflect the material complexity observed in their physical counterparts. Two different approaches to mesh spring *clustering* are tested:

- Field-based clustering: This method involves dividing the mesh into several areas based on the distribution of forces observed in the structural analysis of the membrane geometries. The number of areas is manually defined as five, aiming to achieve a desired level of smoothness in the gradation of material differentiation. This clustering approach is explained in more detail in referenced research papers[6,43].(Fig.2, B).

- Mesh-density based clustering (dual set up). This is a novel method of mesh clustering, explored in this paper, where mesh springs are clustered into two groups, forming a dual mesh set up, representing the stitch density concentration used for digital fabrication of related membranes. Here white springs represent tight stitches, while black ones - loose ones. (Fig.2, C).

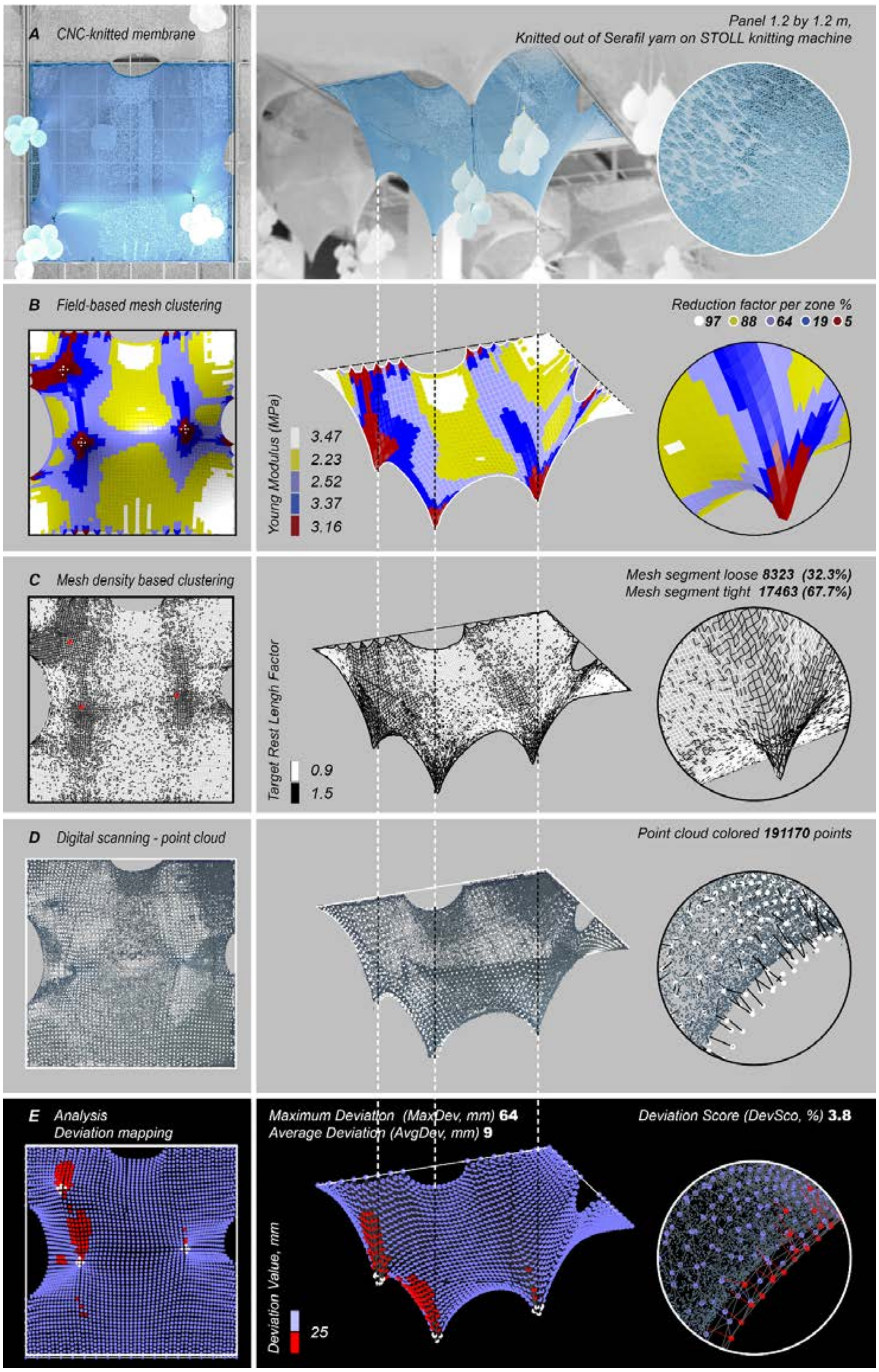

Figure 2: Representations modes of differentiated knitted ceiling panel. A - physical membrane, B - Clustered mesh derived from the structural analysis (field based), C - Mesh density based clustering up (reflecting material density), D - Point cloud from digital laser scanning, E - Discrepancy analysis, deviation mapping

3.3 Scanning and Evaluation of models

Digital laser scanning is employed as a mean of connection between physical and digital realms. Here, point cloud is generated through laser scanning, capturing the detailed geometry of the physically manufactured counterpart. This point cloud is then compared to the digitally constructed mesh representation of the membrane (Fig.2, D). The primary objective of the experiment is to minimize the deviation between the digital membrane and the point cloud representing the physical membrane. To quantify the deviation, a fitness value is calculated based on the distance between the closest points on the simulated mesh and the point cloud. The deviation is visualised through the color mapping. In particular, areas where the mesh deviates over 25mm from the point cloud are highlighted with red dots (Fig.2, E). These serve as visual indicators of significant discrepancies. By visually mapping the discrepancies onto the simulated mesh, we can easily identify and analyze regions where the simulation model may require further calibration or improvement. The goal is to iteratively refine the simulation parameters and configurations in order to minimize the deviation (fitness value), thereby achieving a closer match between the simulated and physical representations of the membrane.

3.4 Evolutionary calibration tool set up

In the experiment, the evolutionary algorithm plug-in Galapagos is utilized to search for the optimal stiffness values of the mesh. The Genepool, which represents the range of values to be searched, is set up to align with the clustering of the mesh and consists of five separate genepools for the first experiment, and two - for the second. The objective of the evolutionary algorithm is to minimize the average deviation value, which serves as a fitness value in the optimization process. The deviation score is evaluated by calculating the percentage deflection from the scanned point cloud on an area basis. This scoring method provides a quantitative measure of the discrepancy between the simulated mesh and the physical point cloud data.

The evolutionary optimisation process is conducted initially on the most topologically complex panel, panel number 5. It is assumed that finding suitable stiffness values for this challenging geometry will likely yield improved results for the geometrically simpler panels as well. The resulting set of stiffness values obtained from the evolutionary algorithm is then applied to the other panel designs for evaluation. During this evaluation, the deviation values are compared to the previous simulation calibration to assess the progress of improvements. Positive improvements in the deviation values are indicated by upright-looking arrows, symbolizing the enhancement in accuracy. The negative improvements are marked with downward-looking red arrows, indicating a decrease in accuracy and worsening of the results. This visual representation helps to track and analyze the effectiveness of the evolutionary algorithm in refining the simulation and reducing the discrepancy between the point cloud data and the simulated mesh.

4. EXPERIMENTAL WORK

The experimental work is organized into two calibration exercises, each representing a different simulation setup. These exercises are compared to the initial simulation (*Simulation A*) which utilizes an *arbitrary* stiffness value. In *Simulation B*, a field-based mesh setup is employed, where the mesh is divided into several areas based on the forces distribution domain. This setup aims to achieve a smooth material differentiation gradation. For the evolutionary optimisationof stiffness value discovery, *five* genepools are used. In *Simulation*

C, a dual mesh setup is implemented, consisting of white and black springs. This setup is specifically designed to represent the stitch density concentration used in the digital fabrication of related membranes. The evolutionary optimisation in Simulation C utilizes *two* genepools. By conducting these calibration exercises and comparing them to Simulation A, the effectiveness of the different simulation setups and evolutionary algorithms are evaluated. The goal is to determine which setup yields the most accurate results and reduces the discrepancy between the simulated mesh and the physical point cloud data. Each evolutionary optimisation run is set up to minimize fitness value with threshold of 10, where the evolutionary solver set up to maximum stagnation of 50, population 50.

4.1 Quantitative evaluation of earlier experiments - Simulation A, B, B2

In the previously conducted *Simulation A*[6], an arbitrary stiffness value of 30 MPa was applied uniformly across the entire design set of six panels. This value was chosen to approximate the overall shape and define the material differentiation strategy to achieve field-based clustering of the mesh. However, when quantitatively evaluating the simulation results using this stffness value, significant discrepancies between the digital mesh and the physical counterpart were observed (Fig.3, *top*). The average maximum deviation (Average MaxDev) across all panels was found to be 234mm, indicating a considerable difference between digital mesh and the point cloud. Similarly, the average deviation (Average AvgDev) was calculated to be 78mm, while the deviation score (DevSco%) was determined to be 75%.The inaccuracies in capturing the true geometry of the knitted membranes in Simulation A emphasize the need for further calibration exercises. In a previous study conducted by the authors, a calibration using homogeneous material samples was carried out[6]. The results of this calibration exercise are quantitatively evaluated further in *Simultion B*.

Previously published results revealed a range of stiffness values from 720 MPa to 2 MPa, which indicates a substantial deviation from the initial arbitrary value of 30 MPa. The application of these values still showed a considerable difference of 61.6% when compared to the scan. However, the deviation score improvement of 14% is observed compared to the preliminary Simulation A (which had a deviation score of 75%), as well as reduction of maximum deviation down to 176 mm and average deviation down to 46 mm (Fig.3, *middle*).

To examine the effect of a narrower range of stiffness values on membrane simulation, a smaller range from 4.5 MPa to 2.5 MPa is manually incorporated within *Simulation B2* (Fig. 3, *bottom*). This selection of smaller values aims to simulate less stiff membranes, contrasting with Simulation A that exhibits very shallow shapes. Preliminary findings indicate promising positive improvements in the deviation mapping, as the adjustments made with the smaller stiffness range have resulted in a reduction of discrepancies. This suggests that narrowing down the range and reducing the stiffness values itself has a positive impact on the accuracy and alignment of the simulation with the real-world counterparts. This particularly applicable with the given material set up of a gradient membrane density differentiation, using double jacquard (tight) and unravel double jacquad (loose) stitches.

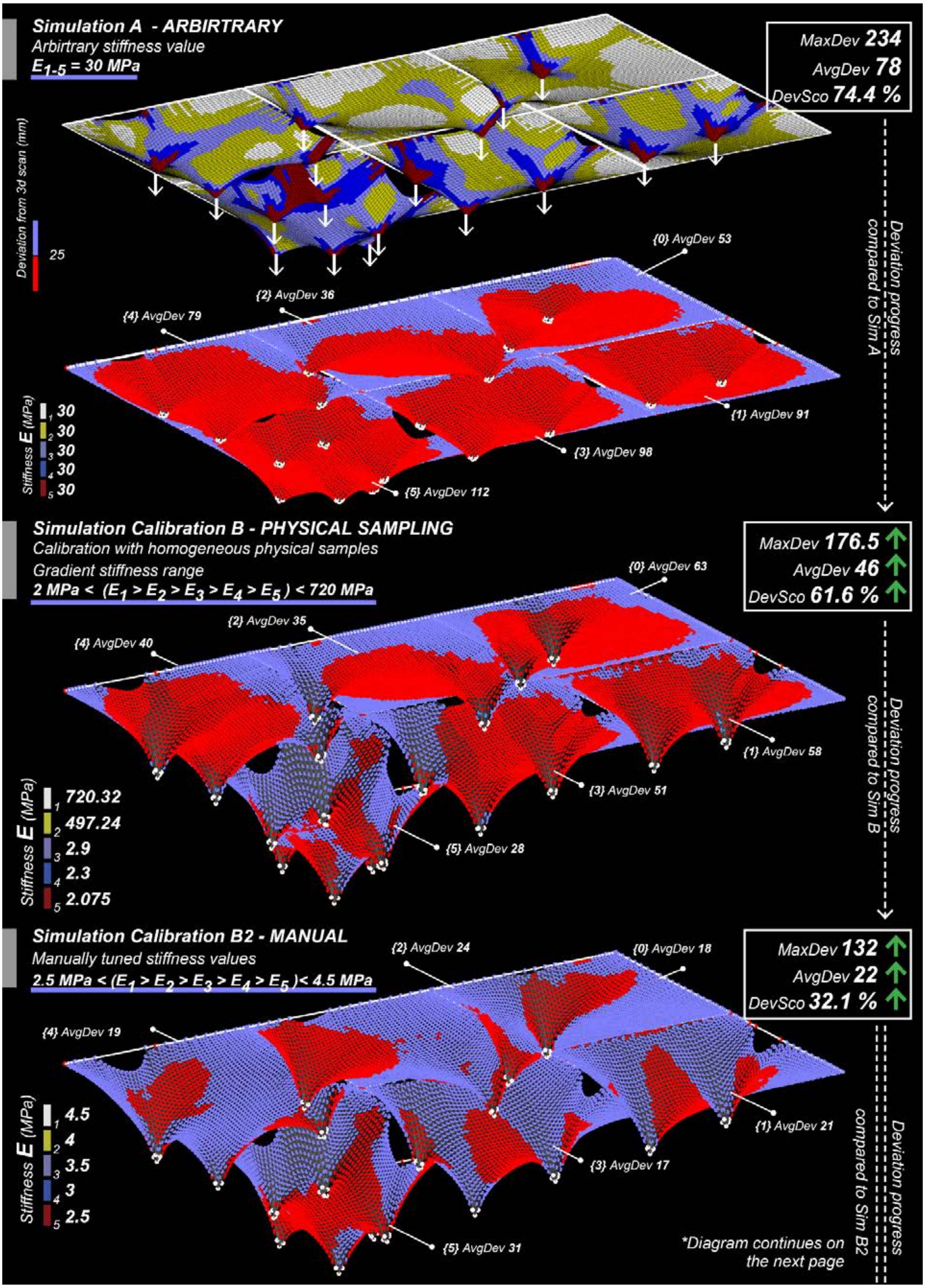

Figure 3. Simulation A, B, B2

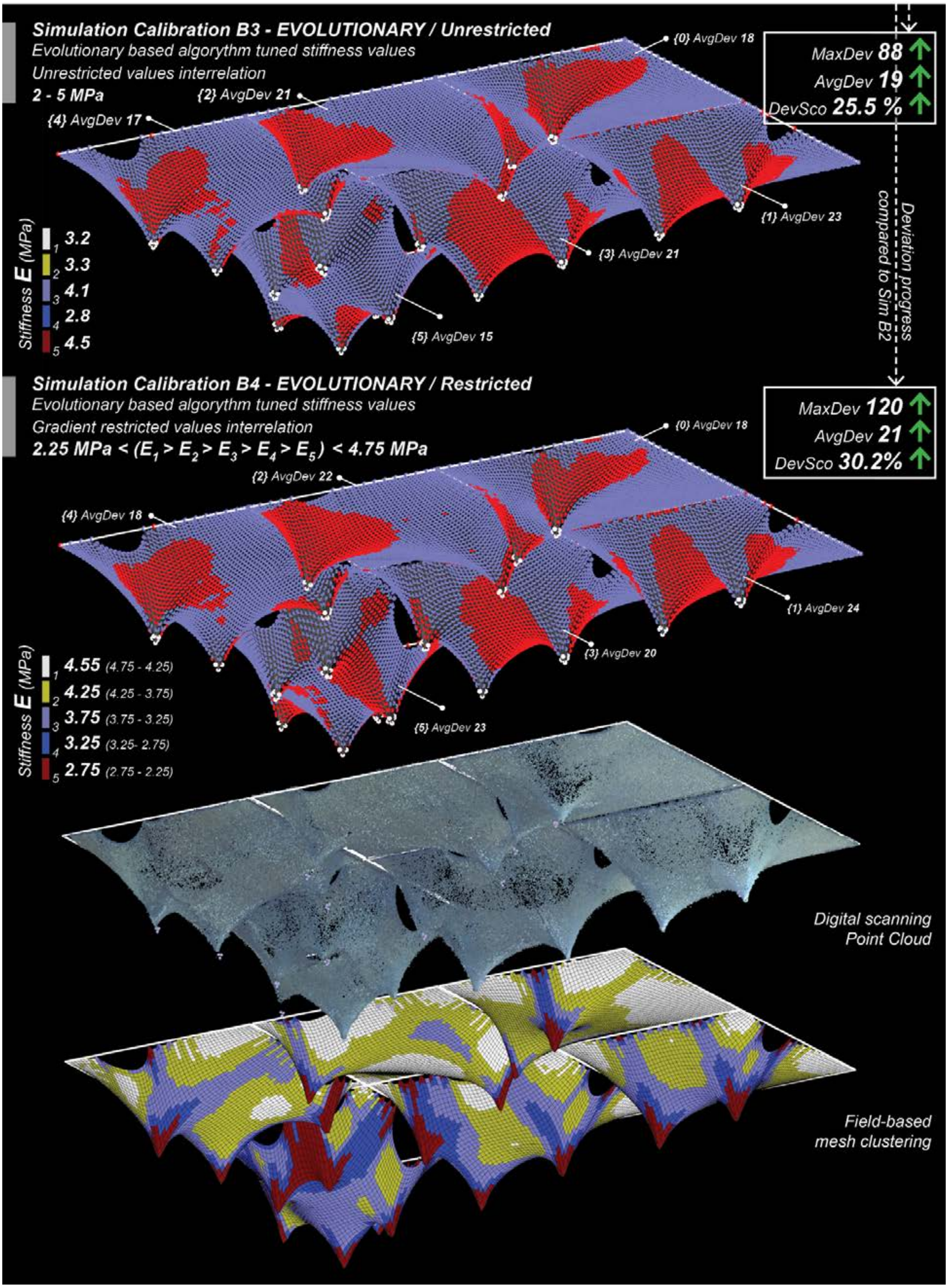

Figure 4: Simulation B3 and B4

4.2 Evolutionary optimisation calibration

4.2.1 Field-based mesh clustering (Sim B3, B4)

Simulation B3 and B4 employ a more targeted and automated optimization process to refine the stiffness values and minimize the differences between the simulated and physical membranes (Fig 4). This optimization is facilitated by the Galapagos plug-in, which utilizes evolutionary algorithms to iteratively search for the optimal values. By integrating Galapagos, the simulation aims to achieve a higher level of accuracy and alignment with the physical membranes. The stiffness range was set to 2 to 5 MPa, with additional 0,5 MPa increments at the upper and lower ends of the range.

The optimisation *for Simulation B3* (Fig.4, *top*) is conducted in the *unrestricted* manner, meaning that each genepool of values is allowed to receive any stiffness value within the overall range, without any specific constraints. On the other hand, the optimisation for *Simulation B4* (Fig. 4, *bottom*) is set up in *restricted* mode, where genepool values are forced to obtain gradiently increasing values per each membrane field zone.Here the optimisation is conducted on multiplier coefficients rather than the stiffness values themselves. Importantly, this method is considered more appropriate as it acts in accordance with the compositional nature of the material, where gradually changing density of knit corresponds to the gradual change of stiffness values.

The comparison between these two simulations revealed that Simulation B3 provided results that are closer to the scan, while Simulation B4, although performing a bit larger discrepancy than Sim B3, conceptually better suits the nature of the material, leading to the improved alignment between the simulated and physical membranes.

Upon reflection on remaining discrepancy, it was considered that the restricted gradient in Simulation B4 may have been too rigid. The pre-defined even difference between areas stiffness values range didn't accurately represent the non-linear nature of material density influenced by knit-related programming. Increasing the range of stiffness values or introducing a more flexible starting value could lead to better results. This observation sparked an idea for further improvement, exploring a transition to a dual setup (mesh density based clustering), described further down. This alternative approach to mesh clustering and stiffness assignment is expected to improve calibration results, as it incorporate a dual mesh setup that is expected to accurately capture variations in material density, while also improving optimisation time by utilising only two genepools for the value search.

4.2.2 Mesh density dual set up (Sim C1, C2.A, C2.B).

Within Simulation C, optimization is conducted through three exercises. The first exercise, Simulation C1, utilized an *unrestricted* genepool range of 1-8 MPa, starting position at 50% - 4.4 MPa. This optimization process achieves an average deviation of 15mm on panel 5 and proposed homogeneous stiffness values of 3.5 MPa for both tight and loose mesh springs (Fig.5, *top*). Reapplication of these values to other panels yields the average deviation of 20mm across all structure, 114 mm maximum devation and overall deviation score of 28.9%. Despite this outcome being quite convincing in terms of deviation lowered value, it is important to note that the application of homogeneous values in a heterogeneous experimental setup contradicts the hypothesis of establishing heterogeneous simulations for heterogeneous materials. The use of homogeneous values limits the ability of the simulation to accurately

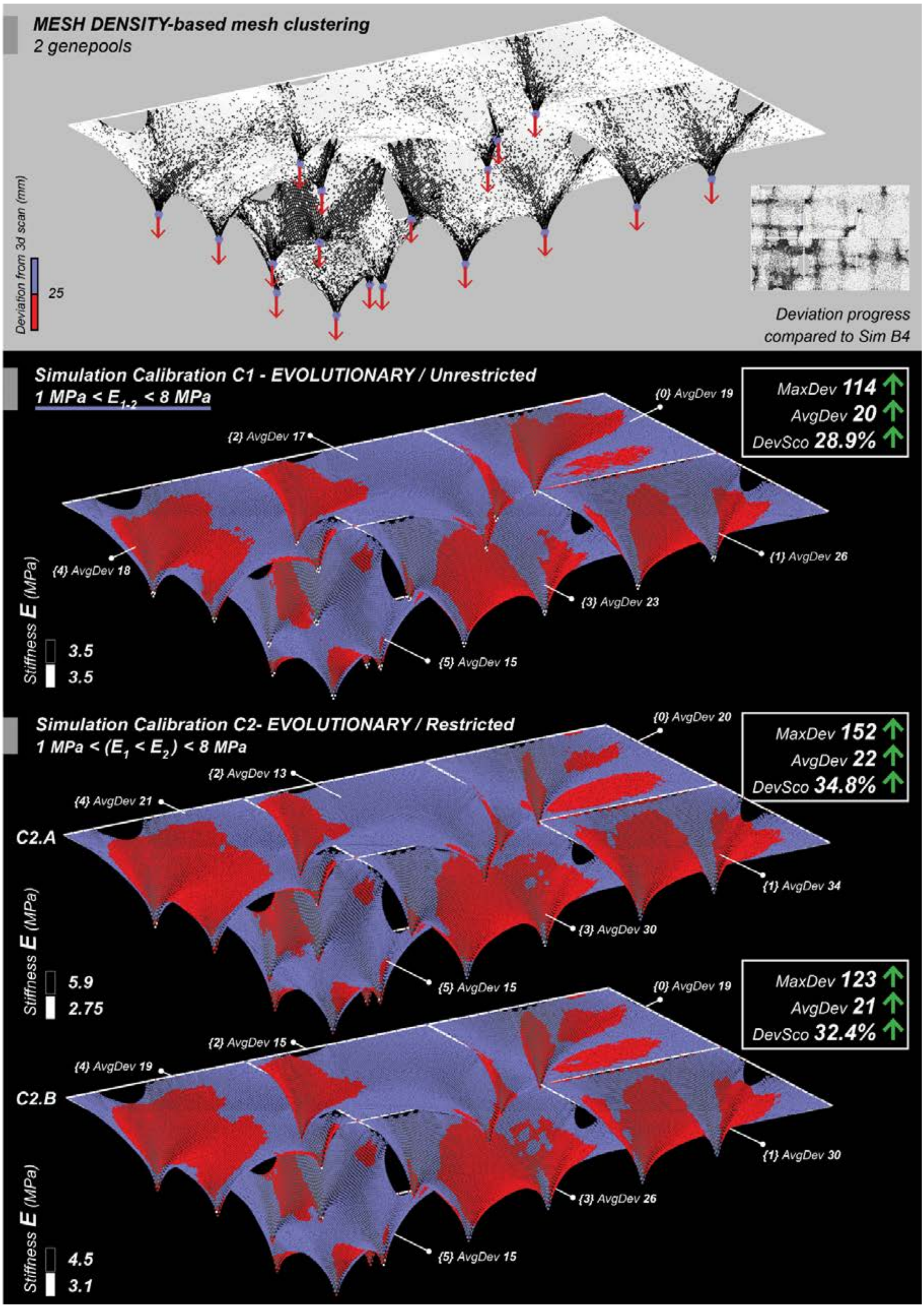

Figure 5: Simulation C1, C2.A, C2.B

represent the varied behavior and properties of the heterogeneous materials. This indicates a need for further exploration and refinement of the simulation approach to better capture the complexity of the materials being studied. For that further optimisation excercise of Simulation C2 is conducted with restricting condition to keep proposed stiffness values in relation of tight stitches being assigned a higher stiffness value, while loose ones - lower. Two sets of values are proposed by the algorythm and both are tested across all the panels. In Simulaton C2.A proposed stiffness values of 2.75 MPa (loose) - 5.9 MPa (tight) result 22mm of average deviation, 34.8% deviation score and 152mm of maximum deviation (Fig.5, *middle*). For or SimC2.B 3.1 MPa (loose) and 4.5MPa (tight) proposed values resulted in slightly better results of reduced average deviaiton to 20mm, maximum deviation to 123mm and deviation score 32.1% (Fig. 5, *bottom*).

5 CONCLUSION

The aim of the presented research is to investigate stiffness values using evolutionary optimization algorithms to reduce discrepancies between digital and physical simulations of knitted membranes. Two mesh representation setups are tested: field-based and mesh density-based. The field-based approach uses five genepools to optimize stiffness values for each zone, while the mesh density-based approach uses two genepools but higher mesh resolution. Both methods provide viable options for achieving accurate simulations while managing computational resources effectively. However, the second method is more attractive as it allows for operating with a high-resolution mesh. This is particularly advantageous when working with intricate and complex materials like knitted membranes, as it enables a finer level of detail and representation in the simulation. Achieved average deviation of 19-22mm is considered satisfactory, given the scale and flexible properties of the membranes. Although some individual points may have a maximum deviation of up to 152mm. This discrepancy can be attributed to the calculation of the distance to single outlier points in the point cloud. The numerical progress of the simulation calibration improvement is summarised in Table 1.

	Field-based mesh clustering					**Mesh-density** based clustering		
	Prelim.	Simulation calibration						
Value search	Arbirtrary	Manual and semi-manual		Evolutionary algorythm value search				
	Sim A	**Sim B**	**Sim B2**	**Sim B3**	**Sim B4**	**Sim C**	**Sim C2A**	**Sim C2B**
Used / proposed stiffness values (MPa)	**30**	**720.32** **497.24** **2.9** **2.3** **2.097**	**4.5** **4** **3.5** **3** **2.5**	**3.2** **3.3** **4.1** **2.8** **4.5**	**4.55** **4.25** **3.75** **3.25** **2.75**	**3.5** **3.5**	**5.9** **2.75**	**4.5** **3.1**
Analysis for deviation form the physical counterpart								
AvgDev (mm)	**78**	**46**	**22**	**19**	**21**	**20**	**22**	**21**
MaxDev (mm)	**234**	**176.5**	**132**	**88**	**120**	**141**	**152**	**123**
DevSco (%)	**78%**	**61.6%**	**32.1%**	**25.5%**	**30.2%**	**28.9%**	**34.8%**	**32.1%**

Table 1: Summary of the calibration activities and results

The unrestricted optimization setup, despite yielded low deviation values, did not align well with the material's gradient nature. For example, in Simulation B3, randomly distributed stiffness values proposed by the algorythm did not correspond to the organized gradual density change of the physical mesh. On the other hand, Simulations B4 and C2.B better replicated the material density change but had slightly larger deviations compared to B3 and C1. Simulation C1 had an identical stiffness value, indicating that these can bring mesh closer to the digital scan, however conceptually questionable.

While evolutionary algorythms offer great potential for design and simulation optimisation tasks, they also come with several challenges that need to be addresses in further research. Some of the key challenges include:

- Computational complexity. As evolutionary algorithms involve the iteration and evaluation of a large number of candidate solutions, process can be computationally expensive, especially for complex design problems with high-dimensional search spaces. Here, efficient strategies when building the code and clear understanding of optimisation criteria are nessessary in order to manage the computational complexity and reduce the time and resources required for optimization.
- Selection of appropriate fitness function. The definition of the right fitness function is crusial for guiding the evolutionary search towards desired design or simulation calibration objectives.
- Parameter tuning. Evolutionary algorithms have several parameters, such as population size, mutation rate, and crossover rate, that need to be carefully tuned for optimal performance. The selection of appropriate parameter values can significantly impact the convergence speed and the quality of solutions obtained.
- Premature Convergence and Local Optima. Evolutionary algorithms may suffer from premature convergence, where the search process gets stuck in a local optimum solution and fails to explore the entire solution space. Techniques such as diversity preservation mechanisms and adaptive strategies need to be employed to mitigate this issue and ensure a more thorough exploration of the search space.
- Scalability: Scaling up evolutionary algorithms to handle large-scale design problems is a significant challenge. As the dimensionality of the search space increases, the computational requirements and the search complexity grow exponentially. Developing scalable algorithms and parallel computing techniques is necessary to handle large-scale design optimization problems effectively.

Future research and development efforts should aim to overcome these challenges and improve the effectiveness and efficiency of evolutionary algorithms for design and calibration tasks when working with CNC-knitted archtectural membranes. Additionally a better correspondance of differentiated properties of the physical mesh should be established through special markers to be tracked by the laser scanning in order to ensure the digital mesh clustering alignment with the physical counterpart.

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