PhD Thesis

DIFFERENTIATED KNIT MATERIALITY

Yuliya Sinke

PhD Thesis
by publication

DIFFERENTIATED KNIT MATERIALITY

SIMULATION FOR DISCOVERY OF NOVEL MATERIAL GRADINGS OF CNC-KNITTED ARCHITECTURAL MEMBRANES

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ABSTRACT

This PhD thesis rethinks form-matter relationships in architectural materials by introducing graded CNC-knitted textiles as an innovative, lightweight solution for tensile membrane architecture. Addressing the challenges of material's environmental impact in architecture, this PhD research shifts the paradigm of how materials are designed and utilised, proposing form-matter integration as a sustainable design strategy.

Knitting, an additive manufacturing technique traditionally used in garment production, offers significant potential for architectural applications due to its inherent ability to support local differentiation and its compatibility with digital fabrication, offering precise programmability and industrial scalability. However, current practices for simulating and specifying knitted materials in architectural contexts often fail to address the challenges of predicting material behavior at architectural scales and translating performance targets into physical textiles.

Situated at the intersection of architecture, computational design, engineering, and digital fabrication, this research tackles critical issues in sustainable material production, material behaviour prediction, and interdisciplinary design workflows. By leveraging the capabilities of knit for functional material grading and harnessing simulation-driven design, the study transforms simulation from a post-validation tool into a proactive instrument for design exploration. By integrating simulation and analytical tools early in the design process, this research enables novel material gradings for textile membranes, forging a closer bond between form and matter and advancing sustainable design paradigms for architectural structures.

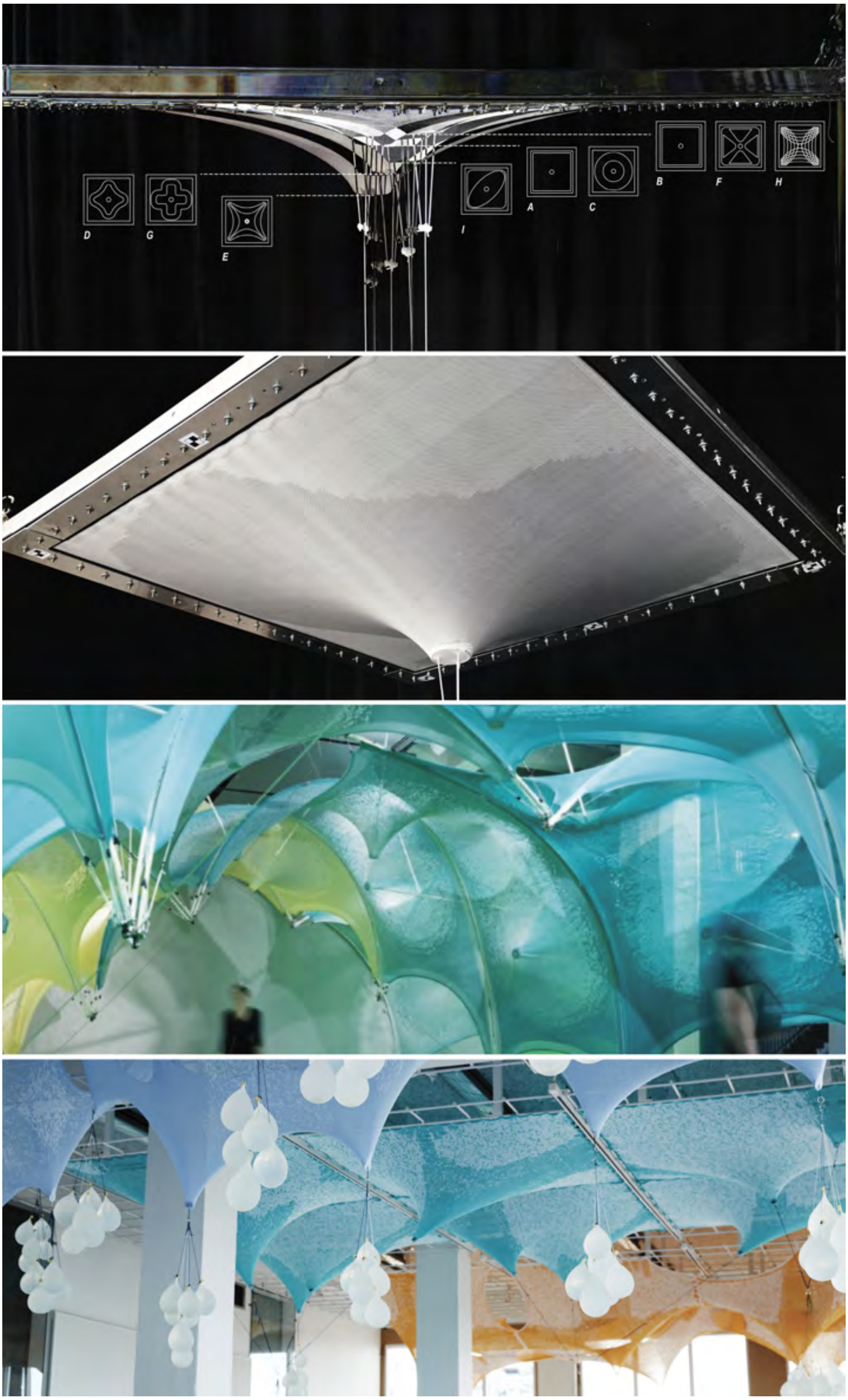
This thesis investigates the use of simulation and computational tools to program the material properties of CNC-knitted textiles. These properties are precisely executed using industrial knitting machines, resulting in controlled strain behaviour for tensile knitted membranes in architectural applications. A hybrid methodology combining Research-by-Simulation (RbS) and Research-by-Design (RbD) underpins this work. The RbS component visualises and predicts material behaviour, while the RbD component focuses on creating physical prototypes and demonstrators to validate and refine simulation outputs. Together, these methods provide a comprehensive toolkit for iteratively refining design outcomes based on material behaviour, structural requirements, and fabrication constraints.

At the core of this thesis methodology is the development of an expanded Digital Design Chain (DDC) for knitted architectural membranes, integrating three interconnected digital models: Design, Fabrication, and Evaluation Models. These models work collaboratively to ensure a seamless transition from digital design to physical fabrication, maintaining smooth data flow across scales and professional domains. The **Design Model** employs simulation and form-finding methodologies to align local material properties with global performance objectives, offering strategies for novel material gradings. The **Fabrication Model** addresses challenges of data flow and domain shifts from 3d design to 2d production, translating digital simulations into machine-readable instructions for industrial CNC-knitting machines. The **Evaluation Model** ensures alignment between digital designs and physical outcomes by calibrating simulations and addressing geometric deviations through optimisation processes such as genetic algorithms. Together the network of models integrates digital form-finding, analysis-driven material specification, and machine-ready production workflows, validated through alignment between digital and physical artefacts.

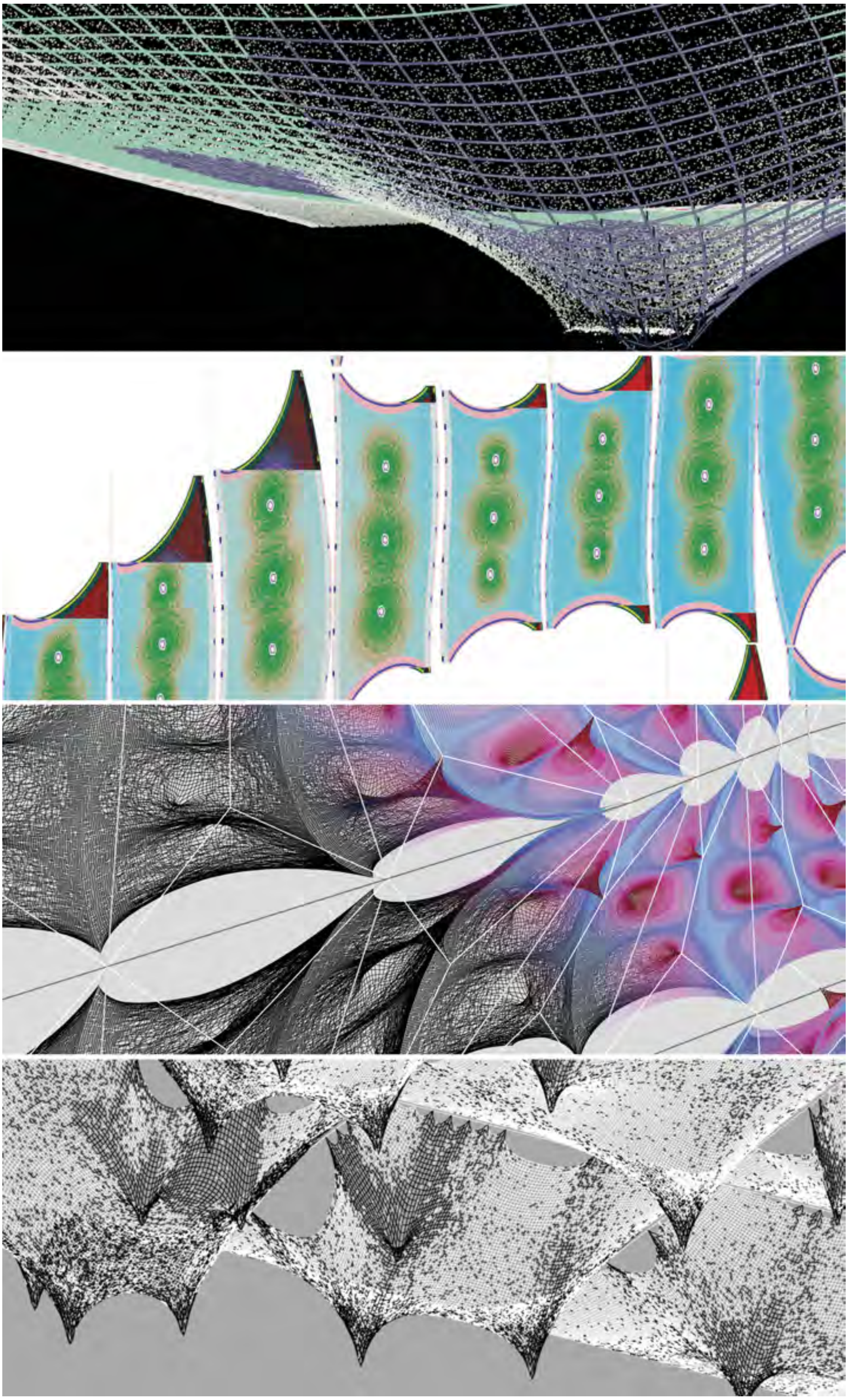
The findings demonstrate that CNC-knitted membranes are high-performance, waste-efficient, and scalable solutions for architectural applications. Full-scale pro-

totypes designed and produced during this research — ranging from scaled probes to full-scale installations such as Zoirotia and GraCe — demonstrate the feasibility and scalability of these methods. The results showcase how localized material differentiation enhances performance criteria such as membrane curvature, flexibility, and resource efficiency, making CNC-knitted membranes a viable alternative to conventional woven composites. These prototypes illustrate the potential of CNC-knitting to address diverse architectural challenges, including tensile structures, adaptive façades, and lightweight canopies.

This thesis contributes to architectural material innovation by providing a structured design framework for CNC-knitted membranes in tensile architecture through redefining the relationship between form and matter of architectural textiles, advocating for material-responsive design and fabrication processes. The findings highlight CNC-knitting as a transformative approach to sustainable architecture, promoting resource-efficient, high-performance, and visually expressive membrane structures. By advancing both the epistemology and methodology of simulations for material specification and behavior prediction, this research provides a roadmap for future interdisciplinary applications of graded knitted textile systems in architectural design.



F 0.1: Membrane structures, developed during this thesis



F 0.2: Digital membrane simulations and computational models, developed during this thesis

RESUMÉ

Denne ph.d.-afhandling gentænker forholdet mellem form og materiale i arkitektur ved at introducere graderede CNC-strikkede tekstiler som en innovativ, letvægtsløsning til trækspændingsmembraner. Afhandlingen tager fat på miljømæssige udfordringer ved materialer i arkitektur og foreslår en ny tilgang, hvor form og materiale tænkes sammen som en bæredygtig designstrategi.

Strik, en teknik inden for additiv fremstilling, som traditionelt bruges til tøjproduktion, har et stort potentiale i arkitektur. Dette skyldes dens evne til at skabe lokal variation, dens kompatibilitet med digitale værktøjer og dens mulighed for præcis programmering og industriel skalerbarhed. Alligevel adresserer de nuværende metoder inden for simulering og specifikation af strikkede materialer ofte ikke de udfordringer, der opstår, når man skal forudsige, hvordan materialet opfører sig i større skala, eller når designmål skal omsættes til fysiske tekstiler.

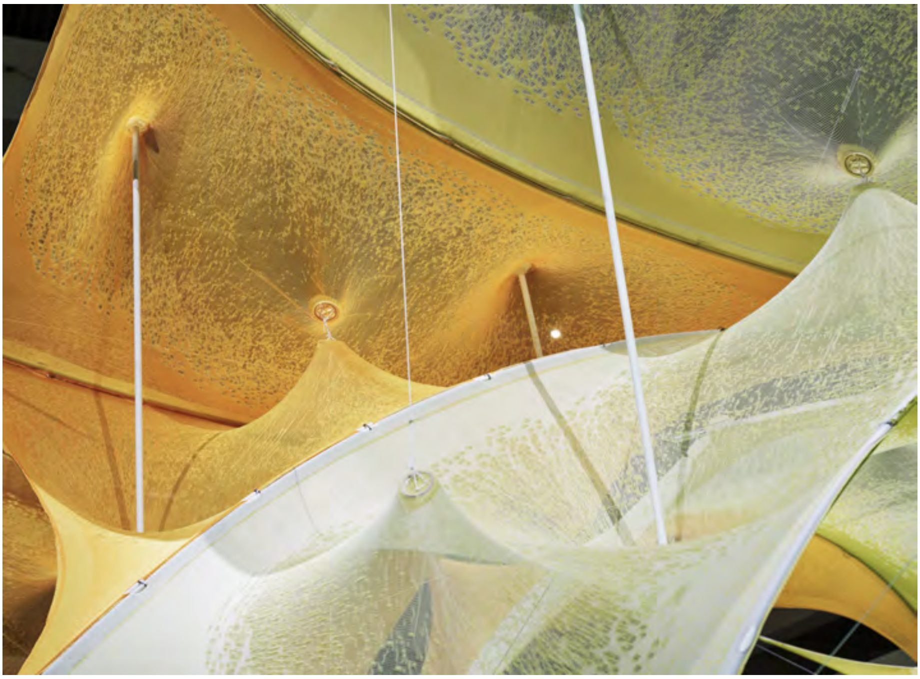
Denne forskning bevæger sig i krydsfeltet mellem arkitektur, digitalt design, ingeniørarbejde og fremstilling. Den udforsker centrale spørgsmål om bæredygtig materialefremstilling, forudsigelse af materialeadfærd og samarbejde på tværs af fagområder. Ved at udnytte strikkede materialers evne til funktionel variation og ved at bruge simulering som et kreativt værktøj, skifter studiet fokus fra simulering som en efterkontrol til simulering som et værktøj, der bruges tidligt i designprocessen. Dette gør det muligt at udvikle nye materialetyper til tekstilmembraner og skabe en tættere forbindelse mellem form og materiale, som understøtter mere bæredygtige designmetoder i arkitektur.

Afhandlingen undersøger, hvordan simulering og digitale værktøjer kan bruges til at programmere egenskaberne i CNC-strikkede tekstiler. Disse egenskaber realiseres præcist ved hjælp af industrielle strikkemaskiner, hvilket resulterer i kontrolleret fleksibilitet og formtilpasning for tekstilmembraner i arkitektoniske anvendelser. Forskningen bygger på en kombineret metode, der forener Research-by-Simulation (RbS) og Research-by-Design (RbD). RbS forudsiger og visualiserer materialets adfærd, mens RbD skaber fysiske prototyper, der validerer og forbedrer simuleringerne. Sammen udgør disse metoder en værktøjskasse til at finjustere designet gennem iterative processer baseret på materialets egenskaber, strukturelle behov og produktionskrav.

Kernen i afhandlingen er udviklingen af en udvidet digital designkæde (Digital Design Chain, DDC) til strikkede arkitektoniske membraner. Denne kæde integrerer tre digitale modeller: en designmodel, en fabrikationsmodel og en evalueringsmodel. **Designmodellen** bruger simulering og formfindingsmetoder til at forbinde lokale materialeelementer med større designmål. **Fabrikationsmodellen** håndterer udfordringer med at omsætte 3D-design til 2D-produktionsfiler og gør det muligt at programmere industrielle CNC-strikkemaskiner. **Evalueringsmodellen** sikrer, at digitale design passer med de fysiske resultater ved at kalibrere simuleringerne og justere geometriske afvigelser gennem optimeringsværktøjer som genetiske algoritmer. Tilsammen skaber denne kæde en flydende overgang mellem design, analyse og fremstilling, der sikrer, at digitale og fysiske resultater stemmer overens.

Resultaterne viser, at CNC-strikkede membraner er højtydende, ressourceeffektive og skalerbare løsninger til arkitektur. Prototyper, der spænder fra skalerede modeller til fuldskala installationer som Zoirotia og GraCe, viser, hvordan lokal variation i materialet kan forbedre egenskaber som fleksibilitet, kurve og effektiv brug af ressourcer. Disse prototyper illustrerer CNC-strikningens potentiale til at løse arkitektoniske udfordringer som trækstrukturer, adaptive facader og lette baldakiner.

Afhandlingen bidrager til innovation i arkitektoniske materialer ved at levere en struktureret designramme for CNC-strikkede membraner. Den gentænker forholdet mellem form og materiale og fremmer materialeresponsive design- og produktionsprocesser. Forskningen understreger CNC-strikning som en bæredygtig tilgang, der kombinerer ressourceeffektivitet med visuel og funktionel kvalitet. Endelig giver afhandlingen en fremtidig vejledning for tværfaglige anvendelser af graderede strikkede tekstiler i arkitektonisk design.



F 0.3: Zoirotia membrane in between the layers. *CITA 2021, Photo: A. Ingvartsen*

PROLOGUE

This thesis reflects the written part of the PhD project, submitted in a *by publication* format, undertaken at the Royal Danish Academy - Architecture, Design and Conservation in Copenhagen, Denmark from July 2019 to December 2024 (including two maternity leaves). The research was pursued at the Institute of Architecture and Technology (IBT), within the Center for IT and Architecture (CITA) as a component within the project "Responsible Consumption and Production", associated with the UIA2023Cph research network, which supported the UIA (Union Internationale des Architectes) world conference "Sustainable Futures, held in Copenhagen in 2023. The UIA project focus lies within the UN sustainability goal 12, which, by questioning the tools for design and representation, asks how the architects can become a part of discussion on foundations of the material practices of architecture. It asks: "What is the material of the future architecture, how can one rethink the practices of standardisation and mass-production and how does a rethinking of materiality and design challenge, what architecture can be?"

This thesis contributes to these discussions by proposing CNC-knitting as a fabrication method that enables material reduction, waste minimisation, and precision- and performance driven textile architecture. In doing so, it engages not only with SDG 12 *(Responsible Consumption and Production)* but also aligns with SDG 9 *(Industry, Innovation and Infrastructure)* through the integration of advanced digital design and production technologies in architectural practice. Here, a knit technique offers a great potential and transformative approach to sustainable architecture in a meaning that it can create a material, which is specifically tailored to architectural needs, allowing for smooth transitions between the material densities, enabling a localized performance optimization.

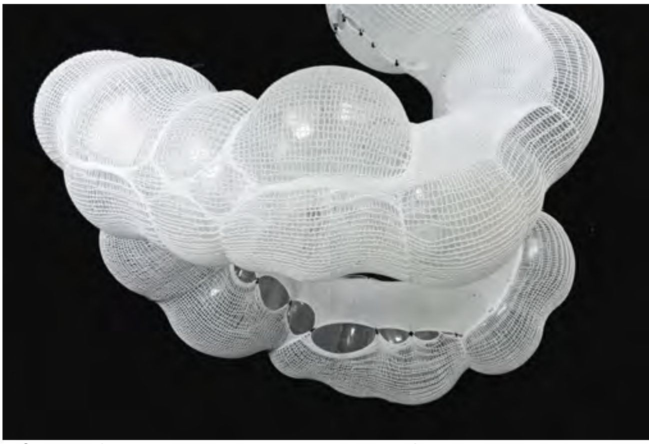
This thesis is addressed to architects, engineers, and design researchers, who recognize the potential of lightweight textile systems, in particular, knitting as a functionally graded material for innovative design exploration. It aims to engage with the professionals and scholars, interested in the form-matter relationships and the interplay between the internal material composition and their global behavior, namely material differentiation for additive manufacturing. By providing the insights into the development of computational tools and methods for designing, simulating, and fabricating the differentiated CNC-knitted membranes, this research offers a foundation for advancing the design culture within textile architecture and hopefully promote the wider application of knitted membranes at architectural scale.

While the primary focus in this thesis is on knitting as a material system, the insights and methodologies developed in this thesis could also be translated to other material systems that leverage controlled deformation for structural performance. This adaptability makes the research relevant beyond its immediate context of knit, offering the pathways for further exploration and innovation in architectural design and engineering of other dynamic material systems.

PERSONAL BACKGROUND & MOTIVATION

My journey into the world of textiles and material systems began long before I realized it would become the focus of my research. Trained as an architect, my curiosity always leaned towards the fibrous structures, and I found myself fascinated by the potential of thread-based systems to form three-dimensional volumes. From an early age, I experimented with the net making, knitting, and knotting, and these activities shaped my interest in exploring the textile material systems that could be both lightweight, dynamic, three-dimensional, and resilient. Additionally to the textile's flexible material properties, their binary programmable nature and the opportunity to shape incrementally excited my imagination.

During my master's studies at ITECH Studio at the University of Stuttgart, my understanding of the potential of fiber-based materials further expanded. The exposure to the computational and digital fabrication techniques revealed the new possibilities for integrating the textiles into architecture. I began to see how the manipulation of a single filament into the complex, adaptable structures could create the building elements that were not only lightweight but also highly efficient in terms of material distribution. This ability to create the forms that were elegantly shaped by both the fabrication and the structural constraints became a driving force behind my research.



F 0.4: Knitflatable Architecture, Master Thesis of the author. *Baranovskaya 2015*

At the same time, being immersed in Stuttgart's renowned culture of creative engineering and membrane design was profoundly inspiring. The collaborative environment fostered a fearless approach to experimentation with novel structures,

F 0.5: Hybrid Tower by *CITA 2016, Photo A. Ingvartsen* blending rigorous engineering principles with expressive spatial outcomes. Observing how this interdisciplinary approach produced groundbreaking designs deepened my appreciation for the transformative potential of integrating materials, fabrication techniques, and design thinking. These experiences not only broadened my technical understanding but also shaped my vision for research, particularly in exploring the synergies between structural logic and material behavior.

Building on this foundation, I became particularly fascinated by knitting as a material system, given its inherent ability to create graded materials through the manipulation of continuous filament. Knitting allows for the creation of variable material properties, offering an exciting avenue for resource-efficient design. As the digital fabrication and the computational technologies advanced, I observed how the knitting, usually associated with garments, could be applied in new roles at the scale of architectural construction. The prospect of creating the customized, waste-free, and even reusable materials for building applications motivated me to further explore this technology.

The potential of knitting as a material, that can be programmed for controlled stretch through the manipulation of density was especially compelling to me. In my master's thesis project **F**0.4 I explored how the manipulation of the yarn filament during an additive manufacturing on the semi-electronic knitting machines Brother from the 1980's could influence the differentiated textile behavior, when subjected to the pneumatic forces. Through the form-finding simulations, I was able to encode the specific binary properties into the knit, guiding the controlled expansion of the fabric under the tensile stress. The results of this project were published in Baranovskaya et al. 2016, which marked a significant milestone in my research journey.

Driven by a desire to push the boundaries of the material programmability, I continued my exploration in a role of research assistant at the Centre for IT and Architecture (CITA) in Denmark for the period of 2016-2019. Here, I was challenged to bridge the gap between the digital membrane models and the industrial CNC-knitting manufacturing processes. This research task required the development of the custom workflows, that would ensure a seamless collaboration between the designers, engineers, and textile manufacturers. Through the projects like Hybrid Tower **F**0.5 (Ramsgaard Thomsen et al. 2020b) and Isoropia **F**0.6 (Ramsgaard Thomsen et al. 2020c), I had the opportunity to test the limits of the knitted membranes within the domain of architectural application and industrial scaled production.

F 0.6: Isoropia, interior space. *CITA 2018, Photo by A. Ingvartsen*

Additionally, the involvement in these projects also raised the new research questions about how the digital simulations could be applied to guide the material differentiation and fabrication. This became the central theme of my PhD research, presented in this dissertation. Through constant prototyping and simulation, I delved deeper into how to translate the material behaviours, such as stretch and flexibility, into the digital models and gain a better understanding how to align the local material differentiation with the global membrane behavior.

One of the most significant milestones of this phase was my involvement in CITA's largest commission, Zoirotia in 2021 (Ramsgaard Thomsen 2021), depicted in F0.3. This project, which required the industrial scale of manufacturing of 88 custom knitted membranes across the three production sites in Europe, tested the scalability of my research. By collaborating closely with Drua Sif Albrechtsen, a textile designer and technician at the CNC-knitting machine at school, we developed a novel design-to-production model that allowed for the precise manufacturing of these membranes, directly using the digitally generated G-codes on the external industrial machines. This experience further cemented my belief in the potential of knitting technology for large-scale applications.

At the time of submitting this thesis, I am already committed to continuing my research in the manufacturing domain of CNC-knitted textiles, with a focus on bio-based materials such as hemp, as part of the EU-funded project RAW (*Computation for a new age of Resource Aware Architecture*, www.rawproject.eu). This progression feels like a natural step, as during my Phd I became increasingly aware of the sustainability challenges associated with the use of fossil-based fiber materials explored in this thesis. While the discoveries and insights, gained during my PhD, will undoubtedly inform my future work, it is exciting to recognise that there is still so much to explore in the interplay between the CNC-knitting, natural fibers, and their architectural applications, which I look forward to exploring further in the coming years.

ACKNOWLEDGMENTS

This thesis would not have been possible without the support, guidance, and encouragement of many remarkable individuals and collaborators I met along my research adventures. I would like to take this opportunity to express my sincerest gratitude to everyone who has played a role in this journey.

First and foremost, I extend my deepest appreciation to my brilliant academic advisors, Professor *Mette Ramsgaard Thomsen* and Associate Professor *Martin Tamke*. Their generous support and insightful guidance have been instrumental in shaping both this thesis and my academic growth. Under their supervision, I have evolved as a researcher, continuously refining my understanding and approach to the complexities of computational design and material systems, as well as my academic research thinking. The journey, both before and during my PhD, has been a transformative experience, and I am profoundly grateful for their mentorship.

I have also had the great privilege of working with interdisciplinary collaborators, whose openness and expertise have immensely enriched this research. Working on research projects alongside with commercial companies has been an invaluable learning experience, and I deeply appreciate the contributions of *Paul Stollberger* from Kobleder and *Elena Bruzuka* from ViolaStils, who brought their trust in research we do with knit at CITA and their professional knitting expertise to this ambitious research endeavour I was honoured to be part of during Zoirotia project. A special thank you goes to *Vladimirs Demetjevs*, the knitting programmer from ViolaStils, whose technical insight was indispensable in bridging my prior experience with Shima Seiki to the Stoll knitting system, the transfer I did during the thesis.

I also want to extend my gratitude to *Drua Sif Albrechtsen*, with whom I shared the immense challenge of developing a workflow for the large-scale Zoirotia installation. Together, we navigated the intense production process, taking turns knitting in the lab in shifts, an experience that will stay with me for years to come.

A heartfelt thank you to the students from our CITA Master's program in Computation in Architecture for their enthusiasm and dedication during the workshop I had the pleasure of teaching alongside with Sif, where we explored simulation and machine knitting. It was a joy to work with *Damo Qiao, Abdiel Reigh Borbon, Maya Kenzie Campbell, Tiansu Wang, Sze Chit Liu, Niklas Elsgaard, Andrew Smith, Camilla Martinez, Sandro Siefert, Søren Henning, Daniel Bilesky, Carly Ichiniowski, Aleksandra Krasheninnikova, Alex Buchthal, Xiaoyu Luo,* and *You-Wei Yen*. Thank you all for your productive efforts!

I would also like to acknowledge the collaborators on prior to PhD research projects – Hybrid Tower and Isoropia – which laid the groundwork for my engagement with industrial knitting and provided me with a strong foundation in the field. My gratitude goes to *Filipa Monteiro* and *Jorge Vieira*, from whom I learned so much about textiles and knit during these earlier projects. Their expertise, positive approach and willingness to share knowledge have greatly influenced my research trajectory and engagement in the domain.

The engineering insights I received along the way have been extremely crucial in refining my experiments. I sincerely thank *Julian Lienhard* from University of Kassel and *Daniel Sang-Hoon Lee*, from the Institute of Architecture and Technology here at the Academy, for their invaluable feedback during my half-way viva, for recognizing the value of my experiments, and for sharing their expertise so generously.

I am deeply grateful to my research colleagues at CITA – Center for IT and Architecture, where I have had the privilege of working in an inspiring research environment. It has been a pleasure to collaborate on various projects, write papers, and engage in intellectually stimulating discussions — whether over lunch or in meetings — constantly learning from one another.

A special thanks to *Gabriella Rossi, Ruxandra-Stefania Chiujdea, Katie Heywood*, and *Toms Svilans* for their friendship and unwavering moral support. I am also grateful to *Simona Hnigkova, Martynas Seskas, Sebastian Gatz, Vasiki Fragkia, Ida Tinning*, and *Anders Holden Deleuran*, my direct and indirect partners in knitting research projects at CITA. Each collaboration has been a unique adventure, and I cherish the memories we created together. I am also deeply thankful to *Ilaria Pugliese*, who supported me in my pre-defence period greatly, while being at her research exchange stay at CITA.

I would also like to acknowledge my colleagues at CITA whose computational developments played a crucial role in my thesis — *Mateusz Zwierzycki* and *Henrik Evers* for the excellent Squid and Volvox plug-ins, and *Paul Poinet* for the insightful computational discussions that helped me navigate technical challenges I had along the way. You all have all been wonderful colleagues, invaluable sources of technical and conceptual knowledge, and an incredible support network throughout this journey. My nine years at CITA felt far too short with you around.

I am deeply grateful to *Natalie Mossin*, the head of the Institute for Architecture and Technologies, where I belong, for cultivating a strong research, humane working environment and for playing a crucial role in negotiating together with Mette and Martin the acquisition of the CNC-knitting machine at the school —an essential milestone for this PhD research.

I also want to acknowledge the invaluable institutional support from the Academy that made my research process smoother. Librarian *Gæk*, for her efficiency in fetching research articles at lightning speed — thank you for your tireless assistance. A warm thank you to Campus Service, always ready to help with practical matters, and to *Mads Johnsen*, whose expertise in metal cutting were very helpful for my prototyping activities. Also I am thankful to my danish friends, *Maren* and *Henrik* for their help in proofreading the Danish resume of this thesis.

F 0.7: Close up of differentiated CNC-knitted membrane. One of tests from Zoirotia knitting prototyping process. Photo: *Y. Sinke 2021*

Beyond academia, I am deeply grateful for the love and encouragement of my family, whose support has been a constant source of strength. To my parents, thank you for always standing by me, even from afar in Siberia. Though kilometres apart, I always feel your warmth, support and belief in my work. To my grandmother in Ukraine, who finds the strength to encourage my research work. In times when the world's attention is drawn to instability and pressing concerns, she reminds me that pursuing knowledge, even now, is not just meaningful but necessary.

To my three best friends, *Zarina*, *Ksenya*, and *Olga*, who are always impressed by my research — responding with the most encouraging emojis every time I share an update. Your support gives me the courage to keep going. Thank you, girls!

This PhD journey has been uniquely intertwined with the joys and challenges of motherhood. To my two little children, who were both born during this PhD — you have given me a great source of motivation and energy. Our moments of play, bedtime stories, and laughter have been the perfect counterbalance to the focus and dedication that this research has demanded. You have unknowingly taught me the art of organization and resilience, positive thinking, which helped me to make this PhD journey through to the end.

And finally, to my husband — the greatest pillar of support through this intense PhD period. You have been there in every possible way - from stretching my textile prototypes with me in the lab and offering invaluable insights into the business potential of my research to taking care of our children so I could dedicate weekends to writing this thesis. Your enduring belief in my research, your patience, and your love have carried me through the most demanding moments of this process.

To all of you — colleagues, mentors, collaborators, family, and friends — I am deeply grateful. This thesis is as much a reflection of my research as it is a testament to the support and generosity of the incredible people around me.

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Chapter I

INTRODUCTION

CHAPTER OVERVIEW

The growing urgency of environmental sustainability in architecture calls for a fundamental reassessment of how materials are designed, fabricated, and applied in construction. This thesis explores novel methods for material formation, positioning knit as a platform for developing functionally graded materials (FGMs) in architectural applications. By leveraging digital modelling, simulation, and CNC-knitting, this research investigates how differentiated knitted membranes can serve as lightweight, adaptable, and resource-efficient alternatives to conventional materials.

At the core of this study is the integration of form, matter, and fabrication, shifting from standardized material applications toward tailored material behavior. Functionally graded materials, characterized by their seamless variation in properties, offer a promising alternative to composite-based structural membranes. Their inherent adaptability makes them particularly suited for lightweight architectural systems, where material differentiation directly informs structural performance.

Knitting, an inherently additive and programmable manufacturing process, presents unique opportunities for multi-dimensional material grading. Unlike woven or composite materials, knitted structures can be customized at a fine scale, enabling precise material distribution that responds to specific performance criteria. Through CNC-knitting, this research explores how spatial, mechanical, and structural properties of materials can be modulated, offering a new paradigm for architectural materiality—one that is computationally driven, digitally fabricated, and performance-oriented.

By establishing a digital design chain that interconnects design, simulation, fabrication, and evaluation, this thesis presents a structured framework for realizing CNC-knitted membranes as functionally graded architectural materials. It introduces computational models to simulate material behavior, translate digital designs into fabrication-ready instructions, and validate the performance of fabricated membranes. Through this approach, the research contributes to expanding the role of CNC-knitting in architecture, bridging the gap between material specification and structural application.

This introduction lays the groundwork for the subsequent chapters, which systematically address the theoretical, methodological, and experimental foundations of this PhD research.

Chapter I: Introduction, is structured into six sections, each laying the foundation for the research by addressing the key themes, challenges, and approaches, central to the study of CNC-knitted membranes as architectural materials.

The opening section, the **Context**, emphasizes the environmental challenges faced by the building sector, particularly the shift from focusing on operational carbon to addressing the embodied carbon questions. This shift calls for sustainable practices in material sourcing, the adoption of innovative technologies, and alternative design and construction methods. The section critiques the limitations of standardized materials and advocates for a paradigm of designing materials that embody form-matter relationships as a pathway to sustainable material innovation.

The second section, the **Background**, introduces the domain of structural membranes as lightweight, high-performance building systems. It explores their potential applications and highlights their reliance on composite materials. The subtractive approach of membrane composite materials is however effective for large structures, it presents the challenges for the smaller-scale applications due to waste and sustainability concerns. The discussion transitions into highlighting the need for Functionally Graded Materials (FGMs), where the differentiated CNC-knitted material system is positioned as a promising alternative to composite-based woven membranes.

In the third section, **Knit as Architectural Material**, the discussion focuses on the unique capabilities of knit as a material system, particularly its capacity for multi-dimensional grading due to programmable and additive manufacturing of knitting. This capability positions the knitting technology as a key tool for addressing form-matter relationships in architectural material design.

The fourth section, the **Problem Statement**, outlines the challenges, associated with the knitting as a graded material system for architectural applications. These challenges include the difficulties of predicting the knit material behavior, linking the local material grading to the global membrane performance, and scaling up the knitted designs for architectural contexts. Addressing these issues sets the stage for outlining the research scope of this thesis.

The fifth section, the **Scope of Research**, articulates the Research Aim and Hypothesis, alongside the Research Questions and Objectives that guide this thesis. It outlines the methodology employed, focusing on the development of simulation and digital models along with physical prototypes to address the challenges of design, fabrication and validation of CNC-knitted membranes. Additionally, the format of this PhD dissertation is presented as *article-based*, leveraging the benefit of work published during the thesis period in peer-reviewed venues.

Finally, the sixth section, the **Thesis Structure**, provides a chapter-by-chapter guide for navigating the dissertation. This section outlines a content of each chapter, which help a coherent understanding of the thesis as it unfolds.

1.1 CONTEXT

1.1.1 ENVIRONMENTAL IMPACT OF THE BUILDING SECTOR

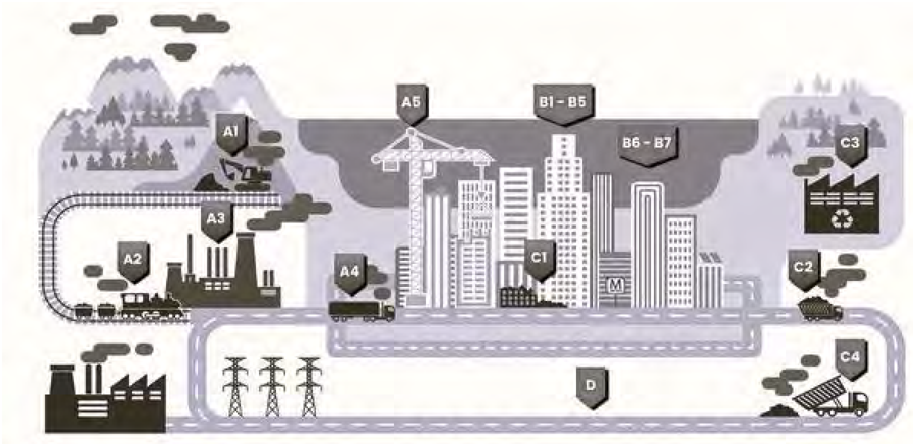
SHIFTING FROM THE OPERATIONAL TO EMBODIED CARBON FOCUS

In recent decades, the building sector's focus on environmental sustainability has predominantly revolved around the reduction of the operational energy consumption. Previously, the dominant perspective in Architecture, Engineering, and Construction (AEC) has emphasized the need for energy-efficient buildings, particularly in terms of heating, cooling, and electricity use during their operational life (Röck et al. 2020). This approach stems from a recognition that buildings contribute significantly to energy demand, greenhouse gas emissions, and resource depletion over their lifespan. However, this understanding is increasingly seen as insufficient in addressing the full extent of the building sector's environmental impact. A more comprehensive approach is now emerging, which considers not only the operational phase of buildings but also the significant contribution of embedded carbon emissions, namely the carbon footprint associated with the material consumption, production, transportation, and assembly of the building materials (De Wolf et al. 2017).

This paradigm shift highlights a growing recognition that the embodied energy in materials often constitutes the largest share of a building's total carbon emissions, particularly when considering the entire lifecycle of production, construction and demolition (Allwood et al. 2011). As the AEC industry addresses the global urgency of mitigating the climate change, the focus gradually shifts from the operational efficiencies to a deeper understanding of building material production environmental cost. In this context, attention is moving towards reducing embodied carbon emissions through sustainable sourcing, innovative material technologies, and alternative construction methods that minimize the impact of resource-intensive processes and reducing the human energy required to produce and assemble those (Pomponi and Moncaster 2016). Additionally, the emerging standards and certifications, such as the Embodied Carbon in Construction Calculator (EC3), reflect this shift, encouraging the industry to consider the entire lifecycle of buildings - not just how they function once completed, but how the materials, used to construct them, contribute to a long-term environmental harm (Simonen et al. 2017).

CONVENTIONAL PRACTICE OF STANDARDIZED MATERIALS

The construction industry relies heavily on standardized materials, developed to suit the established industrial processes and produced *en-masse* to meet the growing demands of the global construction market. While this approach ensures the efficiency in manufacturing and scalability, it is often associated with universal homogeneous material, that lack specificity, designed to accommodate a wide range of applications and structural requirements. To adapt these universal materials for a particular use and achieve the specific performance characteristics, these materials are cut into elements and joined together in order to address the target performance, resulting in composite materials, that indeed help to synthesise



F 1.1: Environmental impact of a building across four key stages. A1 - A3: Product stage (extraction, transport to manufacturing site and manufacturing itself). A4-A6 - Construction stage (transport to construction site and assembly). B1 - B5: Usage (use, maintenance, repair, operational energy use). C1 - C4: End of Life (deconstruction, demolition, transport, waste processing, disposal). *One-Click LCA 2024*

multiple aspects and properties for the target performance and contributes to their superiority in specialized applications (Wiscombe 2012). However, the subtractive approach of composites generates the significant amounts of material waste, while their permanent bonding hinders their further reuse and multi-material composition complicates their further recycle.

RETHINKING MATERIAL PRACTICES

F 1.2: UN sustainable goals: 9 - Industry, Innovation and Construction ; 12 - Responsible Consumption and Production. *UN STG*

The urgency of resource scarcity and the environmental challenges posed by the traditional construction practices demand a fundamental shift in how materials are designed, manufactured, and applied. Addressing these issues requires a shift towards the design strategies that prioritize the material efficiency, such as creating products that fulfil their intended functions using less material and in smarter ways through strategic material tailoring, thereby minimizing the waste and saving the resources.

The advancements in production technology, particularly in additive manufacturing, offer the opportunities to transition from the *generic mass-production* to the *targetted mass-customization*, enabling the materials to be specified during the production directly for their particular needs and applications. This approach ensures that the materials remain homogeneous in composition, which facilitates their recycling, while achieving the functional heterogeneity to steer their behavior and improve their performance, simultaneously reducing the amount of waste during production.

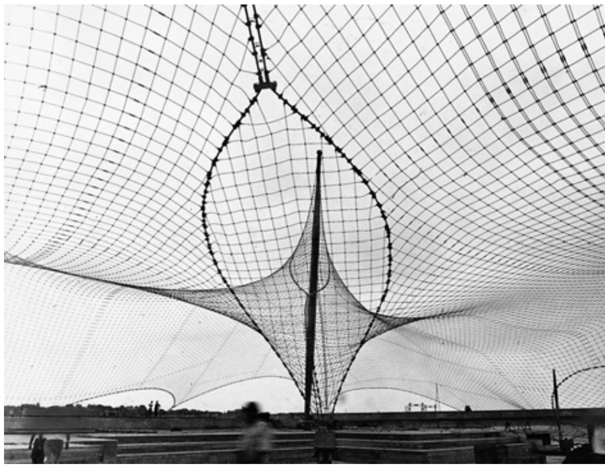
Such practices align with the UN Sustainable Development Goals (SDGs), particularly SDG 9 (*Industry, Innovation, and Infrastructure*) and SDG 12 (*Responsible Consumption and Production*) **F**1.2, by promoting the resource-efficient and sustainable industrial processes (United Nations 2015). These new material practices prioritize hyper-specific, functionally graded materials (FGMs) tailored to the site-and use-specific applications, establishing smarter and more sustainable approaches for building with fewer resources (Ramsgaard Thomsen et al. 2019a).

1.1.2 FORM-MATTER RELATIONS AS A SUSTAINABLE DESIGN PARADIGM

MATERIAL, FORM AND FORCE: SHIFT OF MATERIAL ONTOLOGY

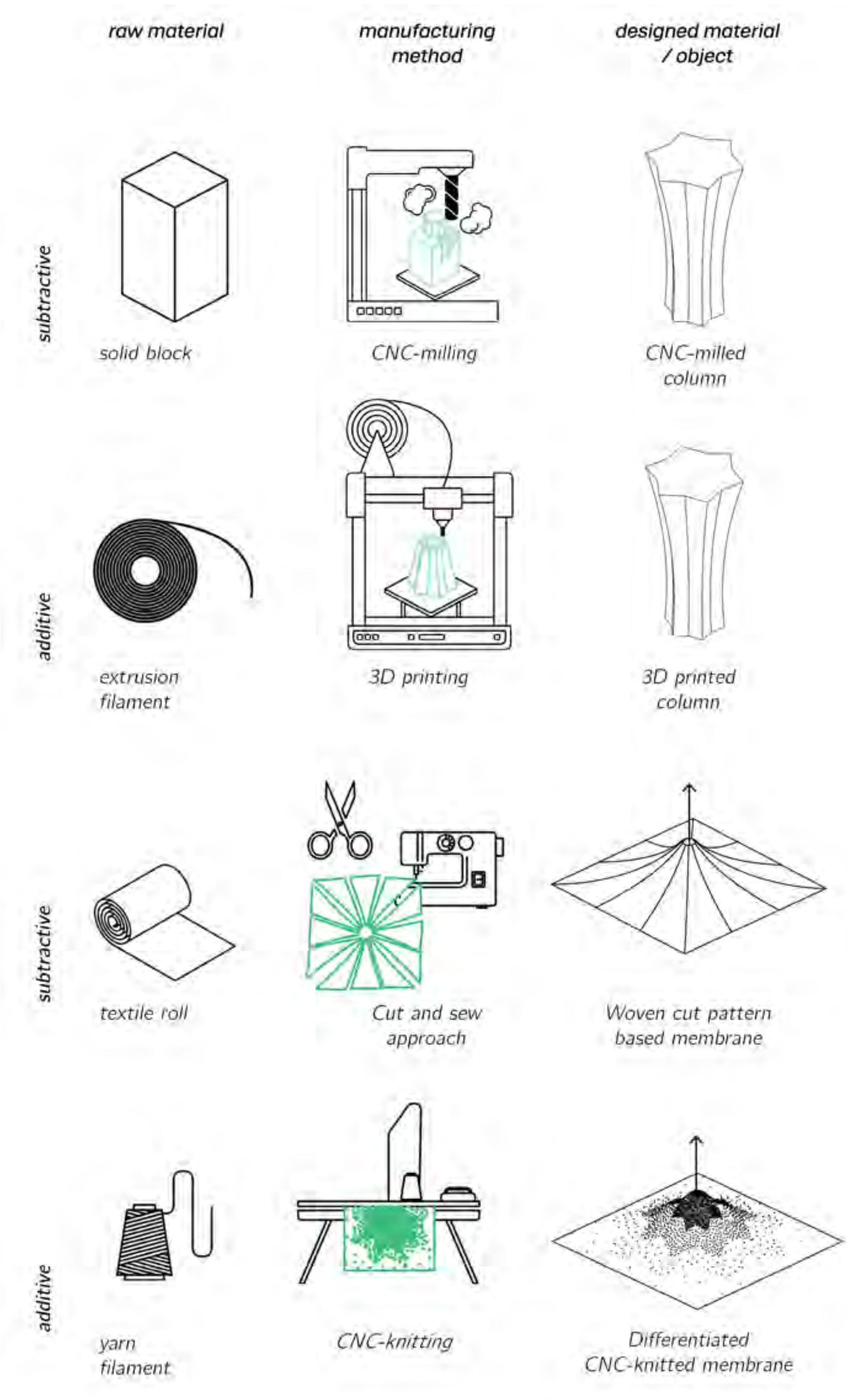
The contemporary discourse in material design and architecture increasingly revolves around the conception of materiality as a dynamic and generative force in shaping the *form* of structures (Löschke 2016). This represents a significant paradigm shift from the static tradition of designing predetermined shapes, where the material is a "servant" of form (Kotnik and Weinstock 2012), to an approach where the material actively informs and influences the design process, integrating material, form and force to unfold a new generative logic of form-finding. In this framework, the material behavior is no longer merely a constraint to be accommodated, but becomes an integral component of the design intent and the outcome. The performance and the behavior of materials - how they interact with the forces, respond to the external conditions, and adapt over time - take the center stage, forging new relationships between the material design and the resulting architectural forms.

This understanding challenges the conventional focus on the static, inherent properties of materials, such as strength and density, by emphasizing their functional capabilities and dynamic actions. As Allan suggests in Points + Lines (Allen 1999), the material's behavior and its capacity to perform specific tasks become the basis for design exploration and innovation.



F 1.4: Net-membrane structure of the German Pavilion during erection at EXPO-67 in Montreal, Canada. *Frei Otto 1967*

In the 1950s the great innovation of structural thinking emerged, being driven by combined knowledge from architecture and engineering. A material composition begins to be understood as a result of the physical forces acting on it (Alexander 1973). The principles of the force-driven design are reflected in the works of Frei Otto through the novel cable-net and membrane prestressed structures, revolutionizing the formal languages of architecture and providing the new structural concepts, challenging the scale and use of novel materials (Nerdinger et al. 2005). Frei Otto's pioneering work in design of lightweight structures, and particularly his exploration of tensile membranes and minimal surfaces, exemplifies this paradigm into the *designed material systems*, rather than found in nature. Otto's designs were inherently tied to the material behavior, as he employed the physical models and experiments to allow the materials to define their optimal forms under specific conditions, leading to the emergence of structures, that undergo the process of self-formation through the capacity of material systems to self-organize (Goldsmith 2016). His emphasis on the material efficiency and responsiveness to the natural forces, is seen in his soap film experiments and later in the large scale realised tensile structures of the Munich Olympic Stadium and the



F 1.3: Subtraction vs. additive manufacturing paradigm

German Pavilion at Expo-1967 in Montreal. These experiments and projects underscore the potential of materials to drive the formal outcomes, rather than conform to the imposed predefined geometries. His work, by combining the topics of form-finding, biological analogies, minimal structures, and complex curvatures, created the basis for a new material practice of lightweight and high-strength membrane structures.

The principle of form follows force is particularly relevant for cable-net and tensile membrane structures, as they transfer the loads purely through the axial and in-plane forces, as there is no bending involved and the surface obtains its shape, being determined by forces and vice versa (Veenendaal and Block 2012)

Building upon these historical and theoretical foundations, modern technologies such as computational tools, digital fabrication, and performance-driven algorithms enable architects and designers to engineer the materials with the specific behaviours aligned with their design intentions and therefore provide a platform for developing and creating the form-matter relations between the *design of structures* and *design of materials* in a domain of architecture. By leveraging these technologies, the material becomes an active participant in the design process, fostering sustainable practices that address both functional performance and resource efficiency.

This context establishes the foundation for the thesis, framing the discourse around the convergence of material performance, form generation, and sustainability. It underscores the critical need to rethink how we design and construct with the materials in a way that respects their inherent properties and capabilities, while embracing the innovative digital driven methodologies to meet the contemporary environmental and architectural challenges. This thesis builds upon these ideas, engaging in a dialogue on the material agency and its transformative potential in shaping the future of architectural practices.

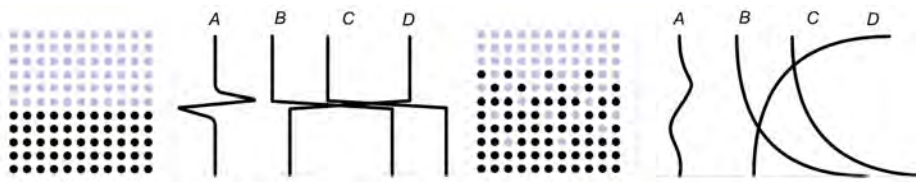
1.2 BACKGROUND

1.2.1 STRUCTURAL MEMBRANES: LIGHTWEIGHT AND HIGH-PERFORMANCE BUILDING SKINS

Tensile membranes have enriched architecture by offering new spatial topologies and enabling lightweight structures to span large distances without intermediate supports. Their design relies on the structural principles where *form* dictates the *performance*: the greater the curvature, the more stable and resilient the membrane becomes. This principle allows for an efficient balancing of external forces, resulting in the high-performative membranes with the exceptional strength-to-weight ratios (Bechthold 2008; Knippers et al. 2011). These equilibrium shapes are achieved through the form-finding processes, essential for generating well-performing three-dimensional surfaces. These membranes address the demands of the force-driven design, elegantly transferring the loads through their thin, flexible surfaces while minimizing the material usage and maximizing the structural efficiency.

COMPOSITE MATERIALS IN MEMBRANE ARCHITECTURE

Traditionally, structural membranes are crafted from the woven, laminated textiles, made of high-performance glass fiber yarns, coated with the waterproof layers. These composite materials contribute to the structural integrity and weather resistance of the tensile membranes, making them suitable for large-scale architectural applications. However, their homogeneous fibrous structure limits the surface pliability and reduces their ability to achieve complex curvatures. To adapt such materials to the form-found shapes, they are discretized into planarized strips, which are subsequently cut-out from the roll of material, sewn or welded together **F** 1.3. This subtractive fabrication approach generates the significant material waste, as the patches should follow the fiber direction, leaving the remaining offcuts often unusable. Additionally, the seam lines, joining the patches introduce internal stress concentrations, which may compromise the structural performance and potential spots of failure (Shinohara 2013) **F**1.5). Not to mention, the amount of human labour, time and energy, that are required in manufacturing these, as the process is primary manual and at large scale.



F 1.5: Composite (left) vs. FGM (right) inner material response. Composite metal + ceramics: A - thermal stress, B - thermal expansion, C - thermal conductivity, D - heat transfer. Redrawn from *Shinohara 2013*

SCALING MEMBRANES BEYOND LARGE STRUCTURES

While the tensile structural membranes are commonly associated with the large-scale applications like stadiums or tent-pavilions, their potential for the smaller-scale uses, such as façade elements, canopies, or sun shading devices, offer significant opportunities. However, replicating the subtractive fabrication processes at smaller scales can amplify the sustainability challenges. The process of cutting and assembling the patches into a three-dimensional form can be rethought by using an alternative textile material system of knit, that is closely aligns with the FGMs as can be actively structured and shaped into the target form by steering its internal material composition by taking the advantage of additive manufacturing process. The fine scale of CNC-knitting enables highly refined material differentiations, allowing for smaller-scale tensile membrane applications with a high degree of material functionality **F**1.6. This approach eliminates material waste and facilitates a more efficient use of resources, precisely

F 1.6: Intricate interior of Isoropia structure integrating the lighting system. Photo: *A.Ingvartsen 2018* placing material where it is needed, not only delivering a high-performing membrane material but also broadening the applicability of membrane structures to diverse architectural contexts.

Beyond structural efficiency, this approach opens a new niche for knitted membranes, where architects can play a more integral role in the design process. Unlike conventional tensile structures, which are often characterized by generic white membrane surfaces, CNC-knitted membranes introduce opportunities for aesthetic exploration alongside structural performance. While membrane architecture often brings to mind the monumental scale of outdoor stadium roofs, this thesis turns attention toward the *indoor* architectural membrane. CNC-knitting is introduced not to replace conventional membranes, but to open up a different class of architectural intervention—one that is more finely detailed and able to explore colour and haptic qualities. We might therefore imagine spatial membranes placed on walls or ceilings that shift geometry in response to acoustic loads or changing structural and spatial demands, panels that modulate light, or kinetic indoor systems that continually reconfigure. All of these are contexts in which the flexible, stretchable, and materially differentiated nature of knit becomes uniquely powerful. By embedding differentiation directly into the material system, these membranes expand the possibilities for expressive, functionally integrated textile structures that move beyond the standardized architectural language of traditional tensile membrane systems.

THE SHIFT FROM COMPOSITES TO FUNCTIONALLY GRADED MATERIALS

The environmental and functional limitations of traditional composite materials highlight the need to rethink the material practices. Functionally Graded Materials (FGMs) offer a novel approach, departing from the subtractive methods of conventional composites into the gradual variation in material composition and properties across their volume, enabling localized performance optimization. This eliminates the stress concentrations, caused by the abrupt material transitions, reduces the waste, and aligns with the form-matter paradigms, where the local material differentiation enhances the global structural behavior (Silva et al. 2024)

FGMs achieve these benefits by leveraging the advancements in additive manufacturing and computational technologies. Digitally controlled processes allow for the precise material programming and deposition across multiple material dimensions. This enables the creation of multi-functional and multi-material structures tailored to the specific performance requirements, with the material's internal structure and functional properties integrated directly into the fabrication process. These advancements introduce new paradigms of form-matter relations, where the local material differentiation complements the global material behavior, leading to a more efficient and responsive architectural design processes (Richards and Amos 2014; Grigoriadis 2015). While specific examples in application of FGMs in architecture are still emerging, the versatility of FGMs offers significant potential for sustainable and innovative design solutions (Hojati et al. 2018). For instance, adaptive façade systems can benefit from FGMs by incorporating materials that respond dynamically to environmental changes, enhancing energy efficiency and occupant comfort. Similarly, lightweight membrane canopies and sun-shading devices utilizing FGMs can adjust their properties to optimize light transmission and thermal performance. Interior space partitions made with FGMs can provide tailored acoustic and thermal insulation, adapting to varying functional requirements.

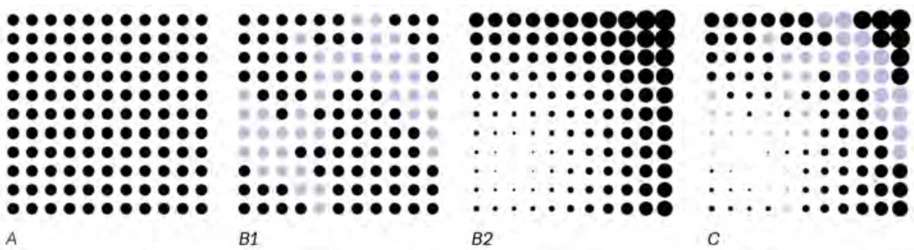
1.3 KNIT AS FUNCTIONALLY GRADED ARCHITECTURAL MATERIAL

ADDITIVE CNC-KNITTING OFFERS NEW LEVEL OF MATERIAL COMPLEXITY

Knitting, traditionally associated with the garment textiles, can be transformed into innovative architectural material system, driven by the advancements in CNC-knitting technology. The advent and constant development of industrial CNC-knitting machines has revolutionized the field, enabling the fabrication of textiles with a greater material complexity and a finely tuned level of material differentiation. This technological leap allows for the precise material programming and the automatic production of large-scale textiles, seamlessly combining efficiency, precision, and design versatility.

As an additive manufacturing process, CNC-knitting creates the material progressively row-by-row, by intertwining the continuous filament into an intricate textile surface, thereby offering a precise control over density, composition, and structural properties of the resulted fabric. Continuous process of CNC-knitting allows for smooth transitions between the material properties, enabling a localized performance optimization without seams or excessive waste. This approach not only reduces the waste, as the material accumulation is directly placed where it is needed, but also aligns with the sustainable practices, as knitted membranes can be unravelled back to yarn and reused, further enhancing their environmental value.

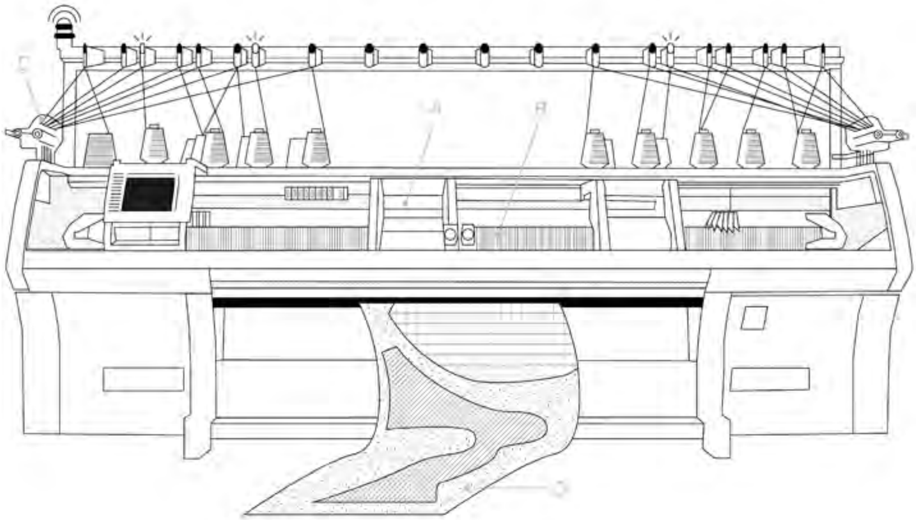
Being inherently both *multi-material* and *multi-structural*, the knit, through the variations in *stitch type* and *yarn properties*, integrates the structural and material differentiation within a single continuous process, wastefree and for targetted performance (Ramsgaard Thomsen 2016). This capability allows for the design of bespoke tensile membranes that achieve three-dimensional forms through material expansion rather than cutting and joining, which aligns with and extends the principles of FGMs by design and fabrication of multi-dimensional functionally graded knitted materials.



F 1.7: Multi-dimensional knit material gradings: A - non-graded material, B - mono-dimensional grading (B1 - same stitch varied color .B2 - same colour, varied stitch). C - multi-dimensional grading combining (varied stitch and color). *Sinke 2022*

FORM-MATTER RELATIONS IN KNIT

The stretch behavior of knitted textiles positions them as ideal candidates for exploring form-matter relations in architecture. The varied loop-based structure of knit enables the large geometric surface transformations as the loops rearrange by redistributing the load, which permits the knitted material to form complex,



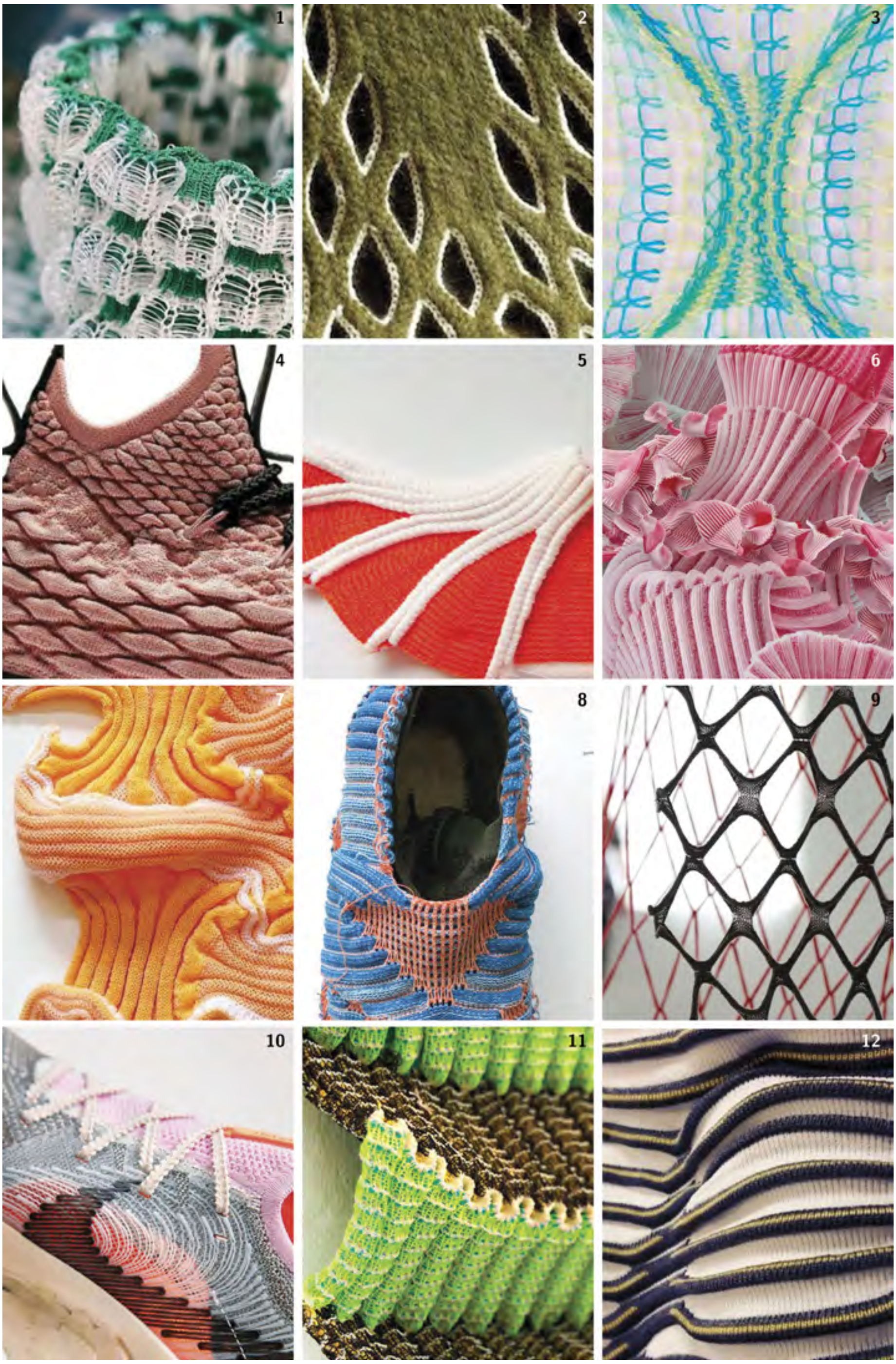
F 1.8: Knitting machine STOLL CMS 822 ki illustration. Machine is operated by sideways driving carriages (A), that control the selection of needles (B), simultaneously passing the yarn to them (C). As the result, fabric is formed by the sequential yarn intertwining into the differentiated fabric surface (D)

adaptive three-dimensional geometries under the external forces. This behavior aligns with the principles of force-driven design, where the interaction between material and force dictates the final form.

By integrating the form-finding processes with the material properties of knit, architects and designers can harness its anisotropic and heterogeneous nature to create innovative structures, targetted for specific performance and geometric shape. For instance, the multi-dimensional material gradation in knit enables a localized control over stiffness, expansion, and therefore steering of the final shape, while additionally integrating other functional properties, contributing to designs that are both resource-efficient, performance-optimized and functional. These properties make the knit a potential alternative to the conventionally used woven fabrics, as it is capable of addressing the diverse performance demands of architecture, such as transparency, adaptability, complex geometry and structural and functional integrity within a single surface.

During the last decade research into knitted textiles for architectural application has gained an increasing popularity and resulted in a wide range of outcomes. The research pioneers has explored the application of knitted textiles for structural tensile membranes (Tamke et al. 2015; Ramsgaard Thomsen et al. 2019b; Sabin et al. 2020), form-work for concrete casting (Popescu et al. 2020; Pal et al. 2020; Scheder-Bieschin et al. 2023), as substructure for the mycelium growth (Kaiser et al. n.d.; Yogiaman et al. 2020; Davis et al. 2024; Scott et al. 2024), pneumatic systems (Baranovskaya et al. 2016; S. Ahlquist et al. 2017; Tessmer et al. 2022), responsive dynamic structures (Scott 2018; Ramsgaard Thomsen and Karmon 2012) and tensegrity shells (Gupta et al. 2020). This research highlights the versatility and potential of knit to engage in form-matter relations within architectural design, offering a smarter and resource efficient alternative to the conventional membrane textile materials **F**1.9).

F 1.9: Form-matter relations in knit applications: 1 - KnitCandela by *ETH Block Research Group 2018*, 2 - Isoropia by *CITA 2018*, 3 - Cam Cad Knitting by *CITA 2009*, 4 - KnitNervi by *TU Delft and ETH Block Research Group 2022*, 5 - Knitted Composite Tower by *Tongji University 2020*, 6 - BioKnit by *HBBE Newcastle 2023*, 7 - Hybrid Tower by *CITA 2016*, 8 - MeiTing Shell by Southeast University 2021, 9 - Myco-Knit CompoSITE by *Ahmet and Romy 2022*, 10 - Sensory Placescapes by *Ahlquist 2017*, 11 - The Edges of the World by *Ernesto Neto 2010*, 12 - Non-Planar 3d Printing on Knit by *Daley, Rasanani 2021*



F 1.10: Material grading opportunities with knit. Examples from fashion and textile design: 1, 6 - by Sagmin Oh Studio, 2 - by Stephanie PearlMcPhee, 3 - by Kieran Foley, 4 - Knitted shoe Nike Lebron XV by Nike, 5 - by Drew McKevitt, 7 - by Marie Van Loo, 8 - by Susanne Oude Hengel and Drew McKevitt, 9 - by Laura Carter, 10 - Nike Zoom Alphafly Next Nature knitted shoe, 11 - by Susan Williams, 12 - from knovus knitmelbourne

F 1.11: Challenge of knit prediction, specification and the scale up demonstrates the radical difference between the scaled model (to the left) and the 1:1 scale prototype, knitted with the stiff Dyneema fibers (to the right). The figure showcases the difficulty of achieving the same depth of the fabric three-dimensionality at large scale in comparison to the small-scale model. Photos from Isoropia project development at CITA 2017. Photos by *Sinke 2017*

1.4 PROBLEM STATEMENT: OPPORTUNITIES & CHALLENGES WITH KNITTED ARCHITECTURE

The knitted textiles have emerged as a promising next-generation material for textile architecture, offering advantages in integrated detailing, material differentiation, and sustainable additive production. Despite these advancements, several challenges still hinder their broader adoption in architectural applications. These challenges arise from the inherent complexity of knits, including their anisotropic behavior and heterogeneous composition, as well as the difficulty in scaling up from their traditional use for garments into larger architectural forms. For clarity, these challenges can be linked to the *knit prediction* and *knit specification* domains, which structure the state of art review in the following State of Art chapter, while the challenges themselves are outlined below.

CHALLENGE OF PREDICTING KNIT BEHAVIOR

The anisotropic and multi-scalar nature of knitted materials presents significant difficulties in predicting their behavior. Differentiated knit surfaces often exhibit the varying properties, such as stiffness and stretchability, within the same structure. It is mainly challenging to understand the material properties, the knit structures provide to the material, as the slightest change in stitch tension or configuration affects the stiffness of the area and propagate to the entire surface and overall structural behavior. This sensitivity and the cohabitation of varied properties complicates the understanding of material's overall response to applied forces, making it challenging to anticipate its global structural behavior (Ramsgaard Thomsen et al. 2019a). Without accurate predictive tools, the complexity of knitted materials undermines their potential, resulting in trial-and-error time and resources intensive approaches during the design and manufacturing processes.

The scaling of knitted materials for architectural applications introduces additional complexity. As the surface area increases, but the stitch scale remain the same, the scalar impact of material differentiation onto the global behavior becomes more difficult to interpret and manage. This challenge highlights the need for advanced digital instruments, that are capable of addressing these multi-scalar design complexities and ensuring that large-scale knitted membranes retain their intended performance characteristics. Addressing this issue requires a synthesis of *advanced computational tools* and simulation, that together are capable of facilitating design exploration, form-finding, and material behavior prediction.These tools must also support the scalability, ensuring the computational efficiency while maintaining acceptable accuracy in predicting the performance of the produced membranes.

To address this challenge, advanced *simulation* tools specifically tailored to the *differentiated* nature of knits, employed at larger scale are required. These tools must integrate the unique anisotropic properties of knitted membranes to predict their behavior under various loading and environmental conditions and take into account the scale of application.

CHALLENGE OF KNIT SPECIFICATION

Knitting's ability to achieve a localized material differentiation through variations in stitch patterns and yarn properties is a key advantage, where it also compounds the challenge of material specification, in particular of linking the local material grading to the global structural behavior. While the technical capability to grade the material properties exists within the CNC-knitting technology, the challenge lies in determining the input parameters of how the local material differentiation should be guided to achieve the desired global outcomes. The existing material grading strategies, derived from the garment manufacturing, do not provide a sufficient guidance for the architectural applications and demands. While the current methodologies from the fields of material science or textile design lack a clear strategy for linking these local variations to the global behavior and performance of the overall membrane to be applied for architectural domain.

To bridge this gap, *simulation* and *analysis* tools must be developed to connect the local material differentiation with the global structural performance. These tools would enable designers to steer the material grading with precision, aligning the material's composition with the intended architectural form and functionality.

NEED FOR NEW DIGITAL DESIGN FLOWS FOR DIFFERENTIATED ARCHITECTURAL KNITS

The challenges of predicting knit behavior, linking the local material grading with the global structural performance for architectural application, emphasize the need for advanced digital design tools and analytical frameworks, that are able of providing the clarity how to align the controlled knit material compositions with the desired structural behavior of the membrane. By tackling these issues, this research aims to unlock the potential of knitted material programmability combined with the digital computational technologies in order to make a step forward in using the knit as high-performance innovative tensile membrane material within textile architecture.

This leads to the formulation of the *Research Scope*, which is outlined in the following section.

1.5 RESEARCH SCOPE

The Research Scope section provides a comprehensive framework for this study, detailing its core components and guiding structure. It begins by stating the **research aim** combined with **hypothesis**, which defines the overarching goal of this work and provides a testable assumption based on the aim. This is followed by the **research questions**, which articulate the specific inquiries driving the investigation and forming the basis for the experimental work conducted in this PhD study, steered by **research tracks**. Additionally, the section outlines the **methodology**, employed by this thesis, offering an overview of the approaches and tools used to achieve the objectives in addressing research questions. Finally, the section concludes with a brief description of the **research activities**, focusing on the development of *digital models* and *physical prototypes* central to this thesis. At the end, section provides a chapter-by-chapter **thesis structure**, as a guidance to navigate the dissertation document. The figure 1.12 offers a visual map through the research scope of this thesis, mapping the research aim, research questions and the related research activities: articles, digital models and physical prototypes.

ARTICLE-BASED DISSERTATION

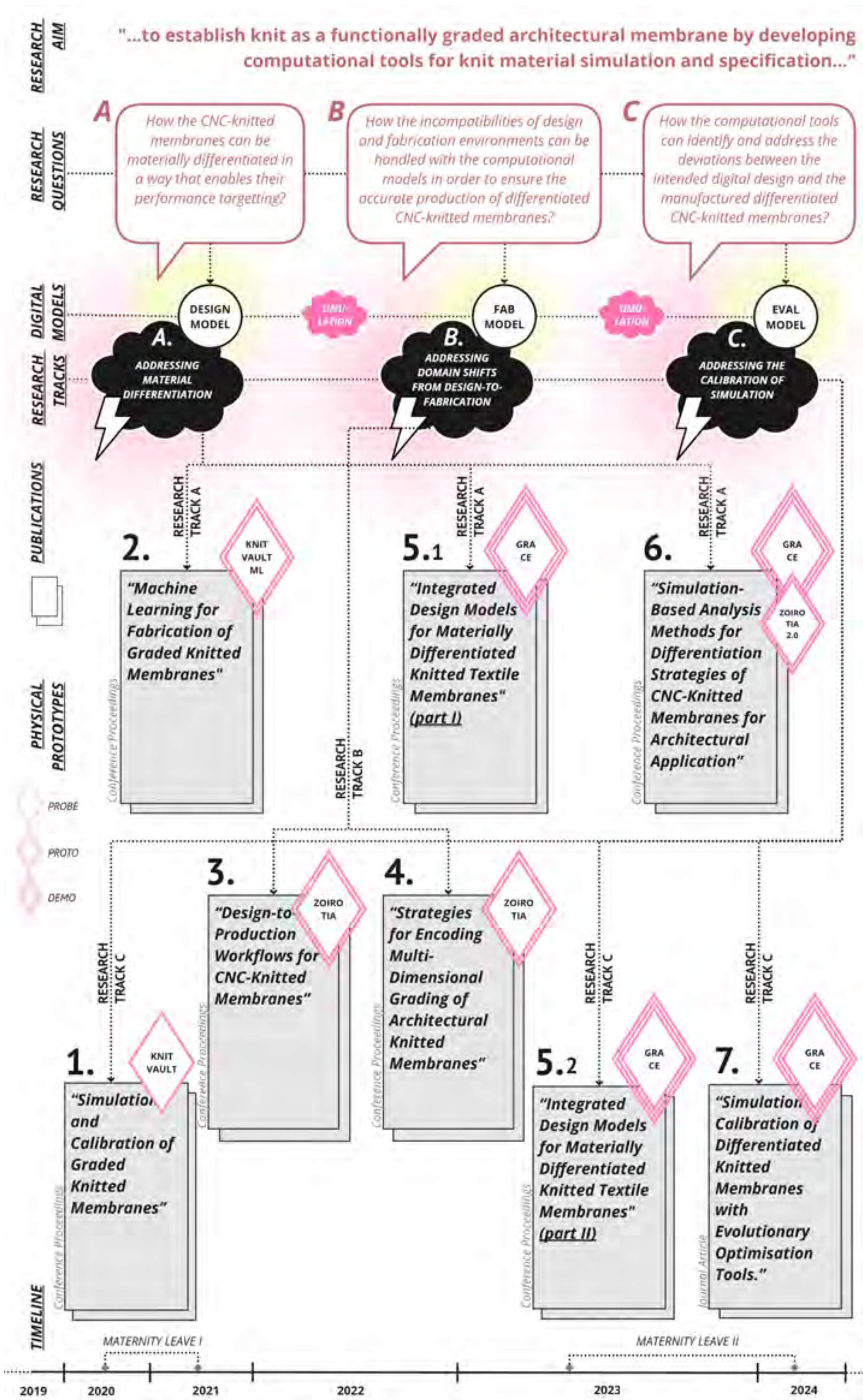
The research development has been documented and disseminated through the peer-reviewed articles, published during the PhD research period of 2019-2024. These articles serve as a formal channel to share and get the feedback on the findings of this thesis. Taking the advantage of the published work, that already contain the detailed technical descriptions of the experiments, this dissertation includes them as descriptive part of the text within the *Experiments* chapter IV, thereby submitting it as an **article-based PhD**.

The thesis includes seven peer-reviewed articles, where six of them are published in the conference proceedings and one - in the scientific journal. Within the Experiments chapter the articles are grouped by their contribution in addressing the research questions, and present within the mentioned above *Research Tracks*. Consequently, the dissertation text is structured around these research tracks while additionally provide an envelope for linking the experiments, described in articles The visual mapping of the research scope to the articles is structured in **F**1.12.

The structuring of the articles within the dissertation text is aligned with three research questions, mapped onto the research tracks, related to individual digital models. The physical prototypes, each marked with the diamond label are mapped onto the articles, highlighting their detailed status of probe, prototype or demonstrator by the number of outlines in the diamond label. For clarity and visualisation purposes, the reader can again refer to the diagram in **F**1.12. The fifth article, is splitted into two, as it simultaneously addresses the questions related to two different research tracks. The list of articles can be referred in **F**1.13

1.5.1 AIM & HYPOTHESIS

The statement of the Research Aim and the Hypothesis are combined in this thesis. As this PhD research, positioning itself within the creative design discipline, is of *exploratory* type and seeks to investigate and develop the new design methods for innovative architectural solutions - the hypothesis is closely tied to the aim of the project. By combining them, redundancy is avoided, and the formulation of the



F 1.12: Research scope, mapping the research aim, research questions and the related research activities: articles, digital models and physical prototypes

RESEARCH QUESTION A. DESIGN-MODEL AND MATERIAL DIFFERENTIATION LOGIC

A

Publications: 2, 5.1, 6

5.1 Sinke, Yuliya, Martin Tamke, and Mette Ramsgaard Thomsen (2023). **Integrated Design Models for Materially Differentiated Knitted Textile Membranes as the Means to Sustainable Material Culture within Membrane Architecture (part I)** In *Sustainable Futures, Leave No One Behind: Proceedings of UIA 2023 Copenhagen World Congress of Architects*. Copenhagen, Denmark: Springer, 2023. p.355-366 (until the section 5).

6. Sinke, Yuliya, Martin Tamke, and Mette Ramsgaard Thomsen (2024). **"Simulation-Based Analysis Methods for Differentiation Strategies of CNC-Knitted Membranes for Architectural Application"**. In *Tensinet 2023: Proceedings of Tensinet Symposium. Membrane Architecture: The Seventh Established Building Material.* Nantes, France. p.220-233.

2. Sinke Baranovskaya, Yuliya, Sebastian Gatz, Martin Tamke, and Mette Ramsgaard Thomsen (2020). **Machine Learning for Fabrication of Graded Knitted Membranes**, In CDRF2020: *Proceedings of the 2nd International Conference on Computational Deisgn and Robotic Fabrication*. October 2021. Edited by P.F. Yuan et al. p.309–319.

RESEARCH QUESTION B. FABRICATION MODEL AND MATERIAL FABRICABILITY

B

Publications: 3, 4

4. Sinke, Yuliya, Mette Ramsgaard Thomsen, Drua Sif Simone Albrechtsen, and Martin Tamke (2022). **Design-to-Production Workflows for CNC-Knitted Membranes**. In *Hybrids & Haecceities: Proceedings of the 42nd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, University of Pennsylvania, Weitzman School of Design. Philadelphia, Pennsylvania, USA, 2022. p.168-181.

3. Sinke, Yuliya, Mette Ramsgaard Thomsen, Martin Tamke, and Martynas Seskas (2022). **Strategies for Encoding Multi-Dimensional Grading of Architectural Knitted Membranes.** In *Towards Radical Regeneration*. Berlin, Germany: Springer, p.528-542.

RESEARCH QUESTION C. EVALUATION MODEL AND CALIBRATION OF MATERIAL PROPERTY

C

Publications: 1, 5.2, 7

1. Sinke Baranovskaya Yuliya, Martin Tamke Martin, Mette Ramsgaard Thomsen. (2020). **Simulation and Calibration of Graded Knitted Membranes**. In *Distributed Proximities / Volume I: Technical Papers. Proceedings of the 40th Annual Conference of the Association of Computer Aided Design in Architecture (ACADIA)*. Online and Global. 24-30 October 2020. Edited by B. Slocum, V. Ago, S. Doyle, A. Marcus, M. Yablonina, and M. Del Campo, p.198-207.

5.2 Sinke, Yuliya, Martin Tamke, and Mette Ramsgaard Thomsen (2023). **Integrated Design Models for Materially Differentiated Knitted Textile Membranes as the Means to Sustainable Material Culture within Membrane Architecture (part II)** In *Sustainable Futures, Leave No One Behind: Proceedings of UIA 2023 Copenhagen World Congress of Architects*. Copenhagen, Denmark: Springer, 2023. p.366-375 (from the section 5).

7. Sinke, Yuliya, Martin Tamke, and Mette Ramsgaard Thomsen (2024). **Simulation Calibration of differentiated knitted membranes with evolutionary optimisation tools** In *Advances in Computational Science and Engineering*, Vol. 2, No. 1: Springer, 2023. p 19-36.

F 1.13: List of articles, included in this PhD dissertation research focus is strengthened. It shows how the overarching goal of the research is directly aligned with the specific assumptions being tested.

AIM This research aims to establish the knit as a functionally graded architectural membrane by developing the computational tools for knit material simulation and specification. These tools are designed to address the performance demands of tensile membranes, enabling both the design exploration and the industrial manufacturing of differentiated CNC-knitted membranes.

HYPOTHESIS The hypothesis, underpinning this research, asserts that the materially graded CNC-knitted membranes can be effectively designed, specified, fabricated and their behavior predicted through the use of computational models for material simulation and specification, that align the local material properties with the global performance requirements. This hypothesis assumes that the complex relationships between the membrane topological design, local material composition, knitting patterns, and industrial CNC knitting manufacturing constraints can be effectively captured through custom digital models, facilitating the broader and more sustainable use of knitted membranes within textile architecture.

1.5.2 RESEARCH QUESTIONS

At the core of this thesis lies an overarching research question that captures the central aim of the investigation. The overarching *Research Question* is formulated as follows: **How can we design, fabricate and predict the behavior of the materially graded CNC-knitted membranes, based on their target performance?**

To answer this overarching question, the research finds itself at the three key *research tracks* of investigation, each represented by a focused research sub-questions **F**1.14. These questions address the material differentiation, the aspects of fabricability, and the validation of designed structures against their fabricated counterparts. Each research sub-question is accompanied by a corresponding research objective, which outlines the actionable steps required to address the inquiry. Together, these questions and objectives define the framework for developing computational tools, bridging the digital and physical domains, and ensuring the alignment between the designed and the fabricated structures. By systematically addressing these questions and objectives, this thesis seeks to advance the understanding and application of differentiated knitted materials in architectural design by providing a comprehensive design-to-fabrication-to-evaluation workflow, specifically tailored to differentiated CNC-knitted architectural membranes.

A How the CNC-knitted membranes can be materially differentiated in a way that enables their performance targetting?

The research question A is addressed within a **Research Track A** by developing a **Design Model with integrated simulation**, that would permit to explore not only spatial configuration of membrane as performance target through the form-finding, but as well the local material differentiation strategies with the aid of integrated analytical tools. Research track A addresses the differentiation of local material properties in CNC-knitted membranes in response to their performance target of achieving a specific geometric shape under strain conditions.

A

HOW THE CNC-KNITTED MEMBRANES CAN BE MATERIALLY DIFFERENTIATED IN A WAY THAT ENABLES THEIR PERFORMANCE TARGETTING?

B

HOW THE INCOMPATIBILITIES OF DESIGN AND FABRICATION ENVIRONMENTS CAN BE HANDLED WITH THE COMPUTATIONAL MODELS IN ORDER TO ENSURE THE ACCURATE PRODUCTION OF DIFFERENTIATED CNC-KNITTED MEMBRANES?

C

HOW THE COMPUTATIONAL TOOLS CAN IDENTIFY AND ADDRESS THE DEVIATIONS BETWEEN THE INTENDED DIGITAL DESIGN AND THE MANUFACTURED DIFFERENTIATED CNC-KNITTED MEMBRANES?

F 1.14: Research Questions of this PhD Thesis.

B How the incompatibilities of design and fabrication environments can be handled with the computational models in order to ensure the accurate production of differentiated CNC-knitted membranes?

The research question B is addressed within a **Research Track B** by developing a **Fabrication Model**, that would translate the incompatibilities between the design and fabrication environments, accounting for their *spatial*, *metric* and *resolution* differences. Research track B addresses the translation of data from the design domain, where the data is represented three-dimensionally, in metric units and at lower resolution, into the manufacturing domain of CNC-knitting, which operates with two-dimensional data, at finer resolution and in stitch based units. The track explores the notion of fabricability, ensuring that the digital designs can be translated into physical artefacts with the minimal distortion while preserving the original design intent, performance and functionality.

C How the computational tools can identify and address the deviations between the intended digital design and the manufactured differentiated CNC-knitted membranes?

The research question C is addressed within a **Research Track C** by developing an **Evaluation Model**, that *identifies* the deviation between the intended digital design and the manufactured physical prototype by aligning the form-found mesh from the Design Model with the point cloud of the produced physical knitted membrane. This model *addresses* the deviations by calibrating the simulation the **Design Model** through the discovery of unknown stiffness values with the aid of integrated genetic evolutionary optimisation algorithm.

1.5.3 METHODOLOGY OF THIS THESIS: RBS + RBD

The methodology used to carry out the research work in this thesis, will be described in more detail further in Chapter III on Methodology, however it is introduced already briefly here, to help the reader to understand the scope of research activities. In order to answer the above mentioned research questions, this PhD thesis employs a **combined methodology** of Research-by-Design (**RbD**) and Research-by-Simulation (**RbS**). The scientific methodology of simulation, originally developed for the natural sciences and technical disciplines, is adapted and expanded in this thesis within the concept of the Digital Design Chain. This integration enables a structured investigation of design, material differentiation, and manufacturing processes within a computational framework.

While Research-by-Simulation (RbS) has traditionally focused on the study of pre-existing systems through predictive modelling, this research also incorporates an engineering perspective on simulation, specifically **Research-by-Simulation with a fabrication focus (RbS(f))**. The adaptation of simulation methods from structural engineering, particularly the form-finding methodologies developed by Knippers et al. 2011, provides for this thesis a framework for balancing global equilibrium-driven form generation with local material differentiation of knit.

By incorporating the workflow of structural engineering form-finding into the Digital Design Chain, this research extends its methodology beyond conventional simulation applications in design. Instead of treating structural analysis as a post-evaluative validation tool, this thesis positions it as an integrated component of the design process, enabling the simultaneous development of form and material specifications.

This methodological approach facilitates the creation of custom digital models with integrated *simulation*, supporting the complex processes of textile membrane *design*, material differentiation, behavior prediction, and industrial manufacturing. These digital models are continuously informed by physical evidence across various scales, including material samples, smaller probes, prototypes, and full-scale demonstrators. These prototypes systematically test different aspects of tensile CNC-knitted membranes, encompassing their topological design, material differentiation, and functional performance, as examined in subsequent chapters.

RESEARCH ACTIVITIES

The introduced combined methodology defines the landscape of activities, present in this thesis, structured around three *research tracks*. Within each track, the research activities include the development of *simulation and the digital computational models, the design and production of the physical prototypes, and finally, the scientific dissemination of findings through the peer-reviewed articles.* **F**1.12 can be again referred to to navigate the clustering of the articles, based on the research questions.

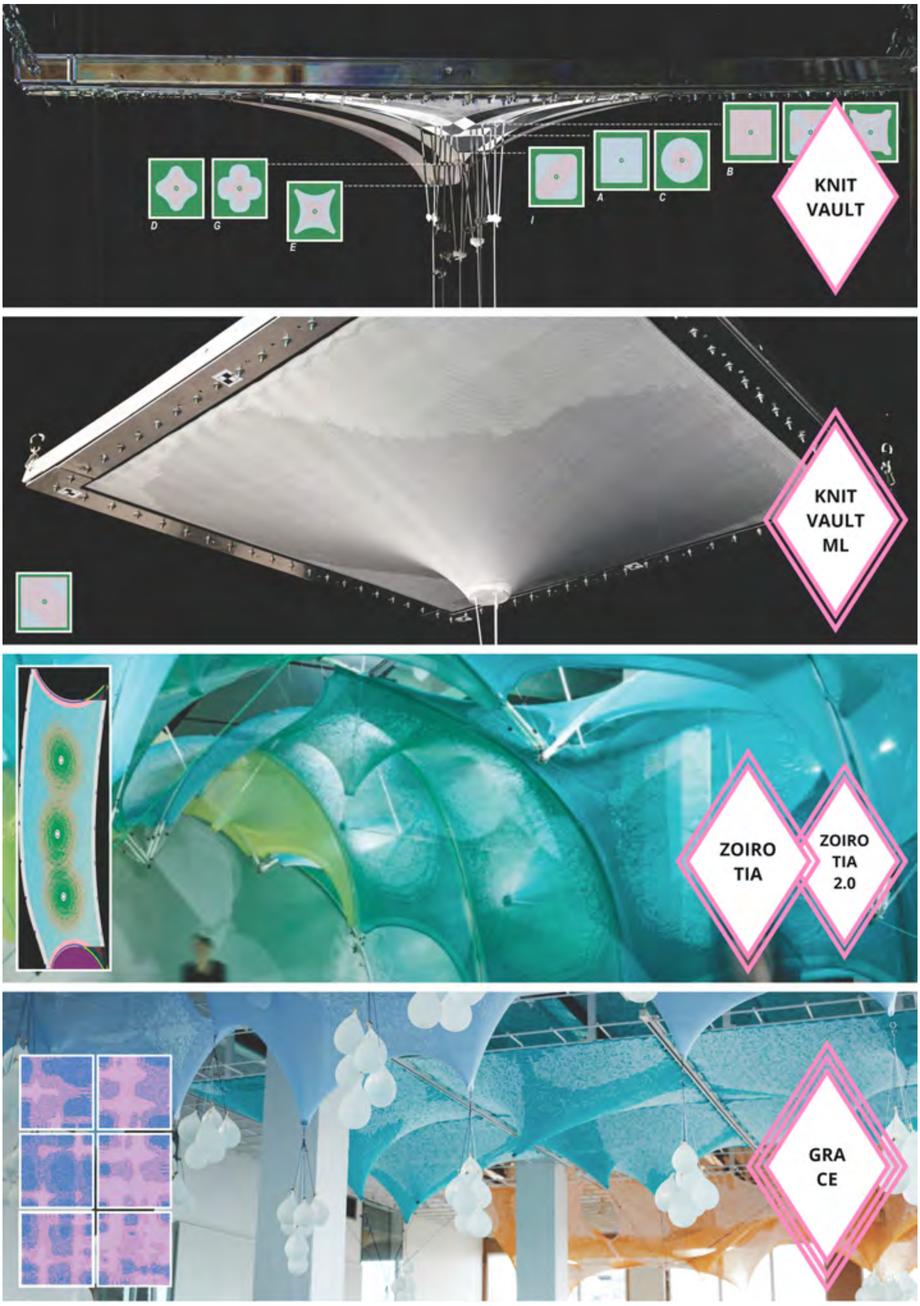
THE DEVELOPMENT OF THE DIGITAL MODELS

The **digital models** are defined as the principal substance of this PhD thesis project, that structure the experimental work. These models include: 1) the **Design Model**, which focuses on predicting the shape and analysing the behavior of the differentiated knitted membranes during the design process; 2) the **Fabrication Model**, that translates the digital form-finding and simulation outcomes into the machine-readable instructions for the production of differentiated knitted membranes on the industrial CNC-knitting machine. 3) the **Evaluation Model**, compares the digital simulation with the physical artefact in order to validate and calibrate the simulation integrated within the Design Model, ensuring its closer alignment with the physical CNC-knitted differentiated membrane through the use of optimisation algorithms.

THE DESIGN AND PRODUCTION OF THE PHYSICAL PROTOTYPES

Within the development of thee digital models in this thesis, the design and creation of physical prototypes serve as a crucial validation mechanism for the digital workflows. These prototypes test and confirm the assumptions made in the research and address the stated research questions. Four major physical prototypes significantly contribute to the research inquiry: *KnitVault, KnitVault ML, Zoirotia, and GraCe* **F**1.15 Each prototype uses custom-designed, differentiated CNC-knitted surfaces whose digitally graded material composition accommodates the required surface stretch toward the three-dimensional target form. A more detailed explanation of these prototypes is provided in the Methodology chapter, beginning on p.112, where the role of the thesis author is outlined, along with the broader design and fabrication context.

KnitVault explores the impact of manually designed surface patterns on the form and depth of tensioned fabrics. This prototype establishes a foundational



F 1.15: Physical prototypes developed in this thesis workflow integrating the Design, Fabrication, and initial Evaluation Models. It bridges a manual design exploration of surface patterns with the industrial CNC-knitting production, while setting the foundation for the iterative refinement and calibration of the Simulation Model. KnitVault is an individual work of the PhD author, externally fabricated in collaboration with knitting factory ViolaStils.

KnitVaut ML builds upon the topology of the original KnitVault, but shifts from the manually defined material specifications to a machine learning-driven approach. It explores the generation of potential surface patterns based on a target 3D form, expanding the possibilities for automated material differentiation.

Zoirotia, a large-scale tensile installation, demonstrates the integration of digitally form-found shapes with the local material differentiation guided by the geometric analysis, conducted within Design Model and further specified in the Fabrication Model. This alignment ensures that the 3D membrane form is effectively informed by the 2D pattern distribution. Developed through an interdisciplinary collaboration, Zoirotia showcases an advanced design-to-fabrication workflow, spanning both Design and Fabrication Models.

GraCe, the final demonstrator, comprises of series of medium-scale ceiling panel installations. It highlights the use of advanced simulation-based material differentiation method, by incorporating the structural analysis into Simulation Model, thereby further refining the Design Model. Developed during a teaching workshop at the Royal Danish Academy, GraCe enabled CiA Master programme students to apply the complete design-to-fabrication-to-evaluation workflow with differentiated CNC-knitted material systems. The result was three distinct tensile installations featuring three-dimensional ceiling panels.

SIMULATION AS THE MAIN SUBJECT OF THE THESIS METHODOLOGY

In the synergy between digital models and emerging physical prototypes, digital *simulation* serves as the central subject of the methodology. It operates on digital models, linking them and facilitating the transfer of data across them. Simulation establishes an investigative framework that encompasses problem domains both as epistemological subjects of interest and as directly applicable tools within design modelling practices.

Throughout this thesis, simulation appears in various forms through versatile models, supporting knowledge inference to gain insights, answer research questions, inform hypotheses, and structure the discussion. Drawing on literature from the philosophy of simulation (Winsberg and others), the insights gained provide a novel perspective on digital models and the processes explored in this thesis, leading to a reassessment and elevation of the role of simulation. Within this framework, the Simulation can be seen acting as a *design tool*, in two key ways: 1) Simulation for design of the global membrane behavior, and 2) Simulation for design of the local material differentiation. More specifically, the methodological scope of this thesis therefore defines two primary purposes of simulation: 1) Simulation for knit material behavior *prediction*, and 2) Simulation for knit material *specification*.

1.5.4 CONTRIBUTIONS OF THE THESIS

The contributions of this thesis are primarily methodological, reflecting a structured approach to addressing the challenges of designing, fabricating, and validating materially graded CNC-knitted membranes at an architectural scale. Inspired by methodologies from both the scientific and engineering domains, the research introduces a systematic framework for navigating the intricate processes involved in integrating material differentiation, computational simulations, and physical fabrication.

By drawing on insights from the scientific perspective of simulation (Winsberg et al.) and the engineering understanding of design of tensile structures (e.g., Knippers et al.), this thesis constructs a clear and replicable workflow, adopted to CNC-knitted graded material applied for tensile architectural membranes. This methodological rigor facilitates the exploration of novel material behaviours and design possibilities, while ensuring the alignment between digital and physical outcomes. Beyond its focus on CNC-knitting, the methodological advancements presented here hold potential for adaptation to other material systems characterized by graded properties, produced with additive manufacturing and demonstrating controlled deformation as a design exploration.

The thesis contributions are organized around three interrelated research tracks, each addressing a specific aspect of the workflow: design, fabrication, and evaluation. These tracks correspond to the three sub-research questions and collectively establish a cohesive framework for advancing the state of the art in the design-to-production pipeline of CNC-knitted membranes.

CONTRIBUTION A: A DESIGN METHOD FOR KNIT MATERIAL DIFFERENTIATION BASED ON SIMULATION AND ANALYSIS TECHNIQUES TO ADDRESS THE TARGET SHAPE OF TENSILE ARCHITECTURAL MEMBRANE

The contribution establishes a method that links the local material properties with global structural behavior of the graded CNC-knitted membranes. By integrating the form-finding and the structural analysis through the simulation integrated in the Design Model, this method enables a precise material differentiation, tailored to specific performance requirements, namely the target three-dimensional shape. It opens up new design opportunities for the application of knits in tensile membrane topologies and achieving the volumetric configurations, possible only with the locally graded material differentiation. This contribution responds to **Research Question A** and is realized through the **Design Model** developed within **Research Track A**, technically described by articles 2, 5.1 and 6.

CONTRIBUTION B: A FABRICATION METHOD, INTEGRATING ANALYSIS DATA FROM SIMULATION FOR PRECISE MANUFACTURING OF DIFFERENTIATED CNC-KNITTED MEMBRANES

This contribution introduces a design-to-fabrication workflow, that is specifically tailored for the differentiated CNC-knitted membranes. By addressing the spatial, metric, and resolution discrepancies between the digital and the physical domains, this method ensures that the digital designs are accurately translated into tangible artefacts, accounting for the fabrication constraints of CNC-knitting process. This contribution responds to **Research Question B** and is achieved through the development of **Fabrication Model** within **Research Track B**, technically described by articles 3 and 4.

CONTRIBUTION C: A VALIDATION METHOD FOR IDENTIFYING AND CALIBRATING GEOMETRICAL DEVIATIONS IN CNC-KNITTED MEMBRANES USING EVOLUTIONARY ALGORITHM

This contribution introduces an evaluation workflow within the Evaluation Model, that validate the potential geometrical deviations occurring between the digitally designed and physically manufactured CNC-knitted membranes through the deviation mapping onto the simulation. The Evaluation Model addresses the deviation by calibrating the simulation through discovering of the unknown stiffness values for differentiated CNC-knitted membranes with the aid of genetical evolutionary optimisation algorithm. This method is integrated into the design-to-fabrication workflow and expands it into the design-to-fabrication-to evaluation digital chain, that provides a platform for design exploration, iteration and further calibration, for exploring the alternative to explored in this thesis knitting stitch configurations and their application for stretch. This contribution responds to **Research Question C** and is implemented through the **Evaluation Model**, developed within **Research Track C**, technically described by articles 1, 5.2 and 7.

1.6 THESIS STRUCTURE

The present thesis consists of five chapters: Introduction *(current)*, State of Art, Methodology, Experiments, and Conclusions.

The second chapter, the **State of Art**, establishes the theoretical and practical foundation for research on CNC-knitted differentiated membranes by synthesizing the knowledge across material science, computer graphics, engineering, and architecture. It explores the challenges of designing functionally graded materials (FGMs) through a multi-scalar and interdisciplinary lens, emphasizing the integration of simulation, material specification, and fabrication workflows. The key discussions include current methodologies for **predicting** textile behavior with **simulation**, the transition from the traditional bottom-up to simulation-driven **knit** material **specifications**, and the potential of digital design chains to interconnect the design and manufacturing processes. Additionally, the chapter identifies the knowledge gaps in architectural knit research, particularly in simulation calibration, material grading strategies, and workflow adaptability. This synthesis informs the development of a novel modelling framework withing this Phd thesis, comprising of Design, Fabrication, and Evaluation Models, which collectively redefine the design-to-fabrication processes for differentiated architectural knits.

The third chapter, the **Methodology**, establishes the epistemological and methodological foundations of the research, integrating simulation and physical prototyping into a structured framework. It begins by examining the epistemological role of simulation in science, engineering, and design, situating it as both a predictive and exploratory tool. The chapter introduces a hybrid methodology, *Research-by-Simulation & Design* (RbS+RbD), which combines the predictive capabilities of simulation with the iterative, material-driven approach of design research. This methodology is structured around three interconnected digital models—the *Design Model*, *Fabrication Model*, and *Evaluation Model*—which together form an *expanded digital design chain*. These models facilitate material differentiation, translate design data into fabrication-ready specifications, and enable simulation validation and calibration. The chapter also outlines the research tracks that structure the experimental work, each corresponding to a key research question. By integrating digital modelling with physical prototyping, this methodology enables an iterative, feedback-driven approach to designing and fabricating CNC-knitted membranes for architectural applications.

The fourth chapter, the **Experiments**, presents the research investigations conducted within the hybrid *Research-by-Simulation & Design* (**RbS+RbD**) methodological framework. It is structured around three *Research Tracks*, each addressing a key research question and corresponding to the development of a distinct digital model. The first section, **Research Track A**, focuses on the *Design Model*, exploring knit material differentiation in relation to global membrane performance. It examines form-finding, simulation, and material analysis techniques to establish strategies for controlled differentiation. The second section, **Research Track B**, details the *Fabrication Model*, addressing domain shifts between design and production. It develops computational methods for translating simulation outputs into machine-executable instructions for CNC-knitting, ensuring manufacturability while preserving design intent. The final section, **Research Track C**, introduces the *Evaluation Model*, which benchmarks and calibrates digital simulations against physical prototypes. It employs deviation analysis and genetic evolutionary algorithms to refine simulation accuracy. Together, these experiments validate the integrated digital design chain, demonstrating a structured approach to developing differentiated CNC-knitted membranes for architectural applications.

The fifth chapter, the **Conclusions**, re-instate the context, aim and the research questions, re-outline thesis contributions, followed by the reflection of limitations and the perspectives of further research development.

Chapter II
STATE OF ART

CHAPTER OVERVIEW

The evolution of architectural textiles into CNC-knitted membranes presents a rich interdisciplinary terrain where material differentiation, digital modelling, and fabrication workflows converge. This chapter examines the state of the art in designing, simulating, and specifying knitted materials, emphasizing their capacity to integrate spatial, structural, and fabrication constraints across scales, thereby situating them within the framework of functionally graded materials (FGMs).

Chapter 2: State of Art, is organized into six sections, each addressing critical aspects of knit material design and its integration across scales and professional disciplines. Together, these sections establish the theoretical and practical foundation for the research on differentiated architectural knitted membranes explored in this PhD thesis.

The opening section, **Material Design across Scales and Disciplines**, explores the challenges and opportunities inherent in designing functionally graded materials (FGMs) and links the concept with knits. It emphasizes the necessity of integrating multi-scalar and inter-disciplinary considerations in the design and manufacturing processes of FGMs and knitted structures, drawing the parallels between them. The section provides a theoretical framework centered on scales, disciplines, and design approaches for differentiated materials, with particular focus on knit, as a special case of FGMs, positioned between architecture and material design. This framework helps to navigate through the subsequent sections, which delve into the current practices for *knit behavior prediction* with simulation, and knit material specification, spanning *micro-to-macro* scales and diverse *professional domains* such as material science, computer graphics, structural engineering, and architectural design, that engage with textile materials and knit in particular.

The second section, **Practices for Textile Material Prediction**, reviews the contemporary techniques for predicting textile material behavior across micro, meso, and macro scales by using simulation. It examines the examples from material science, computer graphics, engineering, and architectural computational design research, critically evaluating their strengths and limitations in relation to large-scale knitted material systems. Expanding on the macro scale, the section reviews the simulation methodologies, particularly those related to woven membranes, such as finite element analysis and force-density methods and traces their evolution into dynamic relaxation and particle-spring systems, which laid the groundwork for the development of design-oriented exploratory simulation tools like Kangaroo. This tool, being supported by the development of engineering oriented plug-ins, facilitate the creation of heterogeneous form-finding simulations, permitting the exploration of design and manufacturing of functionally graded knits, considered at larger scale application. Additionally, at the end, the section examines how textile simulations are validated and calibrated, ensuring a closer alignment of digital models and simulations, to their physically manufactured counterparts, addressing the importance of validation methods in enhancing simulation and digital models accuracy and reliability.

The third section, **Practices for Textile Material Specification**, examines the methods used to specify knitted materials across diverse professional domains, including garment design, computer science, and architectural knit design. It traces the transition from the traditional *bottom-up* knit specification approach, characteristic to garment design, to the *top-down*, *data- and simulation-driven* methodologies, pioneered by computer scientists and architects, researching knitting. These advanced methodologies enable a localized knit specification in relation to target three-dimensional shapes. The section highlights the potential of simulation based approaches for knit specification, permitting to gain a better control and higher efficiency in material specifications by using form-finding outcomes and the structural analysis data. The review also highlights the strong connection between the specification practices and the knitting techniques used to shape the three-dimensional textile forms, which underpin the distinct specification methodologies discussed in this section.

The fourth section, **Digital Design Chains**, discusses the integration practices of knit material *simulation* and *specification* within a coherent *workflow* through the examination of existing practices of digital design chains in relation to knit as an architectural material. This section explores how the aspects of knit spatial design, integrated with simulation and manufacturing, are organized in these workflows. identifying contributions and potential gaps. The section critically examines the inherent complexity and inflexibility of digital design chains, which can hinder adaptability in design processes. As an alternative to the parametric workflows, commonly associated with the digital design chains, the chapter introduces a machine learning (ML) technique, by emphasizing its strengths and positioning it as a *complementary* exploration direction for this PhD research. Furthermore, the section illustrates how ML has been employed in knit material specification practices within garment design and architectural knit research, showcasing its potential to enhance and expand existing workflows.

Finally, the concluding section, **Bridging the Knowledge Gaps**, synthesizes the findings presented throughout the chapter and articulates how this PhD thesis addresses the limitations and potentials of existing textile simulation and digital modelling practices, related to knit. The chapter lays the groundwork for the custom-developed workflow, comprised of *three digital models*, that aims to integrate the spatial design, simulation, knit material specification, and simulation validation and calibration, specifically tailored for CNC-knitted membranes as an innovative architectural material.

2.1 MATERIAL DESIGN OF FGMS & KNIT ACROSS SCALES & DISCIPLINES

Knitted textiles can be additively manufactured with fine level of differentiation, delivering multiple localized properties within one continuous membrane. In this thesis, knit is presented as a functionally graded material (FGM)—a class whose properties gradually shift across their volume, enabling dynamic, multi-scalar performance. By bridging micro-scale composition with macro-scale form, knit actively distributes material responses to address specific forces or design demands. Paralleling the concepts of knit and FGMs in this section sets the stage for understanding differentiated knitted membranes in architectural contexts.

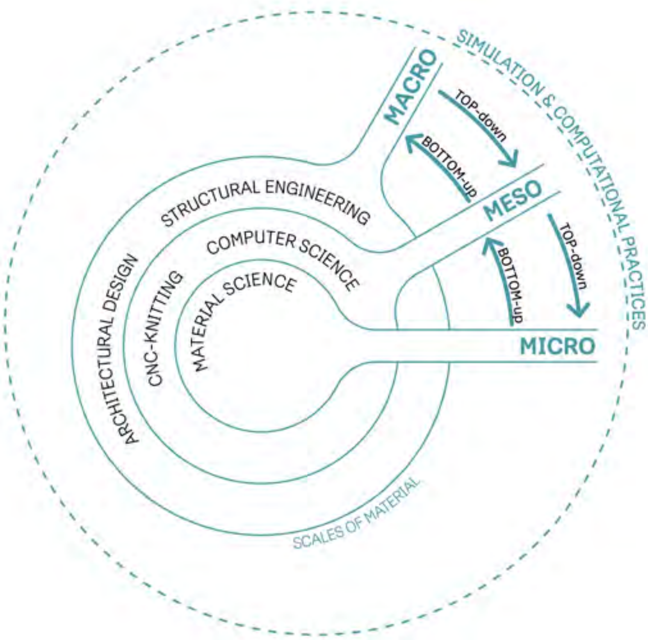
Unlike standardized building materials, which are typically designed to be uniform, static, and predictable in their behavior, FGMs are heterogeneous, with spatially varying properties that enable dynamic responses. These properties result from the material's engagement in mechanical relationships between form and force, where behavior is highly informed by the organization of its components (Nicholas 2013). FGMs dynamically respond to external stimuli, such as environmental conditions or mechanical loads, with these responses occurring across *multiple material scales*.

The multi-scale responsiveness of FGMs presents challenges to conventional design approaches, which rely on static material specifications and are insufficient for addressing the complexities of FGMs. Instead, this shift from static to dynamic material properties in architectural design represents a fundamental transformation in how materials should be conceptualized and utilized. It therefore demands the development and reconciliation of *new logics* and *tools* to effectively steer the design, composition, and manufacturing processes of novel FGMs (Grigoriadis 2016). This demands new methodologies that can incorporate FGMs' intricate behavior and fabrication constraints as integral parts of the design process.

The design of textile materials, and in particular knitted FGMs (kFGMs), operates in complex dynamics of both top-down and bottom-up approaches, across multiple scales (primarily meso and macro), and navigating inputs from other disciplines, supporting their modelling, manufacturing, and evaluation (Oghazian and Vazquez 2021).

This section emphasizes the necessity of integrating these inter-scalar and interdisciplinary considerations in the design and manufacturing of knitted differentiated membranes by providing a theoretical *framework* centered on *scales*, *disciplines*, and *design approaches*, relevant to kFGMs **F**2.1. This framework guides the navigation through the subsequent sections, which delve into current practices for textile *simulation* and *specification*, spanning *micro-to-macro* scales and diverse *professional domains* of material science, computer graphics, structural engineering, and architectural design, each addressing textiles at different scales and design approaches inherent to each field.

By synthesizing these insights, the chapter establishes a foundation for this thesis to develop a tailored modelling framework with integrated simulation and fabrication constraints—one that addresses the unique demands of architectural CNC-knitted differentiated textiles.



F 2.1: State of Art framework, structured around the material scales, interdisciplinary domains and design approach of bottom-up and top-down

2.1.1 INTER-SCALAR & INTER-DISCIPLINARY MATERIAL CONSIDERATIONS IN FGMS AND ARCHITECTURAL KNIT

INTER-SCALAR

In the design of FGMs, the perception of the material as dynamic heterogeneous matter involves the consideration of *inter-scalar* relations within the material, encompassing the interactions between *micro*-structural, *meso*-structural, and *macro*-structural material properties. These interactions ensure that the performance at one scale aligns with and supports the requirements at another. At the micro-scale, the interaction between nano-elements governs the material's local behavior and responses to external stimuli. These localized responses propagate to the meso and macro scales, significantly influencing the material's overall performance, such as stress distribution and the ability to change shape under mechanical forces (Grigoriadis 2016).

Such cross-scale considerations are actively addressed in the fields like aerospace engineering, medical nanotechnology, and material science. In aerospace, for instance, the design of FGMs ensures that materials can withstand extreme temperature gradients and mechanical stresses by tailoring properties across scales—from microscopic fiber reinforcements to macro-scale structural panels (Tosic et al. 2022). Similarly, in medical applications, FGMs are used in nanostructured coatings and implants, where the material's micro-scale interactions with biological tissues determine its performance at the macro scale, such as biocompatibility and load distribution (Shi et al. 2021). These disciplines integrate multi-scalar strategies to optimize the material behavior for specific functional requirements, demonstrating the critical role of cross-scale considerations in advancing innovative applications.

In architecture, the multi-scalar design approach is also present but manifests differently, if compared to mentioned above fields. Materials are considered across the same three key scales — micro, meso, and macro — with each however requiring the specific design and performance considerations (Nicholas 2013).

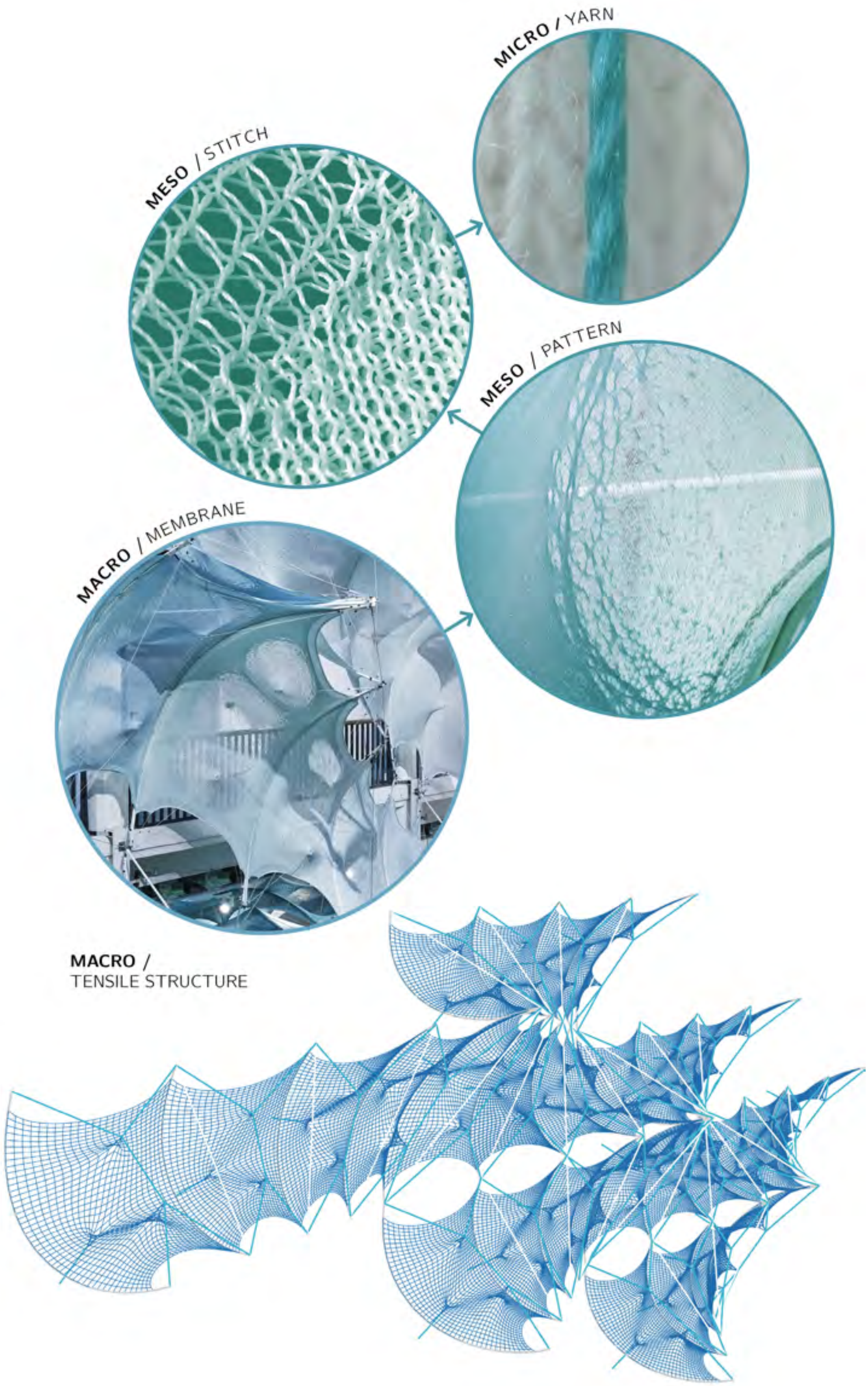
While the architectural macro scale focuses on building forms, spatial configurations, and overall structural performance, the meso scale addresses element design and their interactions through joints, connections, and surface detailing. In contrast, the micro scale, which encompasses the intrinsic properties and composition of materials, is often overlooked in conventional architectural practice. Typically, materials in architecture are selected from standardized catalogues, offering limited opportunities for customization. These materials are treated as static entities, designed to fulfill predefined roles without engaging in dynamic behaviours or interactions across scales. Furthermore, the dynamic interactions between material scales are often perceived negatively, as they are associated with potential risks to overall structural stability. Consequently, conventional architectural workflows frequently exclude material composition-specific considerations from the design process, thereby limiting the potential to integrate advanced material behaviours into architectural applications.

INTER-SCALAR ARCHITECTURAL KNIT

The architectural differentiated knits, explored in this thesis, occupy a unique position at the intersection of FGMs and architectural practice, offering a platform to address the inter-scalar considerations comprehensively. Unlike conventional materials, where scalar relations are often linear and static, knitted materials demand a dynamic understanding of how the yarn composition and the stitch configurations influence the overall textile surface properties and, as the result, the global membrane performance, when tensioned. This inter-scalar fluidity positions the architectural knits as a novel material paradigm, bridging the gap between the micro-structured FGMs and the macro-scale architectural applications **F**2.2.

Commonly, the material system of a differentiated architectural knit can also be analysed across the three conventional scale resolutions of micro, meso, and macro, where each implies a specific understanding of the material as a notion and how the properties of the material at each scale contribute to the overall membrane behavior (Ramsgaard Thomsen et al. 2016; Tamke et al. 2019; Kyosev 2019a).

MICRO At the micro scale, knitted material is defined by the properties of the yarn, which is composed of fibers for plant- and animal-based yarns, while the synthetic yarns are often made of continuous filaments. The molecular structure and composition of yarn determine its tensile modulus (Young's Modulus), influencing its ability to elongate or retain its length under load. These properties directly impact membrane performance, particularly its elasticity, strength, and response to external forces. Material at the micro level is often referred to as *raw material* (Wærsted 2014). Knitted membranes made from elastic raw materials, such as rubber-core or spandex-based filaments, exhibit dynamic stretch behavior and pliable surface characteristics under tension. In contrast, membranes made from high-tenacity yarns, such as polyester (PET), aramid, or ultra-high molecular weight polyethylene (e.g., Dyneema and Spectra), which do not elongate, are stiff, resistant to forces, and consequently limited in their ability to form three-dimensional shapes, as is



F 2.2: Inter-scalar relations within CNC-knitted differentiated material system: Filament, stitch, pattern, membrane, tensile structure experineced working with those in development of *Isoropia* membrane structure **F**1.11 on p.16.

MESO The meso scale offers the additional opportunities for steering the knitted membrane behavior by manipulating the initial yarn into stitches and further into the patterns. Each individual stitch, in particular its geometrical topology and the embedded filament length, defines the stitch dimension and the interaction with the other neighbouring stitches. At this level, the membrane ability for dynamic behavior can be further steered by managing the type of chosen stitches, even though using a stiff filament, which is known for its high strength. This consideration is particularly relevant for large-scale architectural applications, where the three-dimensionality is required along with the structural integrity of the knitted surface itself.

Additionally to the stitch geometry, the overall membrane properties are influenced by the organization of individual stitches into specific patterns. At this scale, the material evolves into a *differentiated functional surface*, where the placement of stitches in relation to each other influences the functional capacity of the surface. Here, the *stitch* and the *pattern* are key elements at the meso scale in shaping the overall membrane behavior. In this thesis, the material at this scale will be referred to as *designed* material, which is specifically customized to behave according to the target performance, in conversation with the manufacturing constraints and its internal material composition.

MACRO At the macro scale, the knit is perceived as an architectural material, employed for a tensile structural membrane that often acts as part of a larger assembly of a tensile structure. At this level, the material's definition becomes fully functional and spatial, as it interacts with the other structural elements the membrane material is connected to. The fabric's performance is understood in the context of a larger system, where the material's behavior is activated through external stimuli from the outside and influenced by inputs from the lower material scales within, highlighting the knit's inter-scalar material nature.

This progression—from the micro scale of the filament as a *raw material*, through the meso-scale of stitch and pattern configuration of the *designed* material, and finally to the macro scale of the final functional architectural element—demonstrates how scalar considerations shape the material's global behavior across all levels. This interplay underscores the critical importance of integrating these inter-scalar relationships into the design process of differentiated architectural knits to achieve cohesive and high-performing outcomes.

INTER-DISCIPLINARITY

In addition to the mentioned scalar considerations, the design of FGMs relies on a *inter-disciplinary* approach, where the insights from various professional disciplines contribute to the material design. As a material concept, FGMs primarily operate at micro and meso scales and have been extensively explored in the fields such as material science and mechanical engineering, particularly for the design of smaller objects. However, FGMs hold significant potential for architectural applications, where the material gradients and dynamic behavior can be integrated into the design of larger structures. In this context, knowledge from the conventional disciplines associated with FGMs can provide valuable input, enabling the coherent design of larger-scale objects and advancing the concepts and methodologies of FGMs to address architectural challenges. This collaboration is essential, as it enables the integration of the material properties with the specific functional and structural requirements, making the FGMs high-performing, technically sound and useful in the real-world applications (Silva et al. 2024).

In conventional architectural practice, interdisciplinary collaboration often centers on integrating the structural, environmental, and aesthetic considerations at the macro level. However, at the meso and micro levels of material composition, the cross-disciplinary insights from the fields like materials science or advanced manufacturing are rarely incorporated. This siloed approach means that the dynamic inter-scalar relationships, where the material behaviours at the micro-scale directly influence the macro-level performance, remain largely unexplored. Consequently, the conventional architectural practice focuses on applying the raw materials rather than innovating through their design, missing the opportunities for tailored, high-performing material systems.

INTER-DISCIPLINARY ARCHITECTURAL KNIT

Architectural differentiated knits present an exceptional opportunity to address cross-disciplinary integration, bridging the expertise of materials science, textile design, engineering, and architecture. Unlike conventional architectural practices, which often treat the material design as separate from the architectural workflows, knits inherently demand the collaboration across diverse fields. The interdisciplinary considerations in architectural knits are inherently connected to the inter-scalar factors, as each scale relies on a specialized expertise from the diverse professional domains.

At the micro scale, the behavior of individual fibers, such as their elongation and tensile properties, is informed by the expertise of materials science. Moving to the meso-scale, the configuration of stitches and patterns, along with the constraints of industrial CNC-knitting, are shaped by the insights from textile design and manufacturing. This scale serves as a convergence point, where the precision of advanced manufacturing techniques meets the creativity and artistry of textile design, enabling the seamless translation of concepts into tangible surfaces. At the macro scale, the structural performance of the knitted membrane is evaluated, relying on the knowledge of structural engineering to ensure the material can withstand forces such as tension and compression. Concurrently, the architectural and design domain integrates spatial, aesthetic, and functional considerations, orchestrating the geometric forms, spatial features, functional details, and color schemes that define its architectural expression (Ramsgaard Thomsen et al. 2016).

These diverse perspectives are essential for tailoring material functionality in terms of performance, fabricability, and aesthetics. The convergence of neighboring disciplines enables the creation of innovative, high-performing, and sustainable material systems, advancing architectural practice into a realm of material innovation previously dominated by FGMs.

2.1.2 TOP-DOWN AND BOTTOM UP DESIGN APPROACH

Building on the necessity of inter-disciplinary and inter-scalar considerations in the design of kFGMs, the negotiation and hierarchy between material scales can be effectively explored through the concepts of *bottom-up* and *top-down* design approaches. Originally rooted in software development and scientific methodologies, these strategies offer distinct methods for information processing and system development (Kung et al. 2012). When applied to FGMs, and particularly to differentiated architectural knits, they provide a framework for understanding how ideas, knowledge, and data are transferred, transformed, and organized across scales and disciplines, facilitating the creation of innovative material systems. These concepts are introduced here to explain the practices of knit material prediction through simulation and knit material specification through grading, presented further down, both of which often interweave with both bottom-up and top-down strategies.

TOP-DOWN

The top-down approach begins with a broad vision or a higher-level goal that is systematically decomposed into detailed components (Kung et al. 2012). In FGMs, this method typically starts with the macro-scale functional requirements, which subsequently inform the material specifications at the smaller scales (Yadav et al. 2024). In this framework, material specifications are intrinsically linked to the additive manufacturing processes — guided by the spatial and compositional gradients — and determine how the raw material respond to the defined performance criteria or form-related objectives.

This approach excels when the global function or performance requirements are well-defined, with the challenge lying in tailoring microstructures and meso-scale configurations to meet these goals. Manufacturing methods, therefore, play a critical role, as the interaction between the raw materials and fabrication techniques must be fine-tuned to meet these functional and structural goals.

In functionally graded knitted materials, the top-down approach is especially relevant to *knit specification practices* for industrial knitting machines. Here, global shapes and structural properties guide manufacturing instructions, while micro-scale yarn properties and meso-scale stitch geometries are specified to ensure the material's elongation behavior aligns with macro-scale design intents.

However, knit specification practices can also occur in a bottom-up manner, complementing the top-down approach. Both directions are examined further in section 2.3, referencing interdisciplinary attempts across garment design, computer science, and architecture to challenge and expand knit material specification methodologies.

BOTTOM-UP

In contrast, the bottom-up approach begins at the lower scales, focusing on the detailed components that are progressively integrated into a cohesive macro-scale system (Kung et al. 2012). This method emphasizes the study of microstructural elements, such as fibers and unit components, and their interactions to develop the emergent global properties. Through the systematic assembly or combination, functional gradients are created, with the behavior at the micro and meso scales, shaping the overall material performance.

Unlike the goal-driven top-down method, the bottom-up approach is inherently exploratory. Global outcomes emerge from the iterative experimentation and the interplay of smaller-scale components. Advancements in manufacturing technologies, such as 3D printing and CNC knitting, have significantly enhanced this process by enabling rapid prototyping and testing.

Though less common in disciplines constrained by strict safety requirements, the bottom-up approach is invaluable in creative fields like architecture and design.

Here, the exploration of local material behaviours, supported by *simulation*, can yield unexpected spatial expressions and innovative design outcomes. Knitting, with its predefined manufacturing rules and stitch types, offers a fertile platform for experimentation, allowing the designers to uncover novel spatial structures and material configurations through an inventive programming of stitches.

COMPLEMENTARY APPROACH

In summary, the top-down approach begins at the macro scale, focusing on achieving the target performance/form and defining the lower-scale specifications to meet these objectives. Conversely, the bottom-up approach starts at the micro scale, where the local behaviors and interactions inform the emergent global properties. In the design of FGMs, however, these approaches are not mutually exclusive but are often used complementarily. Their integration is essential: the top-down perspective establishes the overarching goals and supports the design of the global shape, while the bottom-up approach refines the local properties and leverages digitally driven manufacturing processes, in order to meet the global shape targets. Together, they enable the optimization of material systems, balancing global performance with innovative, localized design.

2.1.3 SIMULATION AS MEDIATOR THROUGH DESIGN, SCALES AND DISCIPLINES

The design of differentiated knitted membranes requires a delicate balance of inter-scalar relationships, integration of cross-disciplinary insights, and bi-directional navigation through top-down and bottom-up design processes. This inherently complex and multifaceted process presents both opportunities, but also challenges.

The cross-scalar material relationships are deeply interdependent - decisions, made at one scale, directly influence the others. This interdependence is further complicated by the concurrent application of top-down and bottom-up approaches, where overarching structural goals inform smaller-scale decisions, while the local behaviours can generate unexpected outcomes that reshape broader design intents. Adding to this complexity is the need for seamless cross-disciplinary exchanges, where the insights and data from diverse fields, often presented in varied formats, must converge cohesively. Together, these interdependencies underscore the necessity of a *robust computational framework* - a network of specialized models with integrated simulation and computational capabilities.

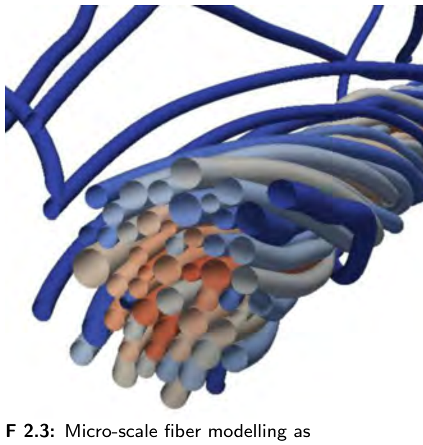
In this network, specialised models serve the distinct purposes: one with the focus on *design* and material *behavior prediction*, while the other addressing the *material specification* and *fabrication*. Simulation there acts as a mediator between the models, enabling the exploration of inter-scalar material relationships, fostering the collaborations across professional boundaries and navigating the bi-directional top-down and bottom-up design approaches, ultimately supporting the design and fabrication of architectural knitted FGMs. In *design* models, the simulation studies the interactions between the local components at the micro- and meso-levels based on the specific manufacturing rules and stitch behaviours. This supports the prediction of global material performance, facilitating the spatial design exploration and optimization. In *fabrication* models, computational algorithms translate the global design intent and performance requirements into the local material specifications, creating machine-readable instructions necessary for the CNC-knitting processes.

While these models fulfill their distinct roles, the simulation integrates them into a network that bridges the gaps between conceptual spatial design, surface composition, and fabrication. This interconnected system enables the flow of data across various inputs and resolutions, ensuring that the kFGMs achieve their intended structural, functional, and aesthetic goals, while remaining compatible with the CNC-knitting technology. By fostering a more integrated and efficient approach to material design, simulations facilitate the development of innovative design processes and, as a result, sustainable, and tailored material systems that can be produced with the efficient manufacturing technologies for outstanding architectural applications.

The following two sections examine how the simulation and computational digital modelling act as the essential tools for navigating the design process by *predicting* and *specifying* textile behaviours, with a particular focus on knits. Section 2.2 presents the practices of textile material prediction through *simulation* at various scales, while the section 2.3 dives into the methodologies of knit material *specification*, related to creation of knitting manufacturing files. This overview explores the application of these methodologies across various professional disciplines, scales, and use cases, addressing the existing challenges and gaps — particularly when adapting differentiated knit systems for architectural contexts. The discussion aims to identify not only the limitations within the current textile simulation and specification practices, but to extract the effective methodologies. These insights inform the development of custom simulation and modelling frameworks tailored to architectural differentiated knitted membranes, as proposed in this PhD thesis.

2.2 PRACTICES OF TEXTILE MATERIAL SIMULATION

Simulation is instrumental in harnessing the potential of textile materials, enabling the *prediction* and understanding of their behavior and performance through digital visualisation. At its core, *predictive* simulation serves two primary purposes: forecasting textile behavior via graphical representation and evaluating structural capacity via analysis to meet the specific performance demands.



F 2.3: Micro-scale fiber modelling as abstracted pipes. *Bral et al.2023*

Simulation is a valuable tool across various disciplines, from material science at the micro-scale to architectural design at the macro-scale. In some fields, simulations are purely representational, without altering local material properties, while in others, they guide the design exploration by iterating global forms and suggesting local manipulations to achieve the desired outcomes. The approaches to textile simulation and digital modelling are shaped by the priorities of each domain, tailored to specific textile systems (*knit, weave*), scales (*micro, meso, macro*), mechanical applications (*compression, tension*), and intended purposes (*animation, visualisation, structural analysis*), which will be reviewed in this section.

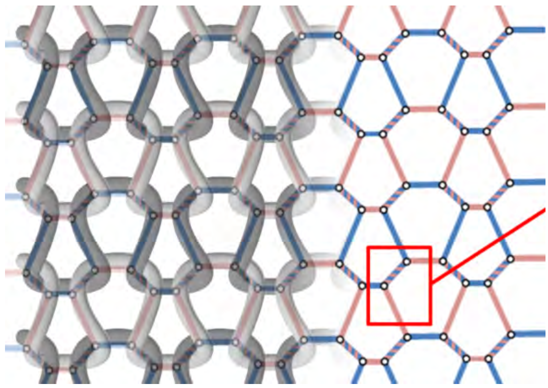
2.2.1 MICRO-SCALE SIMULATIONS OF YARNS

At the micro scale, material science simulations focus on the individual fibres and yarns rather than entire textiles. These simulations aim to model the kinematic and mechanical properties of yarns, accounting for factors such as fiber length, quantity, and spinning methods. For example, Maksimcuka et al. 2017 studies the polyester twisted yarns, using simulations to predict yarn deformation and elasticity, which in turn help to optimize yarn production efficiency and tune the material performance.

Fibres in the yarns are often modelled as cylindrical pipes or abstracted beam elements, as demonstrated in Bral et al. 2023; L. Wu et al. 2020 **F**2.3. The geometry is derived from the X-ray computed tomography (CT) scans (Kyosev 2019a), which yield the precise fibrous structures but are applicable only to the already manufactured yarns. Although this level of detail is less relevant at the architectural scale, it is critical for determining the key material properties — such as tenacity, strength, and elongation — used in data sheets for material specifications. These simulations support the quality control and ensure that materials at micro scale meet the performance criteria, when applied within textile surfaces and larger textile items.

2.2.2 MESO-SCALE SIMULATIONS OF STITCHES

At the meso-scale, textiles are often simulated as patches to study the interactions of their compound units, such as stitches in knitting. This approach is prevalent in computer graphics and material science, where the meso-scale simulations contribute to an understanding of fabric performance and behavior, leading to self formation effects as the result of local stitches interactions (Kyosev 2019b).



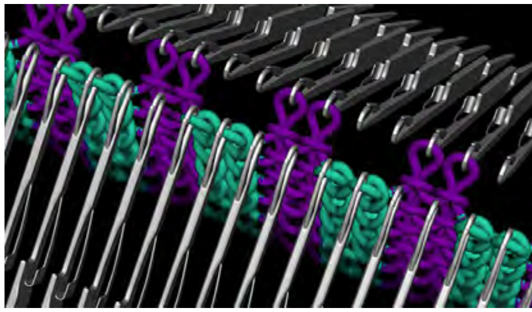
F 2.4: Meso-scale fiber modelling with persistent contact method. *Cirio et al. 2015*

At this level, filaments are typically modelled as solid pipes, introducing elastic rod models that examine interactions between filaments and stitches through collision simulations (Cirio et al. 2014). This method, referred to as a geometrical textile simulation (Chen and Tang 2010; Do et al. 2020), models knitted fabrics as interconnected three-dimensional loops and woven fabrics as interlacing straight elements (Badel et al. 2008; L. Wu et al. 2020). By applying physical and mechanical principles, these simulations reveal the local filament interactions, providing insights into fabric behavior. For instance, woven textiles, composed of discontinuous intersecting fibers, are stiffer and less pliable, while knits, formed from continuous inter-looped filaments, exhibit greater pliability and adaptability due to the local rearrangement of loops.

However, the elastic rod models face a criticism for being computationally intractable, when simulating high yarn densities or larger textile patches. The community of computer scientists addresses the limitations of computational costs through yarn collisions, by developing an alternative approach of *persistent contact modelling*, where the stitch is represented more simplistic through the lightweight network of lines (Cirio et al. 2014; Cirio et al. 2015; Sánchez-Banderas et al. 2020)

F2.4. In this way, it reduces the computational costs, while restoring the fabric volume in the final renderings. Despite these efficiencies, the resolution scale of meso-scale simulations, addressing every stitch, remains computationally impractical at architectural scales.

In addition to behavior analysis, meso-scale simulations are extensively used for visualization, particularly in manufacturing processes. Knitting programming software such as M1Plus (for STOLL) and SDS®-ONE APEX4 (for SHIMA SEIKI) integrates the meso-scale simulations to render the CNC-knitting processes **F**2.5. These simulations visualize the yarn movement through the machine, allowing for the prediction and prevention of potential errors, such as unexpected collisions with mechanical parts during knitting. The software provides the previews of differentiated fabrics based on the programming inputs, including stitch selection, lengths, and needle manipulations. Although these previews primarily serve as abstract diagrams rather than behaviourally accurate representations, they enable error detection and the visualization of pixel-based knitting instructions as fabric-like images, which eases the programming of knits.



F 2.5: Meso-scale fiber modelling for inspection of production errors. *ShimaSeiki*

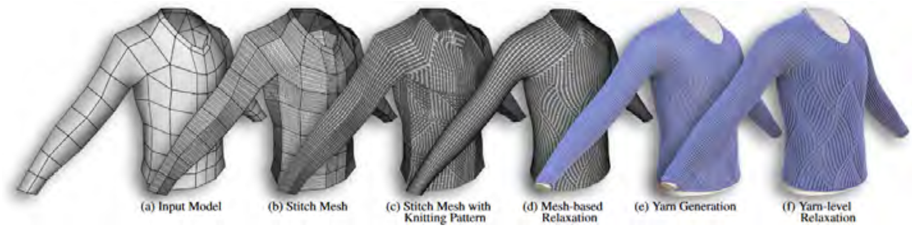
While the commercial softwares for STOLL and SHIMA SEIKI knitting machines offer a built-in numerical models to validate knitting files for errors, their closed systems rely on the predefined stitch libraries, therefore limit the user control over visualizations. This limitation has spurred the development of custom visualization techniques within architectural research. Tools such as those by Karmon et al. (2018) and Anishchenko and Paoletti (2021) offer a greater flexibility, enabling custom knit visualizations based on pixel input files, however remain limited to the patch-level investigations.

2.2.3 MACRO-SCALE TEXTILE SIMULATION

At the macro scale, textile simulations examine the behavior of entire textile assemblies—complete objects situated within specific applications and activated into shape under external conditions. This scale is particularly relevant in computer graphics and architecture, as these disciplines emphasize the practical application of textiles in functional objects. However, the macro scale is interpreted differently within each field. Moreover, this scale of simulation is particularly significant to this PhD, as it is positioned within the architectural design domain, where the integration of textile behavior into large-scale applications is a central focus.

MACRO-KNIT SIMULATION OF GARMENT

In CNC-knitting manufacturing, the macro scale often corresponds to the garment design. Here, computer graphics enable visually realistic simulations of textile clothing, "worn" by the virtual mannequins (Yuksel et al. 2012; K. Wu et al. 2022). The commercial knitting software SDS-ONE APEX4 (Shima Seiki) integrate this technology for *3D virtual sampling* **F**2.6, by visualizing a fabric draping to aid the garment design, size calibration, and the grading of knitted structures for improved fit and aesthetics. These simulations enhance the stakeholder communication and

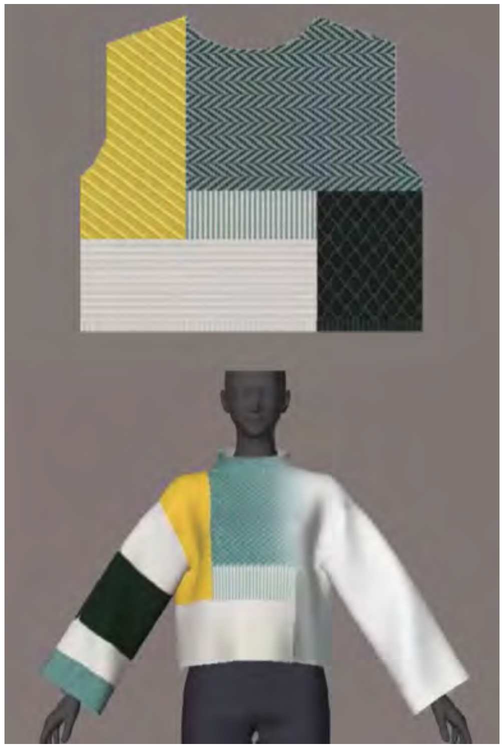


F 2.7: Stages of knitted garment simulation with yarn level detail. *Yuksel 2012*

reduce the reliance on physical prototyping, thereby saving time and resources. According to the APEX developers, this technology also shortens the garment product development cycles by enabling an accurate market research through the visualized prototypes (ShimaSeiki n.d.).

While effective, these simulations face criticism for their proprietary nature and accessibility barriers (Wang et al. 2022; Lin et al. 2024). This closed, commercial software requires specialized hardware — a dedicated computer with a touchpad and custom input device — making it costly and less accessible. Mastery of such tools also demands an extensive training, further limiting their usability to a narrow group of specialists. Additionally, their focus on predefined garment-like forms restricts the applications for unconventional or complex textile structures.

In response to that, the alternative workflows have been developed by the computer science community, offering open-access solutions that extend beyond the traditional garment simulations to encompass more complex textile shapes and behaviours (K. Wu et al. 2022; Yuksel et al. 2012; Sperl et al. 2021). These simulation approaches discretize the target surface, into the mesh,where each cell is populated with the individual stitch configurations (Yuksel et al. 2012; Anishchenko and Paoletti 2021). By employing pre-computed simulations of stitches and lightweight methods of persistent contacts, these techniques reduce the computational costs and are widely adopted in computer graphics and animation. For instance, the simulations of animated characters, wearing the knitted garments, rely on these pre-calculated yarn patterns to ensure realistic fabric behavior during motion (Sperl et al. 2021).



F 2.6: Macro-scale virtual sampling. *ShimaSeiki*

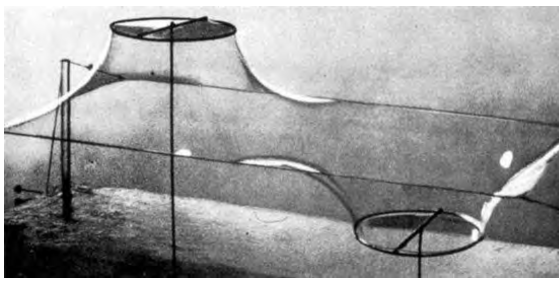
A simplified persistent contact modelling, while effective for textile garment simulations, becomes computationally redundant at architectural scales. In tensile architecture, the focus shifts to broader material properties, such as stretch and expansion under tension. Architectural tensile simulations, using textiles in tension, demand simulations to predict fabric behavior being stretched. Although individual knitting stitches contribute to global behavior, modelling at the resolution of every stitch is computationally too heavy and therefore unnecessary in architectural simulations. Instead, simulations for architectural applications would benefit more from understanding the overall mechanical performance of knitted fabrics through establishing links between lower-resolution models, commonly used in architecture for global shape exploration, and the distribution of stitches at finer scales, corresponding to a knit material system.

MACRO-SIMULATION OF ARCHITECTURAL STRUCTURES

At the macro scale, textile simulations in architecture and structural engineering address the *building elements* or *entire structures*, shifting the focus from draping behavior of garment textiles to their activation under tensile forces. This scale emphasizes the lightweight tensile membrane structures, where their shape determines the structural and functional performance. The *curvature* of the three-dimensional canopy defines its stiffness, contributing to the membrane load-bearing capacity by redirecting the external forces such as wind, snow, and rain. However, for structural stability, the curvature must be *transverse*—bending in multiple directions—to prevent buckling and distribute stresses more effectively (D. S.-H. Lee 2024), which is highly relevant for tensile membranes to enhance their load bearing capacities. The image in **F**2.9 illustrates the critical role of transverse double curvature in membrane structures, where an increased curvature enhances stability and resilience, effectively reducing deflections under wind load. Recognising this, the design task focuses on defining a geometry with sufficient transverse curvature—an aim realised through a dedicated *form-finding* stage that is essential for determining the shape of tensile membranes as form-active structures (Silver et al. 2013), require a *form-finding* process to determine their shape. This process simulates the textile behavior to achieve the structural stability and aesthetically expressive three-dimensional forms.

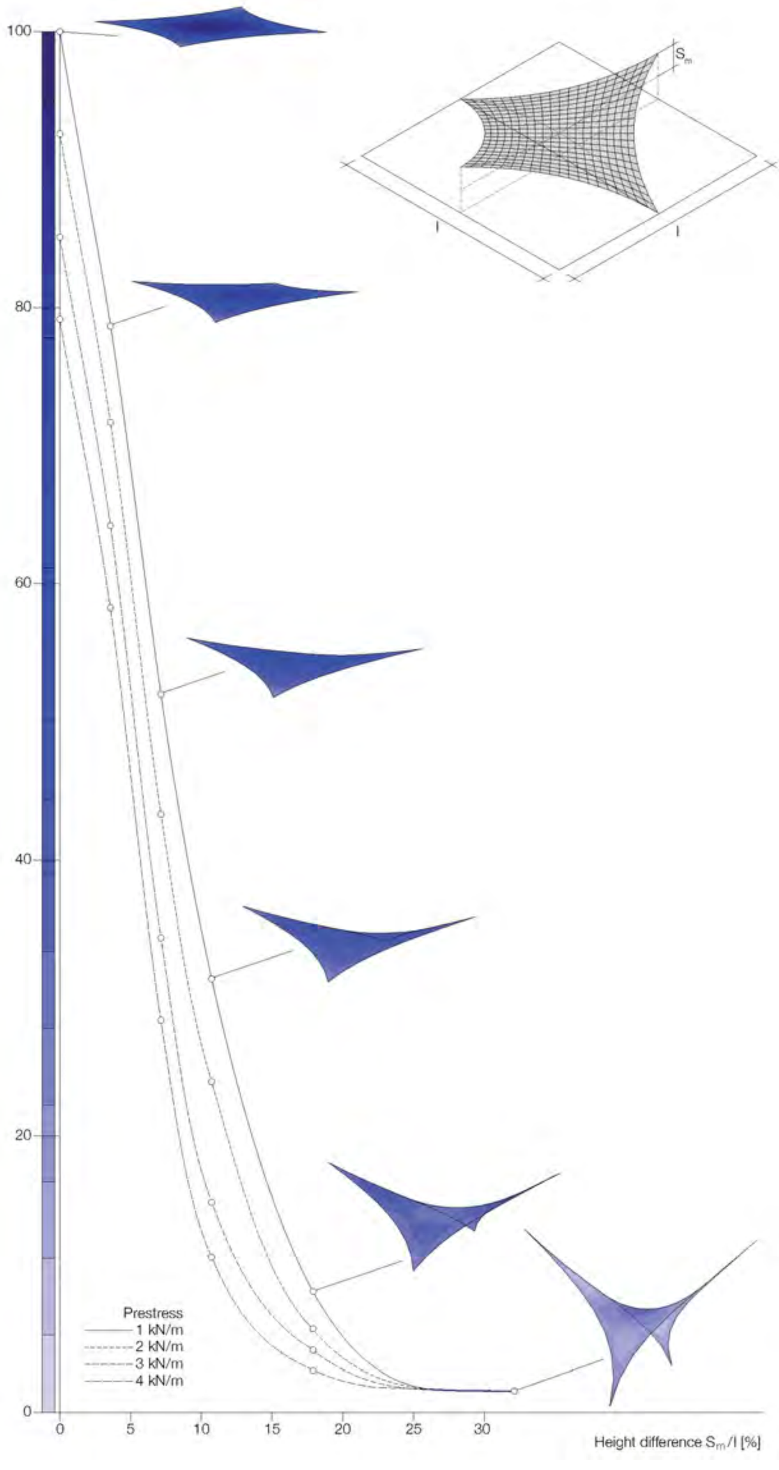
ANALOGOUS SIMULATION THROUGH PHYSICAL MODELLING

Historically, physical modelling has played a significant role in understanding material behaviour and the structural form of tensile membrane structures. Early analogue simulations, such as scaled models made of nylon fabrics, rubber, or soap films, explored dynamic form-finding by leveraging the physical properties of these materials (Huerta 2006). Pioneers like Antonio Gaudí, Heinz Isler, Frei Otto, and Pier Luigi Nervi used physical models—such as catenary chains and fabric membranes—as design tools to investigate structural performance and material logic. Soap films, for example, exhibit zero stiffness and a homogeneous stress distribution, naturally forming minimal surface shapes that achieve equilibrium upon stabilisation (Knippers et al. 2011) **F**2.8.



F 2.8: Soap-bubble model of membrane structure by Frei Otto

These early exploratory models function as physical computations, abstracting complex material behaviours into accessible design mechanisms. By translating the interactions of local material properties into physical processes, they enabled designers to bridge the gap between material logic and architectural form-finding (Stasiuk and Ramsgaard Thomsen 2016; Kotnik 2011).



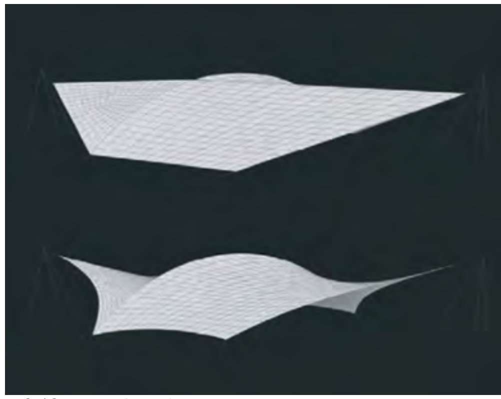
F 2.9: Comparison of the curvature-dependent deformations of various four-point sails with the same material properties, prestresses, spans and wind loads. *Knippers et al 2011*

NUMERICAL SIMULATION OF MEMBRANE STRUCTURES

While the physical experiments remain valuable, the digital simulations using advanced numerical methods now dominate the membrane form-finding processes (Kotnik 2011). Since the 1960s, the widespread application of textiles in lightweight membrane structures — primarily made from woven coated fabrics — has driven the development of specialized digital tools for their design and form-finding. Among these, Finite Element Method (FEM), Force Density Method (FDM), and Dynamic Relaxation (DR), which have become essential for design and analysis of membrane structures, offering the precision and the efficiency in form-finding workflows for woven based textile structures (Knippers et al. 2011).

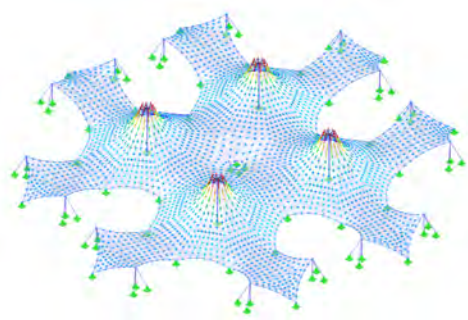
FINITE ELEMENT METHOD (FEM)

The Finite Element Method (**FEM**), originally developed in 1943 by Richard Courant and later formalized for engineering applications in the 1950s by Turner et al. 1956, is a numerical technique used to solve complex structural problems by discretizing large structures into smaller, simpler elements, each with defined mechanical behaviours. In FEM models of tensile structures, the surface is divided into smaller elements, connected at shared nodes **F**2.10. The properties of these linear elements are typically represented using spring models. By analysing variables such as stress, distortion, and displacement within the elements and ensuring that displacements at shared nodes remain consistent, the forces and deformations across the structure can be approximated. For membrane form-finding tasks, a state of stress equilibrium is calculated using specialized membrane elements that disregard elastic stiffness. When the pre-stress is applied, this approach is often referred to as the "soap film analogy" (Knippers et al. 2011).



F 2.10: FEM form-finding method. *Knippers et al 2011*

FEM, rooted in the Stiffness Matrix Method (SMM) as categorised by Veenendaal and Block 2012, strictly incorporate the material properties for a reliable structural analysis of Finite Element Analysis (FEA), which makes this method particularly well-suited for the form-finding and structural analysis of conventional woven membranes, where material properties are homogeneous, stiff, predictable and consistent across the entire surface **F**2.11. The reliance on the predefined material properties ensures the analysis accuracy, making FEM ideal for engineering applications involving standardized materials. However it is computationally intensive and less adaptable to heterogeneous materials, such as differentiated architectural knits, which exhibit spatially varying properties.



F 2.11: Vector principal forces, FEA, *Dlubal Software*

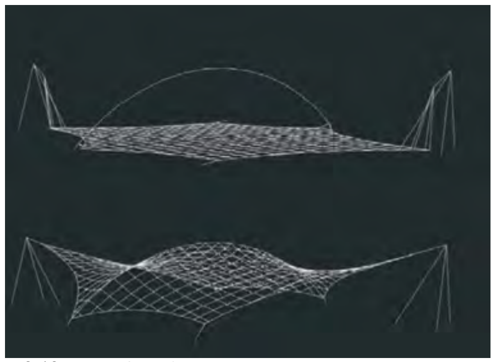
However, while FEM is highly precise, it is computationally slow for design exploration, as each node in the model must be solved individually, often leading to iterative and time-consuming processes. For complex structures, solutions may not converge, requiring manual tuning to achieve equilibrium. As noted by Holden

Deleuran et al. 2015a, this iterative nature makes FEM less adaptable to exploratory design workflows where quick feedback is essential. Although effective for static analyses and precise predictions, its lack of responsiveness limits its utility in dynamic design scenarios.

FORCE DENSITY METHOD (FDM)

In contrast to FEM, the Force Density Method (**FDM**) emerged as an efficient computational technique in the 1970s, first introduced by Linkwitz and Scheck 1971 and further refined by Schek 1974, particularly tailored for the task of designing the pre-stressed cable nets and membrane roofs. It gained its prominence with the advent of supercomputers like the CDC 6600, enabling more complex simulations, based on the equilibrium of forces at the connecting points (nodes) of a cable net or membrane structure (W. Brandt 2013). With this method, the forces are distributed according to the predefined force density values — the ratio of force to length in each element — allowing the method to achieve equilibrium configurations efficiently. Unlike FEM, which discretizes the structure into elements with detailed material properties, FDM works with a network of forces and focuses on the geometric relationships between these forces, making it computationally simpler for lightweight structures (Aboul-Nasr and Mourad 2015).

FDM has been instrumental in the design of tensile structures, such as the Munich Olympic Stadium, where it was used to optimize the roof's cable net configuration. The method facilitated form-finding by enabling computational adjustments and refinements of the structure's geometry without requiring a detailed mesh. As part of Geometric Stiffness Method (GSM) as categorised by Veenendaal and Block 2012, FDM does not directly account for the material stiffness, focusing instead on achieving the equilibrium configurations through the force-length relationships. This makes it particularly suited for preliminary form-finding, where the primary goal is to define the structure's geometry based on forces rather than material properties.

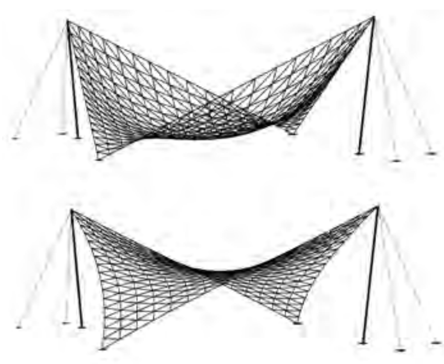


F 2.12: FDM form-finding method. *Knippers et al 2011*

A significant advancement within FEM and FDM was the introduction of an Update Reference Strategy (URS) by Bletzinger and Ramm 1999 , which allowed for direct form-finding over triangulated or quad meshes. This iterative approach simplified the computation of equilibrium shapes in tensile structures and enhanced the flexibility in handling complex mesh topologies.

DYNAMIC RELAXATION (DR)

Building on the computational advancements introduced by FDM, the Dynamic Relaxation Method (DR), introduced by Barnes 1977 emerged as even more versatile form-finding technique, capable of handling more complex and non-linear structural behaviours. While FDM focuses on the predefined force-to-length ratios to achieve the equilibrium, DR expands on this approach, by simulating the dynamic behavior of structures, where a discretionary initial mesh, composed of



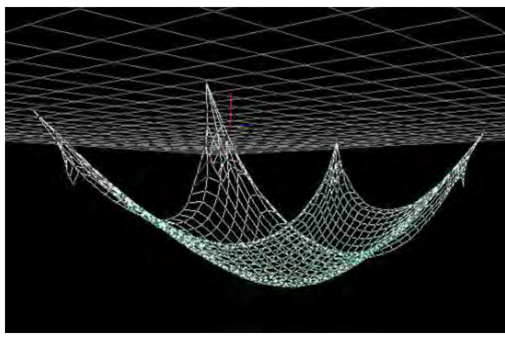
F 2.13: Dynamic Relaxation form-finding method.*Khatibinia et al. 2019* springs is prestressed, thus inducing oscillations (Knippers et al. 2011). An artificially generated decay process enables the equilibrium form to be found for the mesh by means of kinetic damping. In DR, nodes are assigned fictitious masses and allowed to move under the influence of unbalanced forces. As a result, through the iterative adjustments, the system stabilizes into a state of equilibrium, reaching its balanced shape (Khatibinia et al. 2019) **F**2.13. This method, while computationally more intensive than FDM, offers the flexibility to account for non-linearities, material stiffness, and geometric complexity.

FEM, FDM AND DR FOR HOMOGENEOUS MEMBRANE STRUCTURES

All the above-mentioned form-finding methods are inherently designed for *homogeneous* woven fabrics, treating the material as isotropic and uniform in its mechanical properties. While FEM, FDM, and DR theoretically allow for the incorporation of heterogeneous material properties by assigning differentiated stiffness and density values to each node or element, the software environments that implement these methods are primarily stand alone tools developed for structural post-evaluation rather than interactive design iteration and tuning. Integrated into commercial engineering platforms such as Sofistik (AG 2025), Abaqus (Systemes n.d.), Ansys (ANSYS n.d.), EASY.Form (technet-gmbh n.d.), Formfinder (F. S. GmbH n.d.), WinTess (Sastre 1992), and Dlubal (D. S. GmbH n.d.), these methods often require advanced engineering skills, making them less accessible to architects. In contrast, architectural domain CAD-based programs like Rhino, VectorWorks, Sketchup, or 3DMax prioritize design flexibility but alone lack seamless integration with these engineering form-finding tools (Sinke et al. 2023a). Consequently, relying solely on conventional engineering simulation techniques risks overlooking the unique potential of differentiated architectural knits to provide locally adaptive material performance, where surface properties are tailored to meet specific structural or functional requirements.

PARTICLE-SPRING SYSTEM (PS)

The Dynamic Relaxation (DR) method laid the groundwork for more interactive and design-focused computational approaches, such as the Particle-Spring System (PS) (Kilian and Ochsendorf 2005) **F**2.14. While DR simulates the dynamic motion of nodes to achieve the equilibrium, the Particle-Spring System adapts this concept to represent structural elements as a network of particles (nodes) connected by springs (edges), where the forces are calculated and balanced iteratively. This shift introduced a more intuitive, *design-friendly* framework, enabling the real-time feedback and exploration of complex geometries. By integrating the principles of DR with the simplified force computations and interactivity, the Particle-Spring System bridges the gap between structural analysis and architectural design, facilitating innovative workflows for form-finding in architectural applications.

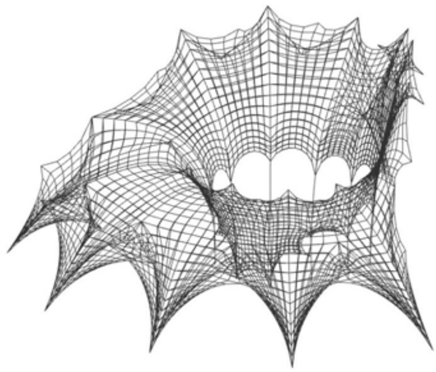


F 2.14: Particle Spring System form-finding. *Kilian and Ochsendorf 2005*

KANGAROO PHYSICS

Advancements in state-of-the-art digital simulations for materially graded knitted structures have been significantly driven by the development of design and modelling environments since the 2000s. These environments, enhanced with the parametric tools, have enabled architects and designers to construct heterogeneous material models, leading to a boost in development of novel spatial complex designs (Deuss et al. 2015; Tamke et al. 2014b; Zwierzycki et al. 2017).

Building on the principles of Particle-Spring System and Dynamic Relaxation, in 2013 Daniel Piker developed *Kangaroo Physics*, as an extension within Grasshopper for Rhino, marking a major step in accessible and interactive simulation workflows (Piker 2013). By integrating the real-time feedback and coupling geometric manipulation with the physical properties and engineering analyses, Kangaroo democratizes the advanced form-finding methodologies, rooted in engineering, making them accessible for creative architectural workflows. This evolution boosted a shift from purely analytical tools, focused on post-analysis to dynamic, design-integrated simulations, empowering architects to explore tensile membranes, knitted fabrics, and other innovative functionally graded material systems.



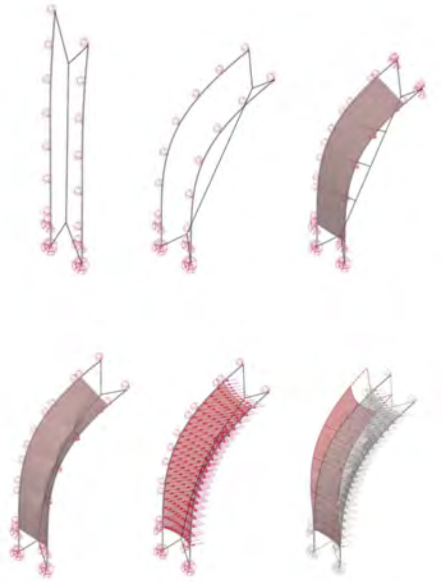
F 2.15: Membrane structure digital design exploration, using Kangaroo2. *Sinke 2017*

Kangaroo operates by minimizing the total energy within a modelled structure to achieve the equilibrium, as explained by Piker (2019). In this system, various *Goals* define the specific types of energy, which become minimal under the certain geometric conditions. The Kangaroo Solver iteratively adjusts the positions of points to minimize the total energy across all the nodes in the system. For instance, the *Length Goal* applies a Hooke's law to the line objects, treating them as springs. The energy is zero, when the spring reaches its target rest length, but increases when the spring is stretched or compressed. Each spring has its defined force density value (force per unit length), making Kangaroo particularly effective for simulating tensile structures and other systems governed by the force equilibrium **F**2.15.

STRUCTURAL ANALYSIS IN GRASSHOPPER

Kangaroo's open-source nature has gained a widespread popularity, fostering a large community of architects and coders, that actively contribute to the development of custom plug-ins for material behavior simulation tasks. Several of these plug-ins integrate the structural analysis within the exploratory environment of Grasshopper, making them compatible with Kangaroo. These tools provide custom structural analysis *Goals* and post-processing utilities for calculating the forces and stress in form-found membrane structures.

Two distinct approaches emerge within these tools, closely related to membrane representations: (1) as *discretized meshes*, employed by K2Engineering (C. Brandt 2016) and Karamba3D (Preisinger and Heimrath 2014) or (2) as *NURB continuum surfaces*, as used by the iso-

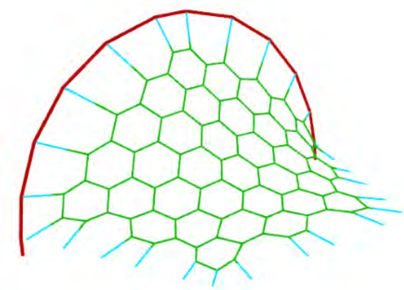


F 2.16: Isogeometric modelling of Isoropia unit, using IGA Kiwi3d. *str.ucture GmbH 2018* geometric (IGA) approach implemented in Kiwi3D (www.kiwi3d.com) (Philipp et al. 2016; Bauer et al. 2018).

The *continuum surface-based* approach in *Kiwi3D* is considered more lightweight, as it uses a smaller number of external control points to describe the membrane geometry through the B-spline formulas. This results in smooth, unsimplified surfaces compared to the discretised shapes, typical to the FE-meshing (Bauer et al. 2017). However, this approach does not support the differentiation options. While the curvature of the continuous BREP NURB surface can be modified through adjusting the surface degree by moving the control points, its inherently non-discretized nature limits its ability to represent internal heterogeneity or variations in surface composition, crucial for differentiated knits and therefore makes it less suitable for creating the simulations with varying surface properties **F**2.16.

In contrast, the *mesh-based* structural design plug-ins, such as *K2Engineering* and *Karamba3D*, model the membranes as discretized cable nets. This approach allows for the assignment of custom material properties, such as rest length or stiffness, to individual mesh segments, therefore facilitating the local surface differentiations. Leveraging the parametric capabilities of Grasshopper, this mesh-based representation enables the automation and control of properties allocation across the large membrane bodies. By integrating the structural analysis and other global inputs, these tools are particularly well-suited for representing the differentiated nature of graded knitted membranes, effectively linking global parameters to local surface components.

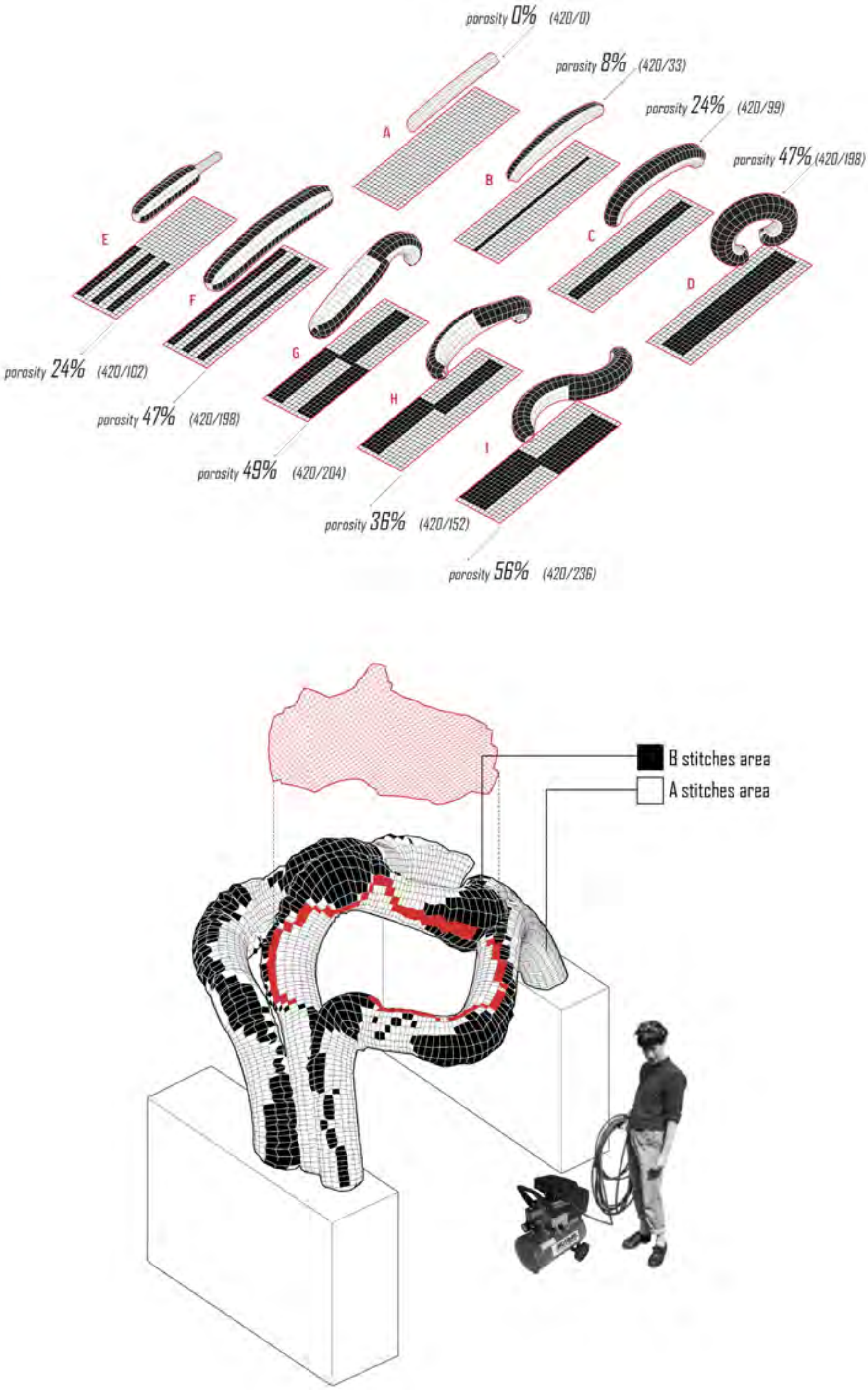
SIMULATION OF ARCHITECTURAL KNIT



F 2.18: Hexagone mesh modelling of knits. *Schmeck, Gengnagel 2016*

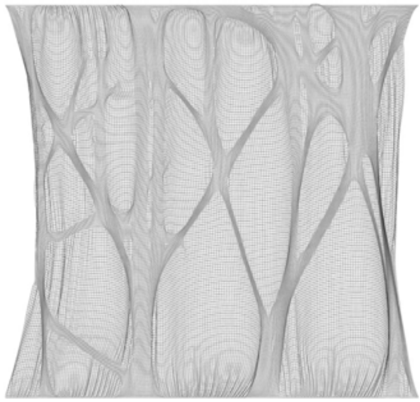
Since the advent of parametric modelling and simulation tools, research into novel knitted structures has expanded. However, this exploration has primarily focused on overall design, with limited attention to local material grading. Knitted membranes, despite their capabilities for differentiation, have often been treated as homogeneous materials in both digital modelling and their physical prototypes. This homogeneity typically means that these structures lack significant surface variations, affecting their structural capacity, or are knitted uniformly across their surface, occasionally incorporating minor, evenly distributed differentiations that still maintain a homogeneous surface character Anishchenko 2021; Tamke et al. 2016; Holden Deleuran et al. 2015b. Consequently, their digital representations have relied on homogeneous mesh structures of various types. Research projects have explored different discretization approaches, including quad-based meshes (Sabin 2013; Sharmin and S. Ahlquist 2016; Ramsgaard Thomsen et al. 2019b), triangular meshes (Holden Deleuran et al. 2015b), and hexagonal meshes (Schmeck and Gengnagel 2016; S. M. Ahlquist 2013). Among these, quad-based meshes, with their dual directionality, align particularly well with the warp and weft structure of knitted fabrics, making them a natural fit for simulating weft-knitted membranes, explored in the present PhD thesis.

Departing from the homogeneous structures, the recent practices have sought to introduce the distinct material differentiations related to the structural capacity of surfaces (La Magna et al. 2018). However, these differentiations are often implemented manually and remain disconnected from the form-found simulations,



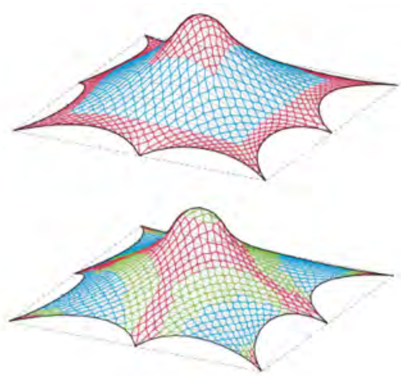
F 2.17: Heterogeneous simulation for differentiated knit. Knitflatable Architecture, Master Thesis by Baranovskaya 2016 (author of this PhD thesis) treating the material variations as static and predetermined. For instance, certain studies have employed the digital mapping techniques to translate predefined images into the heterogeneous mesh structures (Karmon et al. 2018; Hörteborn and Zboinska 2021), resulted in arbitrary surface patterns, not related to the behavior or target shape of these surfaces.

Other works have developed the more advanced parametric simulations, investigating the force flows (McKnelly 2015), stress distribution (Liu et al. 2020a; Tan 2021), and curvature mapping (Baranovskaya et al. 2016), in order to relate the global structural behavior with the local material differentiation. These practices are reviewed a bit more in detail below.



F 2.19: Simulation of knitted differentiated wind break. *Hörteborn and Zboinska 2021*

The computational tool Knit IT by Karmon et al. 2018 integrates the heterogeneous material structures into simulations, however primarily focuses on the self-formation at the patch scale rather than architectural applications of membrane structures. Similarly, the McKnelly's work (McKnelly 2015), while simulating the differentiated meshes, though at the very small scale, raises the doubts whether the global shape outcomes are driven by the fiber elasticity or by the stitch variation, complicating the interpretation of results.



F 2.20: Uniform vs. specific to flow of force knit material assembly. *McKnelly 2015*

In the works of Tan 2021 and Liu et al. 2020a, the active properties of knits for creating the form-active structures are largely neglected. Instead, the knitted surface shape is formed primarily by the rigid structural components, rather than by the intrinsic properties of the knit itself. This approach is reflected in their simulations, which adopt a top-down design method—using a predefined shape as a static target to derive the local material differentiations for manufacturing, while excluding the integration of the knitting's differentiated properties into the simulation. While effective for generating innovative local material specifications, this method does not guarantee the precise target shape outcomes. However, this project prioritizes other aspects of the design process, as shape accuracy is ensured by external rigid framing elements.

By contrast, Baranovskaya et al. 2016 seeks to leverage the knitting's form-active ability to expand under the external forces, steering the formation of pneumatic beams. However, the simulations employed deviate significantly from the real-world outcomes, necessitating an extensive calibration to achieve a closer alignment between the digital models and physical results.

While these research efforts provide the valuable insights and inspire the advancements in material differentiation research, their limited integration of heterogeneous simulation with advanced structural analysis highlights significant opportunities for further exploration. Employing the generative parametric tools with the integrated simulation and analysis could establish a stronger connection between the global material targets and the local knitting differentiations. Moreover, these approaches could benefit from the application of structural analysis at larger architectural scales and the development of more advanced interfaces with industrial knitting machines. The lack of extensive validation and calibration in these simulations underscores the need for rigorous practices, which are addressed in the following subsection.

2.2.4 SIMULATION VALIDATION AND CALIBRATION

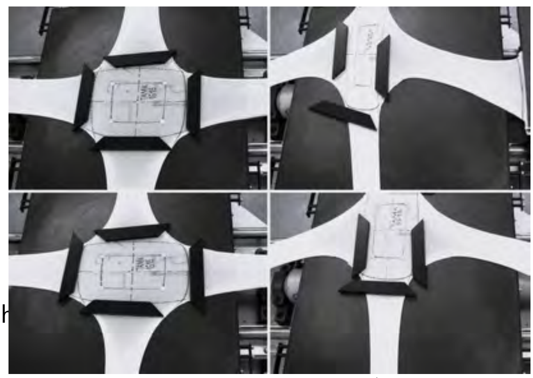
The effective use of simulation in architectural applications depends on its ability to closely approximate the behavior of physical artefacts. In the context of architectural knits, simulations often simplify the knitted structures using low-resolution meshes that abstract the intricate density and complexity of the material. While this approach improves computational efficiency, it introduces challenges in achieving *accuracy*, necessitating for the careful *calibration* to align the low-resolution digital representations with the dense physical knitted counterparts.

SAMPLING AND 1:1 PROTOTYPING

Sampling, a common exploratory practice within the textile design discipline, involves rapid small-scale sampling to understand the effects of yarn choices, machine settings, and stitch combinations on the material behavior of the surface. The material insights gained through systematic experimentation with these samples and probes uncover the underlying *principles of the craft* techniques used in CNC-knitting.

F 2.21: Scanning of Isoropia unit 1:1 scale prototype. *CITA 2018*

Until recently, the method of material sampling and 1:1 scale prototyping has been used in order to tune the knitting simulation and the production of knitted objects. Material sampling is particularly well-suited for calibration of simulations, representing homogeneous textiles. Uniformity in these structures allows the representative samples to be extracted and subjected to uniaxial or biaxial tensile testing, a standard method for determining material stiffness and dimensions, widely adopted by material science, civil engineering and garment design (Knippers et al. 2011; Monticelli and Zanelli 2022). The stiffness values obtained from these tests are then scaled up and applied to larger structures as seen in research by Do et al. 2020; Liu et al. 2020a; Ramsgaard Thomsen et al. 2016; Schmeck and Gengnagel 2016; Tan 2021; Tan and T. L. Lee 2018, with the assumption that th observed in the sample testing holds true to the scale



F 2.22: Bi-axial testing procedure of MSAJ/M–02–1995 on the knit for Hybrid Tower. *CITA 2015*

For heterogeneous knitted membranes, the complexity of patterns and non-uniform stitch distribution complicates representative sample extraction. In such cases, 1:1 scale prototyping provides a feasible alternative, as seen in studies by Holden Deleuran et al. 2015b; Ramsgaard Thomsen et al. 2019b; Tan and Tat 2019. By fabricating a full-scale physical model and digitally scanning it into a point cloud, researchers directly compare the physical prototype with the digital simulation (Holden Deleuran et al. 2015b; Tamke et al. 2019) **F**2.21. This iterative process offers the valuable insights into the material behavior and aids fine-tuning, although the deviations due to the assembly tolerances often require further calibration.

VALIDATION AND CALIBRATION

The calibration process involves the matching of digital simulations to the 1:1 prototypes by comparing the scanned data of tensile knitted membranes with their digital counterparts. Adjustments are made to the simulation parameters, such as stiffness values, to reduce the discrepancies. However, defining the accurate stiffness values for such simulations is complex. Material properties, derived from the micro-scale filament data sheets, often differ significantly from the stiffness of resulted knitted surfaces, which are influenced by the yarn properties, machine settings, and knitting patterns.

Some studies, such as Schmeck and Gengnagel 2016, replicate the physical uniaxial tests in digital simulations to manually derive the stiffness values and Poisson's ratios. While this method can achieve the calibration for simple cases, it is less effective for complex geometries or heterogeneous surface properties, as the values may not translate accurately across the multiple surface directions or more intricate shapes.

EVOLUTIONARY ALGORITHMS AS AID FOR CALIBRATION

Evolutionary algorithms offer a promising alternative for calibrating textile simulations, particularly for complex knitted shapes with multiple differentiated areas. Integrated into parametric environments like Grasshopper through plug-ins such as Galapagos (Rutten 2019), Opossum (Wortmann 2021), Wallacei (Makki et al. 2019), and Radical ((MIT) 2019), these tools can help optimize stiffness values by minimizing geometric discrepancies between digital and physical representations. This approach has been explored extensively for calibrating knitting simulations within architectural research by Oghazian 2022; Oghazian et al. 2022, providing precise simulation outcomes.

F 2.23: 3d-scanning and digital model comparison. *Shi, Oghazian, Davis 2022*

This method, combining 1:1 prototyping and evolutionary tools for simulation calibration, undoubtedly enhances simulation precision, but its application comes with limitations. Fabricating the entire physical design before tuning the simulation provides limited benefit during the design process, as structural deviations only become apparent after fabrication. Furthermore, the success of stiffness calibration remains uncertain since the derived values are not validated with alternative geometries and stitch patterns. Oghazian's calibration results for homogeneous knits are highly dependent on factors such as topology and stitch type, which makes them difficult to seamlessly apply to more complex or heterogeneous designs.

Conventional methods, such as sampling and prototyping, continue to hold value, yet integrating evolutionary algorithms and advanced engineering tools presents a scalable path toward more precise calibration practices. Refining these methods further could improve the correlation between digital simulations and physical artefacts, facilitating the broader application of novel differentiated CNC-knitted membranes in architecture. Despite its limitations, this PhD thesis explore the potential of evolutionary algorithms to uncover unknown stiffness values in heterogeneous knitted structures. Advancing this methodology through validation with alternative designs is crucial for enhancing the accuracy, robustness, and adaptability of the simulation approach to diverse architectural forms.

2.3 PRACTICES OF TEXTILE MATERIAL SPECIFICATION

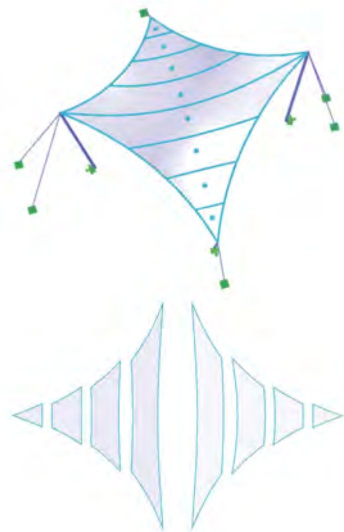
Practices of the textile material specification involve the translation of an original design intent, often represented three-dimensionally, into a set of instructions for producing tangible textile objects. These specification strategies are inherently linked to the target shape and the textile system employed, whether it be weaving or knitting, and as a result related to the fabrication techniques, used to make the fabrics.

As the knit is the primary material system explored in this thesis, the section traces the evolution from traditional, bottom-up knit specification approaches — characteristic of garment design — to the top-down, data- and simulation-driven methodologies pioneered by computer scientists working with knit at the garment scale and architects, investigating the larger-scale knit applications. These methodologies, integrating the computational technologies and simulations, provide a greater control over the production, enabling the localized knit specifications aligned with the target design shapes. The review highlights the strong relationship between the knit specification practices and knitting manufacturing techniques, used to form three-dimensional textile structures, revealing the opportunities and unexplored possibilities for architectural knit applications through simulation and computational technologies.

2.3.1 SHAPE-TARGETTED PRODUCTION

Textile material specification strategies are inherently linked to the target shape the material aims to achieve, which is, in turn, is strongly influenced by the textile system employed. Due to their linear fiber arrangement, woven fabrics are limited in their ability to rearrange their surface without wrinkling to form the three-dimensional shapes. This challenge is typically addressed geometrically through the discretization of the target shape and the application of a cut-pattern approach. The method is widely used in garment design, for example, in producing jeans and other items made from stiff fabrics, as well as in structural architectural membranes.

To achieve their desired three-dimensional form, the structural tensile membranes — primarily made from the coated woven textiles — are divided into patches, which are then joined into 3d shapes **F**2.24. The engineering softwares, dedicated to



F 2.24: Structural hypar membrane cut-pattern. *Dlubal Software* the form-finding of structural membranes, facilitate this process by analysing and proposing the most optimal cut patterns for the designed tensile membrane. Their simulation tools generate the patch outlines for the digital CNC-plotters, which automate the cutting of membranes, which afterwards are manually assembled by sewing or welding (Knippers et al. 2011). While the research, as by Ayres et al. 2018 explores the alternative clustering methods for membrane cutting pattern, focusing on achieving complex unconventional shapes and the efficient use of material, such investigations remain rare and are often considered niche rather than standard practice **F**2.26.

In addition, the structural analysis provides the data, indicating where the membranes require reinforcements, offering the precise pathlines for sewing on the rovings of strong fibers, as seen in high-performance sails **F**2.25. The functional details for interfacing the woven membranes with the other structural elements — such as sewn edges, perforations, or stamped metal eyelets — are usually incorporated during the final stages of production, further highlighting the manual and segmented nature of these cut-and join production processes.

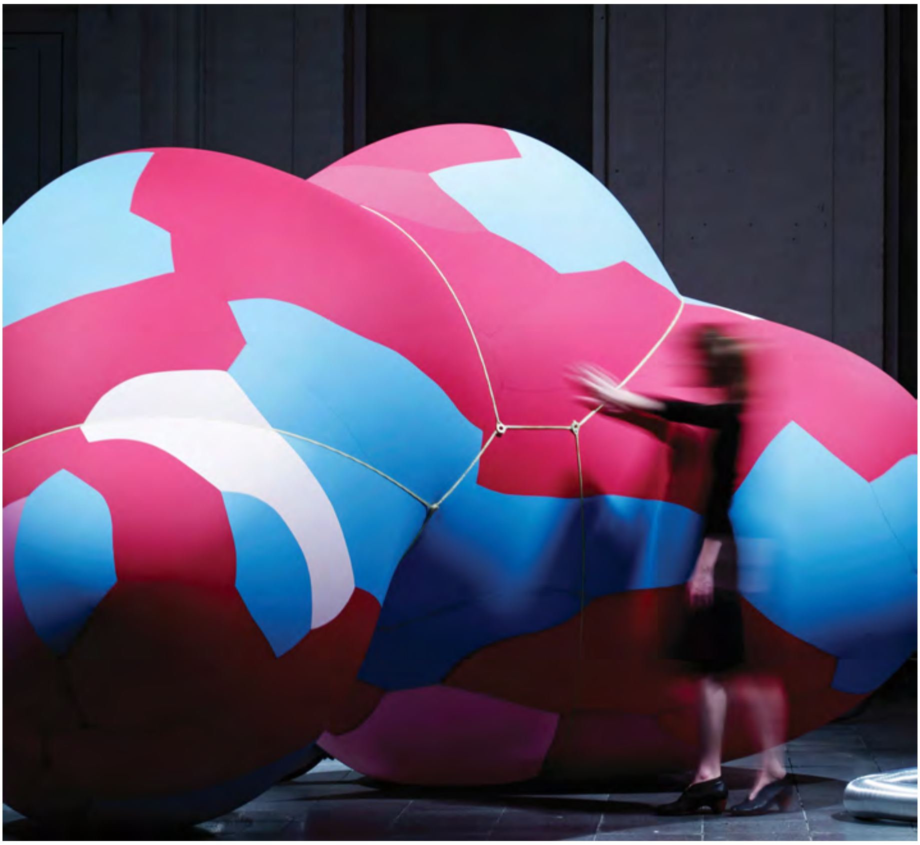
F 2.25: High-Performance Cruiser Sail with visible carbon reinforced lines. Italia Yachts 15.98 Bellissima. *Sailing Stream*

In contrast, the knitted objects exhibit the fundamental differences in how the material specification is approached. In additive knitting technique the specification is organised around intertwining the continuous filament into the stitches, by informing the stitch *structure*, *distribution*, and raw material of yarn, which collectively define the textile's global properties. These properties influence not only the overall behavior of the fabric as it forms three-dimensionally but also the integration of functional details such as holes, openings, and channels. Unlike in woven materials, the three-dimensional shape and functional details of knitted objects are integrated directly into the knitting process and planned in advance during the early design stages.

2.3.2 CONVENTIONAL BOTTOM-UP KNIT PROGRAMMING

The tradition of knit instructions is rooted in linear descriptions, where the material assembly and structural logic are sequentially defined, detailing the needle-yarn manipulations row by row in the order of fabrication. Domestic manual knitting specifications, represented by *knitSpeak language* (Berman Price 2007), in text- or symbol-based formats, organized in lines or grid form. With the advent of digital machine knitting, these formats have evolved into full colour, pixel-based representations. Despite these technological ad-

F 2.27: Manual programming of ShimaSeiki knitting machines by drawing on the canvas. *ShimaSeiki*



F 2.26: Inflated Restraint using the K-means clustering for cut-pattern of membranes. *CITA 2016, Photo by A.Ingvartsen*

vancements, this grid-based system remains the primary method for material specification, as well compatible with the industrial knitting machine processes (Kaspar 2022).

The industrial CNC-knitting machines, primarily designed for the garment industry, rely on the specific workflows and software that require the manual compilation of machine instructions. The encoding process involves the placing of pixels onto a two-dimensional canvas, constrained by the predefined garment templates within the commercial software tailored for industrial knitting. This bottom-up approach is largely non-intuitive and rarely supported by simulation, with only few knitting environments offering the simulation previews. As a result, the process demands a deep and intuitive understanding of stitch behavior and knitting techniques. Designers must anticipate how the local stitch specifications influence the overall form, making the specification process highly complex and heavily reliant on extensive education, prior experience and consequently, depends on the extensive prototyping and iterative, manual fine-tuning of the manufacturing files.

2.3.3 DATA - INFORMED KNIT SPECIFICATION IN GARMENT, COMPUTER GRAPHICS AND ARCHITECTURE

While the bottom-up knit programming workflows are adequate for mass production — where a single, manually tuned file supports the large-volume manufacturing — the new demands have emerged in the fields requiring higher customization and more complex material programming. High-performance sportswear, protective equipment, and medical applications, for instance, have begun leveraging the computational tools and simulation engines to inform the knit material specifications. By linking the body performance attributes to the localized material properties, the technologies of 3D body scanning and advanced simulations enable the design of garments with the improved fit, compression, stretch, and breathability (Adidas 2017; Šurc et al. 2020; Mikucioniene et al. 2020; Tessmer et al. 2022) **F**2.28.

Despite these advancements, the connection between the desired performance and material specification remains complex and underutilized in a broader knit textile production. Furthermore, the private conversations with the people employed in Adidas, NewBalance and Nike, the companies exploring the knit material differentiation in design of their products, suggest that marketing and the manual processes significantly influence the material specification, with the little transparency regarding how the knit material specifications are exactly determined. While a certain progress has been made in the specialized applications, the traditional manual process of compiling machine instructions remains resource-intensive and poorly suited for the projects requiring bespoke, non-repetitive elements, such as spatial membrane design.

F 2.28: Differentiated knit in high performance garment applications. Left - ProElite Knit Sport T-Shirt. *Nike 2013*, Right - 3d knit spacesuit sleeve. *Tessmer 2022*

ARCHITECTURAL KNIT SPECIFICATION, INFORMED BY SENSING, SIMULATION AND MACHINE LEARNING

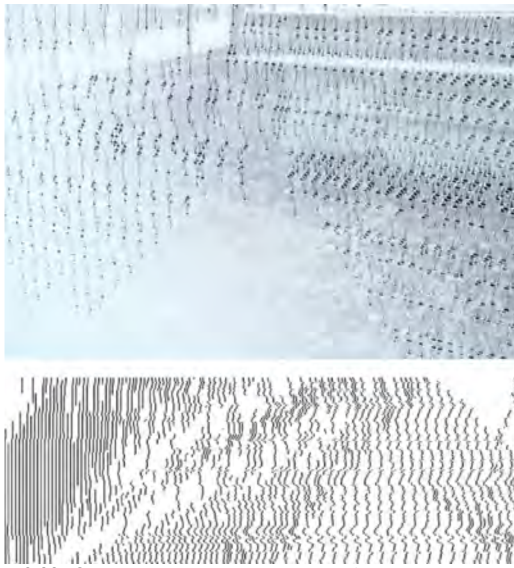
Knitting in the architectural field presents a radically different set of challenges compared to garment production. Architecture demands highly customized, large-scale elements that depend on their three-dimensionality and material differentiation for structural and geometric performance (Ramsgaard Thomsen et al. 2016). These demands necessitate the development of automated, data-driven approaches that integrate material performance analysis, enabling designers to control geometry, strength, and structural behavior at a larger scale while linking these parameters to local material characteristics.

The limitations of garment-based knit specification methods for addressing the needs of alternative applications, such as architectural knits, have driven researchers in computer science (Igarashi et al. 2008; McCann et al. 2016; K. Wu et al. 2022; Narayanan et al. 2018; Nader et al. 2021; Kaspar et al. 2019a; Narayanan et al. 2019) and computational architectural design to develop the novel material specification methodologies (S. M. Ahlquist 2013; Ramsgaard Thomsen et al. 2016;

F 2.29: Hybrid Tower, demonstrating the advanced modelling techniques for unconventional architectural outcomes with CNC-knit. CITA 2016, Photo by *A. Ingvartsen 2016*

Popescu et al. 2017; Liu et al. 2020a; Oghazian 2022). These emerging approaches aim to bridge the global digital design intent, material performance, and automated production through the innovative design-to-fabrication workflows. These workflows challenge the traditional bottom-up knit material specification practices, opening the new possibilities for integrating the architectural knits into a broader design and engineering applications.

In spatial design and architectural knit research, inquiries into informing local variation, developing design criteria, and integrating analysis and feedback into the process have led to the identification of three key approaches for knitted material differentiation: *sensing*, *simulation* (Ramsgaard Thomsen et al. 2016), and *machine learning* (Ramsgaard Thomsen et al. 2019a).



F 2.30: Sensing-driven knit material specification, using light sensor data at the windows. *Ramsgaard Thomsen et al 2016*

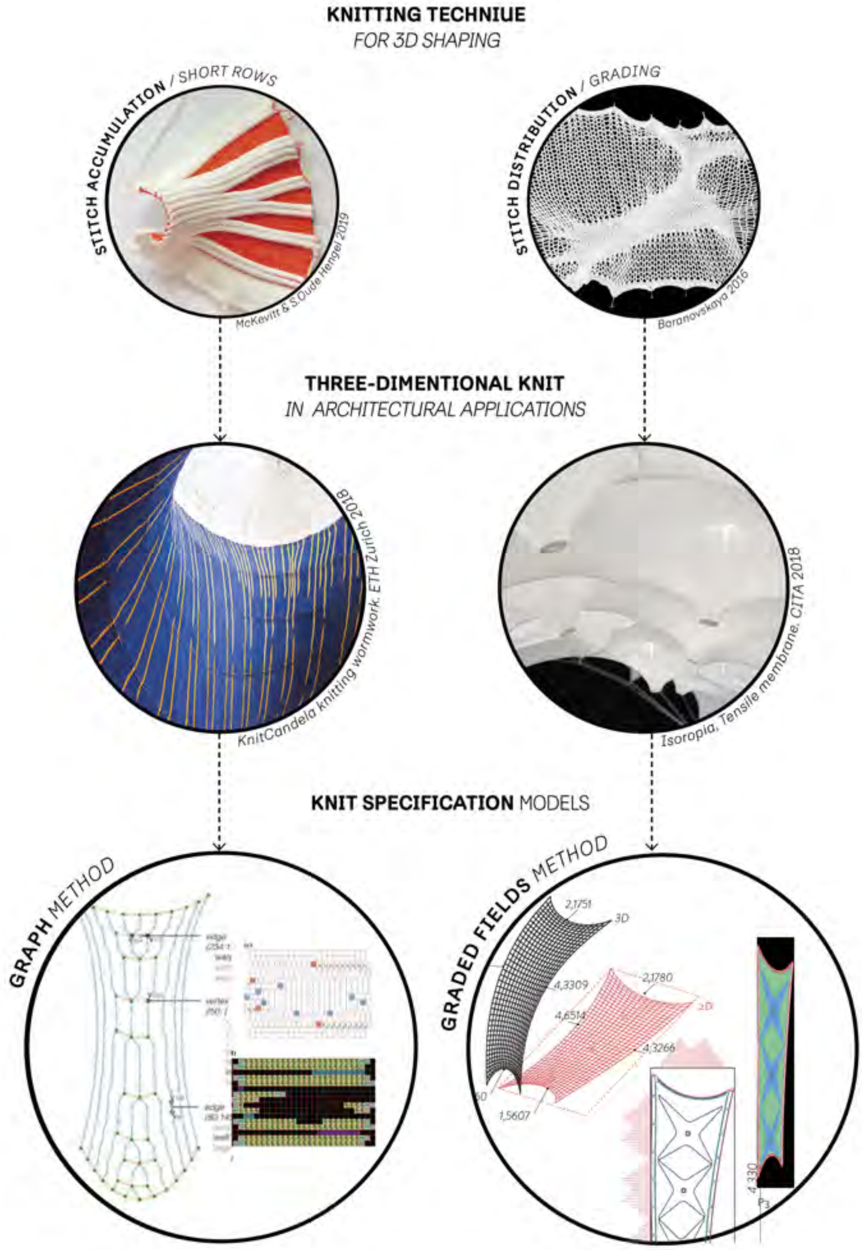
The *sensing* approach collects the localized data from the site and integrates it into the knit fabrication files F2.30. This data enables the transformation of knit pattern structures, resulting in variegated surface properties such as light permeability, as seen in *Sifter* and *Derma* knitted screens (Ramsgaard Thomsen et al. 2016), as well as the integration of runners' data in myThreadPavilion and *DataKnit* by Sabin Studio (Sabin 2021; Sabin 2013), introducing the communicative role of the differentiated knits.

This PhD thesis, however, will not further explore the integration of sensing data into knits but will instead emphasize the importance of simulation-driven material specification practices. These practices will be examined in greater detail below, focusing on their engagement with material performance in relation to form-matter interactions, structural behavior and resulting knit patterns.

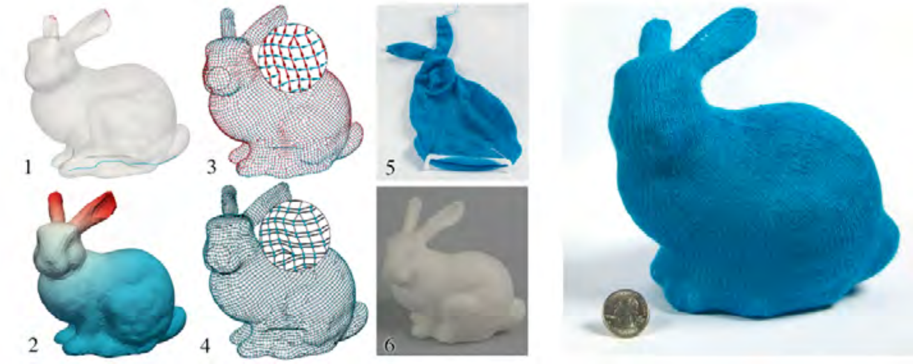
TOP-DOWN: SIMULATION AND SHAPE-INFORMED KNIT SPECIFICATION

Within the *simulation-informed* knit specification practices, two primary methods for automating the design-to-fabrication workflows are emerging. Developed and explored in the fields of computer science and architectural knit research, these digital practices are closely tied to the knitting techniques used to achieve three-dimensionality in knitted surfaces. Both methods enable the creation of non-developable, anticlastic geometries on the flatbed knitting machines, which are programmed and operate in a two-dimensional framework.

The two primary techniques for producing three-dimensional shapes in knitting are *stitch accumulation* and *stitch differentiation* **F**2.31. As mentioned in paper by Sinke et al. 2022a these techniques correspond to two distinct computational strategies for knit material specification: the **Graph** Method and the **Graded Fields** Method. Both strategies adopt a top-down approach, directly linking the specification process to the predefined target shapes through the use of computational algorithms and simulation techniques.



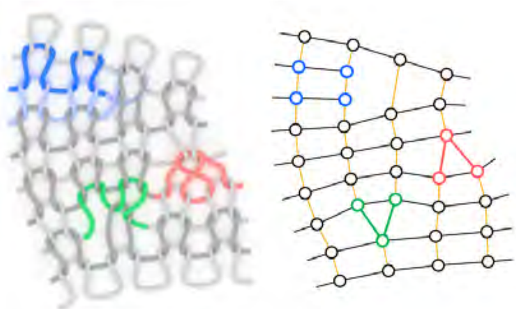
F 2.31: Knit Specificaiton Methods: Graph (left) and Graded Fields (right). *Sinke 2024 with graphic material of Popescu 2018, McKevitt &Hengel 2019, CITA 2018*



F 2.33: Stages of automatic machine knitting of 3D meshes. *Narayanan et al 2018*

3D THROUGH MATERIAL ACCUMULATION: SHORT-ROWS AND GRAPHS

Knitting, as a shaping method through **stitch accumulation**, utilizes the short-row technique to partially knit the sections of fabric, creating a localized excess material. This method achieves the three-dimensionality by increasing the surface area locally through the addition of stitches in specific areas of the knitted row. The resulting material shapes the surface by causing it to bulge out of the plane while maintaining the uniform density and overall homogeneity across the fabric. This uniformity makes the technique particularly useful for everyday garments. Short rows are widely used in garment design to improve the fit and create the three-dimensional effects and volume, as exemplified in the heels of knitted socks or flared skirts (**F**2.31, *left*).



F 2.32: Knit stitch topologies, using short-rows for shaping and its corresponding stitch-graph. *Kaspar 2022*

In CNC-knitting programming, the implementation of the short-row technique demands a deep understanding of its shaping mechanics, particularly related to the passage of machine carriers, which dictates the precise placement of pixels onto the canvas. While this *bottom-up* method works for the predictable garment shapes, where pre-developed templates simplify the programming process, applying it to the more complex forms becomes significantly more challenging. This complexity arises from the need to comprehensively understand the spatial relationship between the resulting form and the placement of individual stitches.

In the domain of computer science, these bottom-up programming approaches have been criticized for their manual nature and lack of control over the final shape. This critique led to the development of the *top-down* **Graph Method**, which inverts the knitting programming process by directly linking the target shape to the arrangement of accumulated stitches, utilizing the short-row technique on industrial knitting machines (Igarashi et al. 2008; McCann et al. 2016; Kaspar et al. 2019a; K. Wu et al. 2019; Narayanan et al. 2018; Narayanan et al. 2019; Nader et al. 2021) **F**2.33.

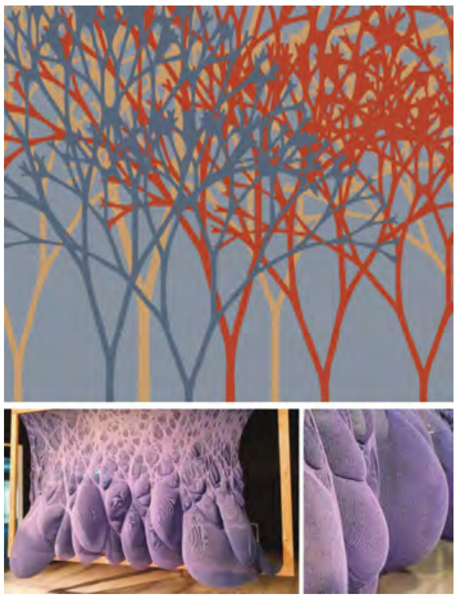
The Graph Method begins with an analysis of the target shape, which can be either a statically modelled geometry or an architectural form-found shape. This analysis defines the start and the end points of the knitting cycle and determines the direction of knitting. The shape is then segmented and sliced into the iso-curves, which represent the knitting rows. Each iso-curve is divided further into evenly distributed points corresponding to the number of stitches per row. These points are vertically interconnected to establish the paired stitches, while the unpaired stitches mark the boundaries of the short row. This pairing process generates a surface network that informs the creation of a *graph* diagram, representing the relationships between the rows and columns and guiding the distribution of the accumulated stitches. The final result is a planar, grid-bound bitmap — a map of square pixels — that serves as the basis for machine programming instructions (Sinke et al. 2022a), facilitating the production of 3d knit.

Originally developed in computer science for smaller-scale applications of knitted toys and textile objects, the foundational principles of the Graph Method have since been extended to the architectural elements and structures. Studies by Underwood 2009; Liu et al. 2020b; Popescu et al. 2017; Popescu et al. 2020; Oghazian 2022; Tan et al. 2022 demonstrate how this method enables the architectural knitted surfaces to achieve their structural three-dimensionality by increasing the surface area, allowing the fabric to remain smoothly tensioned and demonstrate high curvature, which contributes not only to the stability, but also to the aesthetic expression **F**2.31.

3D THROUGH MATERIAL DIFFERENTIATION: GRADED FIELDS

Another knitting shaping method uses the **stitch differentiation** for achieving the surface three-dimensionality by varying stitch lengths across the surface. Unlike the short-row technique of stitch accumulation, which preserves the material uniformity and *homogeneity*, the stitch differentiation introduces the surface *heterogeneities* (**F**2.31, *right*). These variations enhance the fabric's deformation capabilities, enabling it to expand under the stretch and therefore resulting in the three-dimensional surface outcomes.

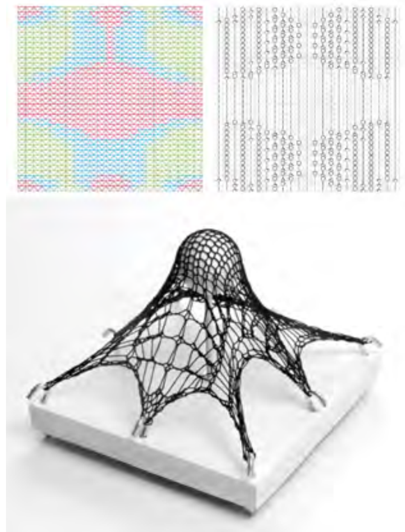
Due to its inherent variation, this technique has traditionally been applied in garment design for purposes such as lacing, decoration of surfaces, or enhancing the garment breathability, as seen in sportswear. However, in the architectural domain, the use of stitch differentiation for three-dimensional and structural purposes has been explored by relatively few researchers (McKnelly 2015; Baranovskaya et al. 2016; Ramsgaard Thomsen et al. 2019b; Hörteborn and Zboinska 2021).



F 2.34: Predefined image knit pattern definition, resulting in volumetric pockets for wind break textiles. *Hörteborn and Zboinska 2022*

Hörteborn and Zboinska, in their exploration of stitch differentiation for creating graded textile windbreaks, highlight the expressive and volumetric effects of drop stitches, which form the extensive three-dimensional pockets on the surface, effectively reducing the wind flow for better comfort (Hörteborn and Zboinska 2021). However, the knit specification strategy there relies on a predefined image to generate pocket geometries, could be improved by establishing a stronger connection between the simulation of textile interaction with wind and the strategic placement of pockets to steer and optimize the airflow through fabric **F**2.34.

Baranovskaya's pneumatic form-finding exercises aim to connect the target curvature of a textile air beam with local knit differentiation. This approach involves the incorporation of more expandable drop stitches in areas where the beam is expected to curve, resulting in a compression and tension effect within the global geometry of air-beam, guided by the differentiated knit. This effect directs the expansion of latex balloons within the knitted cushion, thereby controlling the bending of the air beam (Baranovskaya et al. 2016). While this project showcases the promising potential of differentiated knits for form-active outcomes, its digital methodology could benefit from further refinement. Specifically, integrating more advanced structural analysis could better define the areas of material expansion by linking them not only to the abstract curvature of the target shape but also to the volumetric geometry of the air beam itself, derived through simulation.



F 2.35: Force-distribution driven knit specification and knitting instructions for manual knitting machine. *McKnelly 2015*

McKnelly attempts to integrate the force distribution into the grading of knitting patterns by applying an inverted Hooke's Law to define the areas of stress distribution in the knitted nets. However, both her and Baranovskaya's approach lack the integration with the industrial knitting machines, relying instead on manual toy or semi-electronic Brother machines (McKnelly 2015). While this reliance on simpler tools is understandable given the project limitations, it highlights the untapped potential of industrial-scale production, which could facilitate greater complexity of differentiated surfaces in high-performing structural architectural elements **F**2.35.

Liu offers an exploration of force distribution in knit material composition at the large scale, being linked to the local material specification, although adhering to the conventional material grading paradigm by applying the principles of *material redundancy* and strategic *structural reinforcement* **F**2.36. This approach operates within the paradigm of *resisting* to forces and deformation, by placing the denser material properties in the areas of higher stress concentration, while leaving the less structurally utilized areas porous and material-efficient (Nicholas 2013). By resisting the external forces through strategic local reinforcement, these graded surfaces are constrained to the predetermined forms, often resulting in rigid, static structures. This is also seen in the epoxy-cured rigid shells in the MeiTing project (Liu et al. 2022) and the Composite Knitted Tower (Liu et al. 2020a), where the knit is encased within a polymer matrix rather than employed as a form-active material. While effective for many conventional applications, this grading paradigm of material redundancy may not fully exploit the potential of knitted materials to dynamically engage with the forces. As a result, it limits the opportunities for achieving more adaptive, volumetric, and high-curvature material outcomes, that graded knit can offer.

F 2.36: MeiTing Knitted Shell, specified in relation to force-lines. *Liu 2022*

An alternative to the conventional grading lies in the strategies that embrace the material dynamics and deformation as design tools (Nicholas 2013; Holden Deleuran et al. 2011). Rather than resisting to forces, materials can be graded to respond dynamically, transforming under the load in a controlled manner. This approach has been explored through the stitch differentiation for the active management of membrane structural three-dimensionality in the *Isoropia* project by CITA (Ramsgaard Thomsen et al. 2020c).

In *Isoropia* project, star-shaped, locally specified surface areas, referred to as *fields*, with more expandable stitches are strategically placed around the areas of applied tension by cable-net **F**2.37. These fields enable the fabric to stretch more in the targeted regions, allowing it better achieve the required curvature. This approach moves away from maintaining the rigid, predetermined global design forms and instead allows the materials, particularly knits, to achieve the shapes and configurations inherently aligned with their natural behavior and internal organization. Methodologically, this knit specification approach, which uses the areas of distinct material expansion rates, is supported by a correlated digital design-to-production workflow. Named in this Phd thesis as **Graded Fields** in paper by the author (Sinke et al. 2022a), this methodology initially rooted to 2018, when it was applied in *Isoropia* and introduced diagrammatically in Ramsgaard Thomsen et al. 2020c (**F**2.38, *middle*).

F 2.37: Star-shaped knit material specifications of differentiated knit structures in Isoropia tensile unit, using Graded Fields approach. *CITA 2018*

Although the workflow has been integrated into large-scale industrial production, it still lacks a strong connection between the surface's global shape and the corresponding local material specifications. The star-like differentiation areas, while parametrically flexible and linked to geometric modifications of the patch, are manually designed as rigid geometric forms stamped onto the surface. Their parametric adjustments are performed two-dimensionally on pre-planarized textile patches. This PhD thesis builds upon the knit specification methodology described in Graded Fields, focusing on extending its capabilities by integrating structural analysis and more advanced, intricate knit material specifications. The aim is to establish stronger links between the global membrane shape, its structural performance, and its local knit material differentiation, tailored to fabrication constraints on industrial flatbed STOLL knitting machines.

2.4 DIGITAL DESIGN CHAIN & KNIT: DESIGN, SIMULATION AND FABRICATION

The previous two sections of this chapter provided an overview of diverse computational practices for knit material *simulation* aimed at behavior *prediction*, as well as for knit material specification for industrial manufacturing. These practices, which address the importance of inter-scalar and interdisciplinary inputs, were presented individually. However, in the context of architectural design workflows, they are already integrated into broader *design-to-fabrication workflows*. These workflows interconnect the aspects such as global spatial arrangement, material simulation, manufacturing constraints, and in some cases, simulation validation and calibration, through the interconnected computational and digital models.

2.4.1 DIGITAL DESIGN CHAIN

A paradigm for integrating multiple interdependent models within a coherent workflow is encapsulated in the concept of the **Digital Design Chain (DDC)** (Dohmen and Rüdenauer 2007). This approach envisions several models coexisting within the same or closely linked environments, allowing for continuous cross-influence. The tight integration ensures the minimal data loss during the transitions between the models, where the spatial design, structural evaluation through simulation, material grading, and planning for digital fabrication occur simultaneously. By embedding the structural performance analysis and the manufacturing specification within the design environment, DDC fosters the collaboration, reduces the errors, and enhances the interoperability of tools throughout the design-to-fabrication process, leading to much more effeicient and innovative outcomes ((Bechthold 2008)). This interconnectedness ensures that form-finding, structural analysis, and fabrication instructions are continuously updated and refined in response to the feedback from other processes within the workflow. The DDC therefore shifts away from the isolated simulation methodologies towards a flexible framework, where multiple models, dedicated to design and fabrication tasks, overlap and interact in a feedback-driven manner (Tamke et al. 2013; Ramsgaard Thomsen and Tamke 2013b; Ramsgaard Thomsen and Tamke 2013a). In this framework, each model retains its distinct purpose, but contributes the data and the insights to the adjacent models, ensuring smooth exchange throughout the design process.

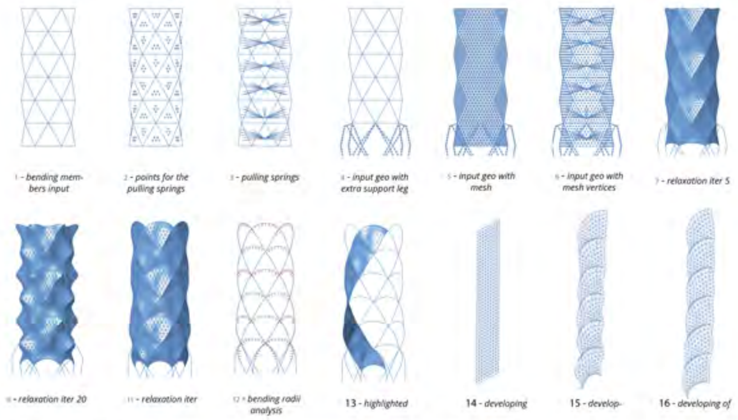
KNIT SIMULATION AND SPECIFICATION IN THE DDC FRAMEWORK

The *practices of knit simulation* for behavior *prediction*, discussed in 2.2, align with the **design models**, where the top-down design considerations integrate with the material simulation to predict the bottom-up effect of knit variation and the global outcomes of the local interactions. Conversely, the *knit material specification practices*, presented in 2.3 relate to the global design targets and outcomes, translated into machine instructions and therefore linked to the realisation of tangible textile objects on the industrial machinery, classifying them as **fabrication models**.

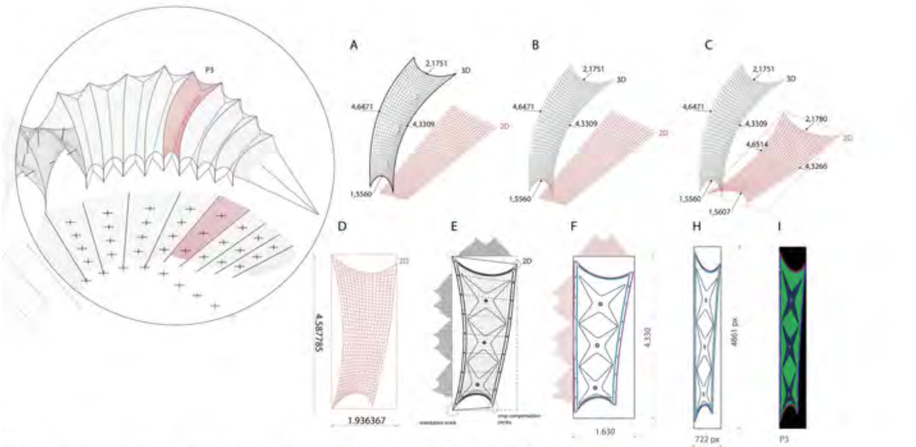
The DDC paradigm links these design and fabrication models by simulation and computational mechanisms, operating two directionally in top-down and bottom-up manner, coupling the initial design concepts with an accurate execution during the fabrication, while simultaneously aiding the generation of design targets through form-finding and integration of material properties. This iterative feedback loop captures the complex interactions between the design, material behavior, and fabrication constraints, described as a continuous digital organizational process linking the initial sketch to manufacturing (Dohmen and Rüdenauer 2007).

KNITTING ARCHITECTURAL DDC WORKFLOWS

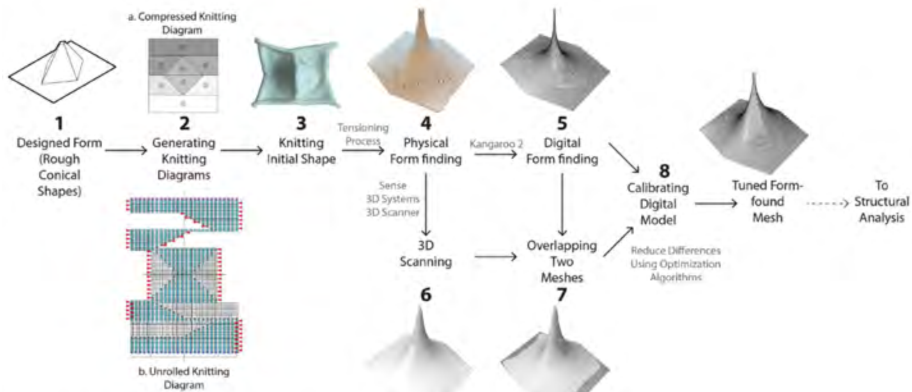
The existing workflows for architectural textile design demonstrate the integration of design and fabrication models, often tailored to distinct textile systems (*weave and knit*), knitting techniques (*stitch accumulation and differentiation*), or specific applications. For instance, Knippers' *Construction Manual for Membranes* presents a coherent, feedback-loop-based workflow integrating spatial design, FEM simulation, and material fabrication, but it is specifically tailored for woven membranes (Knippers et al. 2011).



Deleuran et al et al. 2015. Hybrid Tower: Integrated Analaysis in *Complex Modelling* book.
A Workflow pipeline for hybrid knitted knitted differentiated membranes: from form-finding of bending members, braced with knit mesh to the knit patch.



Ramsgaard Thomsen et al. 2020. Isoropia: Integrated Analaysis in *Complex Modelling* book.
A Workflow for knitted differentiated membranes: from form-finding to knit pattern.



Oghazian et al. 2022. From Physically Knitted Models to Calibrated Digital Simulations:
A Workflow Based on the Behavior and Geometry of the Knitted Tensioned Structures

F 2.38: Digital Design Chain workflows in architectural knitting research. Top to bottom: *Deleuran et al. 2015, Ramsgaard Thomsen et al. 2020, Oghazian et al. 2022*

To address the use of knit as an architectural tensile material, several research efforts have developed the workflows, integrating the design and fabrication of knitted membranes. The *Hybrid Tower* workflow (Holden Deleuran et al. 2015b) introduces design-to-fabrication strategies for knitted membranes but omits the detailed material composition and knit specifications within the process, instead being mainly focused on the modelling and analysis of the bending members. Additionally, it is limited to the repetitive patch designs, which restricts the customization opportunities in the overall structure's design.

Building on these developments, the *Isoropia* workflow (Ramsgaard Thomsen et al. 2020c; Sinke et al. 2022a) incorporates the unit customization, linking the membrane shape with the detailed knit specifications. However, it does not address fully the integration of knit heterogeneity in its simulations, highlighting the need for stronger connections between the form-found shape and the local material specifications.

Oghazian's work establishes a link between the tangible knitted object and its digital design through simulation validation and calibration (Oghazian 2022). However, the calibration relies on comparisons with the knitted object, where the material specification is detached from the form-finding simulation and instead informed by a static solid form (F2.38, *bottom*). The form-finding simulation, developed later in the workflow, overlooks the structural performance of knit-specific membranes, not to mention that the workflow is so far structured around a single unit design. It relies on homogeneous fabrics and employs the material accumulation technique of short rows to achieve three-dimensionality, whereas this thesis seeks to find the workflows for material differentiation techniques in architectural membranes. Furthermore, the structural analysis in Oghazian's work, positioned outside the workflow as a post-evaluation step, overlooks the opportunities of integrating the structural analysis into the design process and material specifications.

Although these digital design workflows for knits provide the valuable insights into the potential of knitting as a material system for architectural applications, they also reveal the significant gaps in research, underscoring the need for further development and refinement. Specifically, they fall short for supporting the customized solutions for the global design of architectural membrane structures, where the knit differentiation actively participates in the surface structural deformation, directly linked to the form-finding and informed by structural performance analysis, further supported by sufficient simulation validation.

2.4.2 MACHINE LEARNING-INFORMED KNIT MATERIAL SPECIFICATION

The Digital Design Chain is widely regarded for its vision of interoperability, enabling the seamless integration across various design stages and disciplines. However, it has also faced a criticism for its inherent complexity and lack of flexibility. This complexity arises from the need to manage numerous inter-scalar and inter-disciplinary interactions, which, once established, are challenging to modify or navigate effectively. (Tamke et al. 2014a). Within the digital chain paradigm, all relevant production information must be integrated into the modelling process and its resultant fabrication data. As a result, digital chains struggle to accommodate even minor changes outside the initial design topology or specification setup, often requiring a near-complete reconstruction of the workflow and recalibration of processes (Ramsgaard Thomsen et al. 2020a).

Machine Learning (ML) opens the new perspectives for architectural fabrication and particularly for the knit material specification, as it holds the potential for short-cutting the cumbersome parametric chained processes, currently prevalent in knit material specification practices and potentially make the knit fabrication faster and more adaptable (Ramsgaard Thomsen et al. 2020a). The advantages of ML in this context are twofold. First, ML's ability to generalize makes it particularly valuable for complex, rule-based production processes such as knitting. It excels at establishing connections between two related material representations, potentially linking local material specifications with the resulting physical outcomes or desired design criteria. Techniques like Generative Adversarial Networks (GANs) exploit this capability by learning from the images to generate new designs, effectively bridging the gap between input data and output specifications (Goodfellow et al. 2020). Secondly, ML, particularly through GANs, operates effectively with the pixel-based image representations, which are inherently aligned with architectural design and knit programming workflows. The intricate nature of programming knitting machines and translating the three-dimensional designs into two-dimensional fabrication instructions poses unique challenges that ML could help to address.

KNIT ML EXAMPLES

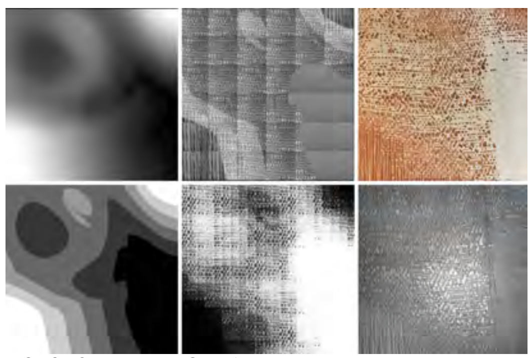
While the application of ML to knit material specification is still in its early stages, several notable examples have emerged.

In computer science, the focus has primarily been on the pattern generation. These efforts are often detached from the three-dimensionality of knit structures, focusing instead on the surface texture effects. For instance, Kaspar's *Neural Inverse Knitting* (2019) establishes the links between the target knit patterns, represented through photos of knitted surfaces, and the corresponding machine knitting instructions (Kaspar et al. 2019b).

F 2.39: SkyKnit, community knitted surfaces, informed by AI instructions. *Shane 2019*

Janelle Shane's *SkyKnit* project (2019) uses the natural language processing to train an AI on a dataset of 5,228 knitting instructions (Shane 2019), which members of the online knitting community Ravelry (raverly.com) realised into the physical creations **F**2.39. The results aesthetically deviated from the conventional garment shapes, showcasing the alternative and imaginative forms that hint at the creative possibilities of AI in knitting.

Other examples include Melnyk's (2022) use of GANs to generate novel punch card patterns based on the ones with traditional patterns (Melnyk 2022), and Ekárt's (2007) exploration of evolutionary algorithms for generating new lace patterns (Ekárt 2007). Scheidt's *deepKnit* project (2020) further highlights the potential of AI for producing the innovative patterns that move beyond the conventional catalogue-based designs for garments (Scheidt et al. 2020), however not too extreme.



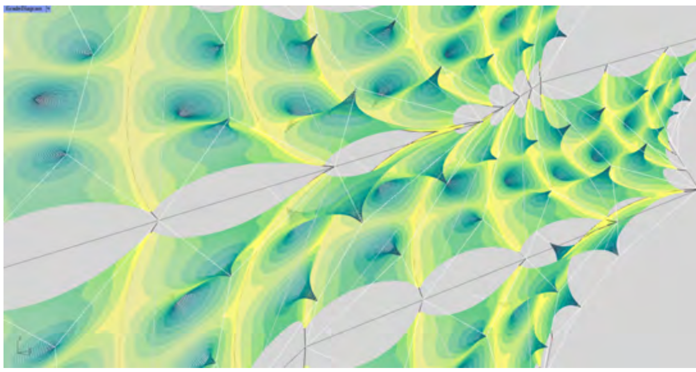
F 2.40: Ombre: Knit Specification based on desired shadow, casted by the differentiated knitted screen. *CITA 2019*

In the architectural knit research, *OmbreKnit* project introduces an ML-driven approach to link the desired material performance, such as light and shadow casting, with the corresponding knit material specifications (Ramsgaard Thomsen et al. 2019a) **F**2.40. While this work makes a significant contribution in linking the *performance* criteria to the local material specifications, it operates primarily within the constraints of *planar* knit screens using the limited complexity of stitch combinations.

Despite these advancements, the application of ML to link the three-dimensional knit targets with their material specifications for manufacturing remains largely unexplored. This gap presents a compelling opportunity for further investigation for this PhD project. By leveraging ML to establish these connections, future research could speed up the design-to-production processes of complex, three-dimensional knit structures that align more seamlessly with the intended performance outcomes.

2.5 BRIDGING THE KNOWLEDGE GAPS

The methodological framework of this PhD thesis builds upon existing practices, addressing critical limitations and advancing design-to-fabrication workflows related to differentiated CNC-knitted membranes. By integrating insights from the state-of-the-art review, this research establishes a foundation for tackling key gaps and lays the groundwork for innovative contributions to the field of CNC-knitted differentiated membranes.



F 2.41: Digital design explorations for knit specification using structural and geometric analysis of the target membrane forms. *Sinke 2022*

This thesis investigation is therefore structured around the three main research questions, introduced in 1.5.2, each corresponding to the development of relevant digital models: **Design** Model, **Fabrication** Model, and **Evaluation** Model. Together, these models form a more robust and expanded Digital Design Chain, tailored specifically for the design and manufacturing of CNC-knitted differentiated membranes, aiming to not be limited to the specific membrane topology, while still demonstrating their reliance and functionality. This framework of models leverages the inherent expansion properties of knitted materials to achieve desired three-dimensionality, providing a cohesive approach to material behaviour prediction by simulation, fabrication precision through intricate material specification, and post-validation for greater accuracy.

The **Design Model**, incorporating integrated simulation and form-finding, tackles the complex challenge of specifying CNC-knit material properties in relation to the global and target geometric shape. Unlike the reviewed practices, this model transcends the spatial design explorations by addressing the structural performance through the advanced material specification, informed by geometric and structural analysis. Moreover, this thesis introduces an alternative paradigm to conventional material grading strategies, that often relies on the material redundancy in areas of force concentration. Instead, this thesis advocates for material-controlled deformation through knit grading, prioritizing the *shape* formation as a primary objective over mere *strength* enhancement. This innovative grading approach ensures the membrane strength at the micro-scale, achieved by using high-tenacity polyester yarns, as Dyneema and Serafil, which provide the exceptional structural integrity and filament resistance to tensile forces. The flexibility of membrane is therefore achieved through the strategic programming of the local material specification surface programming towards the surface expansion deformation, informed by structural analysis and the use of highly expandable unravel drop-stitches.

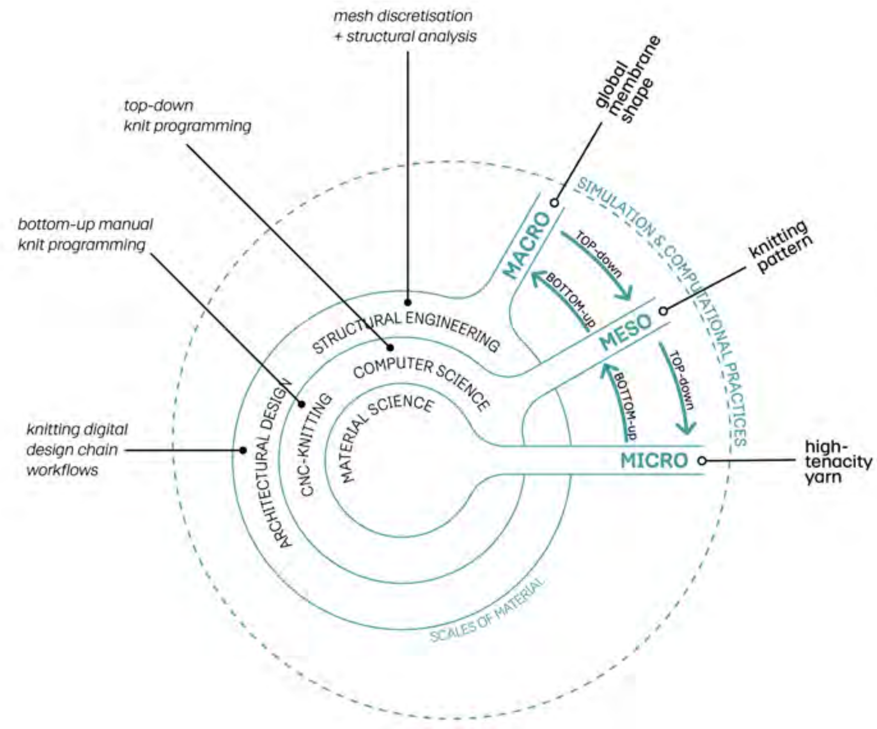
The **Fabrication Model** addresses the inherent incompatibilities between the design and fabrication environments, accounting for their spatial, metric, and resolution disparities. This model emphasizes the inter-scalar and interdisciplinary considerations, ensuring minimal distortion and data loss during the design-to-fabrication workflow. By taking into account the heterogeneous nature of differentiated knitted membranes, the Fabrication Model bridges the gap between the global digital design intents and their physical realization on the machine. It offers a systematic method for translating intricate 3d shapes into machine-readable instructions, aligning the production precision with the envisioned material behaviours **F**2.42.

F 2.42: Zoirotia interior, made of tensile differentiated CNC-knitted highly customised membranes. *CITA 2021, photo by A. Ingvartsen*

The third component, the **Evaluation Model**, plays a crucial role in supporting the design process through simulation validation and calibration. It addresses the challenges of simulating the behaviour of differentiated membranes by refining the unknown stiffness values and integrating these discoveries back into the design‘s model simulation. This iterative feedback mechanism ensures that the digital simulations accurately reflect the physical properties of the differentiated membranes, enhancing both the simulation predictive accuracy and reliability throughout the design-to-fabrication workflow.

F 2.43: Advancements in knit simulation by using mesh with heterogeneous properties. *Sinke 2023*

Together, these three models redefine the conventional boundaries of digital design to fabrication chains, offering a comprehensive framework that addresses critical gaps in the current state of the art within architectural knit research. While this research emphasizes the development of a robust parametric workflow, it also acknowledges the inherent cumbersomeness and specificity of such workflows, which can limit their flexibility and adaptability in broader applications. By recognizing these challenges, this thesis explores the potential of machine learning (ML) as a complementary approach for knit material specification. This thesis aims to contribute to this exploration, proposing ML-driven methodologies for integrating three-dimensional design targets



F 2.44: Updated State of Art framework with relevant to this research aspects

with the industrial knitting machine specifications. ML techniques are investigated as a means to enhance the flexibility of the Digital Design Chain by automating pattern recognition, predicting material behaviours, and enabling data-driven adjustments in material specifications. This exploration seeks to push beyond the constraints of purely parametric methods, offering a pathway towards more adaptable and scalable solutions for CNC-knitted membranes.

The methodological advancements proposed in this thesis are elaborated further in the *Methodology* and *Experiments* chapters, where the integration of parametric workflows and emerging ML approaches is critically examined. By bridging the fields of design, simulation, fabrication, this research establishes a novel paradigm for creating CNC-knitted differentiated membranes with unprecedented performance and aesthetical properties, while also anticipating the future potential for more flexible and automated design processes of using innovative material systems of programmable knit material.

Chapter III

METHODOLOGY

CHAPTER OVERVIEW

At the core of this PhD project, simulation functions as a *mediation tool* between design and fabrication, enabling the development of differentiated CNC-knitted membranes. **Chapter 3: Methodology**, establishes a robust framework that integrates simulation, form-finding, digital modelling, and 1:1 physical prototyping on industrial knitting machines. This framework addresses the complexities of linking global design strategies with local material differentiation while ensuring manufacturing feasibility. The chapter is divided into four sections, each addressing critical dimensions of the research methodology.

The first section, **Simulation in Philosophy, Engineering and Design**, explores the epistemological role of *models* and *simulations* as instruments for generating knowledge, highlighting distinctions between their use in science, engineering, and design. Science engages with simulations to study existing phenomena, engineering employs them to evaluate pre-designed structures with limited design iteration, while computational design integrates simulation as an exploratory tool from the earliest design stages. Theoretical definitions and a classification of models are introduced, providing a foundation for understanding the multifunctionality and diverse model types utilized in this research. Situating the study within a broader theoretical context underscores the transformative potential of simulation, particularly as a means of design exploration, transitioning from descriptive to generative instruments.

The second section, **Research Methods**, introduces two methodological approaches—Research-by-Simulation (RbS) and Research-by-Design (RbD)—as complementary instruments for integrating simulation, design, and physical experimentation. Research-by-Simulation (RbS), widely employed in scientific domains, is a predictive methodology focused on the creation and use of simulations as primary tools for studying complex systems in nature, society, and economics. This methodology, outlined through a series of steps introduced by Winsberg and other contributors in the philosophy of simulation, emphasizes its structural and universal nature, which allows RbS to be applied across diverse professional domains for investigating *pre-existing* phenomena. However, RbS does not encompass the creation of new objects or establish a link to fabrication—critical aspects for creative disciplines and the focus of this PhD thesis.

The section also examines the simulation methodology of form-finding (RbS(f)), commonly employed in structural engineering to address fabrication demands. While form-finding is highly relevant to this research, its engineering methodology is tailored to woven textile systems, requiring significant adaptation for knitted architectural materials. Moreover, the role of structural analysis in RbS(f) is often post-evaluative, focusing on validating structural performance of pre-designed structured rather than enabling extensive design exploration. This approach limits engagement with local material composition—a flexibility that knitted systems allows for.

In contrast, Research-by-Design (RbD), developed and employed in creative disciplines, prioritizes exploratory, design-oriented inquiry. Central to RbD is the creation of design artefacts (probes, prototypes, and demonstrators), which facilitate knowledge generation through direct engagement with materials and iterative making processes. However, RbD methodology of lacks a comprehensive integration of material properties through predictive simulation and lack the specific guidance for establishing a link to digital fabrication processes — key requirements for designing differentiated CNC-knitted membranes.

The section concludes that neither RbS nor RbD, in isolation, sufficiently addresses the complexity of designing and fabricating graded CNC-knitted membranes for architectural applications. This realization leads to the introduction of a hybrid methodology, which integrates the strengths of both approaches to overcome their individual limitations and meet the demands of this research.

The third section,**Combined Methodology (RbS+RbD)**, introduces the hybrid *Research-by-Simulation & Design (RbS+RbD)* methodology developed in this thesis. This integrated framework leverages the predictive capabilities and rigorous structure of RbS, engineering form-finding aspects of RbS(f) and the exploratory strengths of RbD, facilitating an iterative interplay between digital models and physical prototypes. At the core of this approach lies the *Digital Design Chain (DDC)*, comprising three interconnected digital models. The *Design Model* investigate the links between the global topology and predicts membrane behavior through form-finding simulations, simultaneously with the use of structural analysis introduce novel local material gradings to link the global membrane shape and local material differentiations. The *Fabrication Model*, is a prescriptive model, which translates global design intentions into stitch-specific patterns, bridging domain shifts between digital design and CNC industrial production. The *Evaluation Model* validates and refines simulations within Design Model by comparing the digital outputs of form-finding with the physical prototypes, enabling precise calibration through the discovery of material properties.

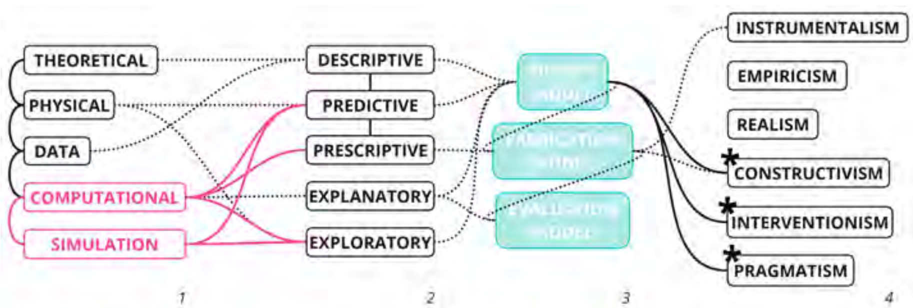
This hybrid methodology addresses challenges such as graded material differentiation, manufacturing constraints, and architectural applications of CNC-knitted membranes. The iterative feedback between digital and physical processes drives innovation, ensuring alignment between design intent, material behavior, and fabrication feasibility.

The closing section, **Research Tracks** provides a roadmap for the Experimental Chapter, structured around three Research Tracks aligned with the thesis's primary research questions. *Track A*, through Design Model, investigates the relationship between global topology and local material differentiation through simulation and form-finding. *Track B*, through Fabrication Model, addresses the domain shifts, related to resolution, metric and spatial differences between design and manufacturing environments, ensuring fabrication feasibility within CNC-knitting constraints and architectural application. *Track C*, through Evaluation Model, examines the deviations between digital designs and physical artefacts, focusing on discovering the uncertain knit mateiral properties by evolutionary algorithms and further calibrates the Design Model in order to ensure its accuracy and functionality for further design explorations.

3.1 SIMULATION EPISTEMOLOGY IN SCIENCE, ENGINEERING & DESIGN

This section establishes a theoretical framework for understanding models, simulations, and their epistemological roles in the pursuit of knowledge, with distinctions made between practices in science, engineering, and design. It begins by defining the concept of a model, outlining its key features and functions. This is followed by a classification of models, enabling an appreciation of the diverse types employed across various disciplines. From this foundation, the section identifies the specific types of models pertinent to this research, situating them within the field of computational design **F**3.1. The role of model-building and simulation creation is anchored in the epistemology of simulation—a branch of the philosophy of science concerned with the knowledge generated through simulations. The section examines the epistemological roles of simulations across disciplines, emphasizing their capacity to generate hypotheses, conclusions, and insights about phenomena—understood here as observed systems in the real world.

Different epistemological perspectives are explored, reflecting the evolution of simulation's role from a purely analytical and observational tool for depicting pre-existing phenomena to a creative and exploratory medium, particularly in design contexts. The distinction lies in how the modelled phenomena are conceptualized in different fields. In science, models and simulations are essential tools for understanding pre-existing systems in the natural world, focusing exclusively on phenomena as they exist. In engineering, simulations are employed to analyse pre-designed structures, influencing design changes only marginally. By contrast, computational design leverages simulations as a tool for exploration, integrating them into early design stages to facilitate the creation of novel solutions. Through these distinctions, the section highlights the shifting epistemological roles of simulation, underscoring its transition from a descriptive instrument to an active agent in creative and innovative processes, so relevant to design and material driven research, this PhD thesis positions itself within.



F 3.1: Epistemology of Simulation: terms and models. 1- model types, 2 - purpose based models based, 3 - models, developed in this thesis, 4 - epistemological perspectives on simulation. Epistemological views, related to this thesis approach, are marked with star

3.1.1 WHAT IS THE MODEL?

Generally, the model can be defined as a representation of a real-world system, capturing its essential characteristics and the relationships between its components. As Eric Winsberg highlights in his recent paper, models exist within a triad consisting of: (1) the phenomena or a system from the real-world, the model is representing, often referred to as the *target system*; (2) the *representational* nature of the model, defining the model‘s level of *abstraction* and (3) the user, who primarily interacts with the model and defines the model‘s *purpose* (Winsberg and Harvard 2024).

As such, the model functions as a framework that scientists use to understand, analyse, or predict the behavior of a target system, where the system is understood as a set of interacting or interrelated components that work together to form a complex *whole*, often governed by specific rules, laws, or relationships. The systems can be found in natural, social, and technological domains, where the system‘s components may include physical elements, processes, or abstract entities, and they can be analysed in terms of their structure, function, and behavior. There, the models are *structure-based*, focusing on representing of systems‘s components and the interactions of a system (Winsberg 2010). They often rely on the mathematical equations to describe the relationships and behaviours of those components. (Rosen 2012).

The key characteristics of models are their *representational* and functional capacities. Models are not intended to be *complete* replications of real world, instead they are designed to capture and simplify the complexity of the real-world systems, emphasizing the key factors, relevant to the research focus.

Winsberg highlights that models are inherently "*selective representations*" rather than exhaustive mirrors of the real-world systems. The process of modelling is guided by a series of the deliberate choices — "representational decisions" — defining, which aspects of the system to include and how to depict them (Winsberg and Harvard 2024). A model is also considered *adequate* if it is *useful* to its user. This is analogous to the creation of metro maps, as they don't represent every detail of reality, but rather highlight only the essential routes and the stops, while omitting the other details of the urban environment and underground metro-line structure, thereby helping the users to navigate a specific aspect of the world. In the same way, the models focus on particular aspects of modelled system and are judged by their utility in providing the insight or aiding the decision taking within a defined scope. Similarly, models are structured to emphasize the specific features, based on their intended purpose, reflecting the subjective though the important choices of the modeller in determining how to best represent the system under the study.

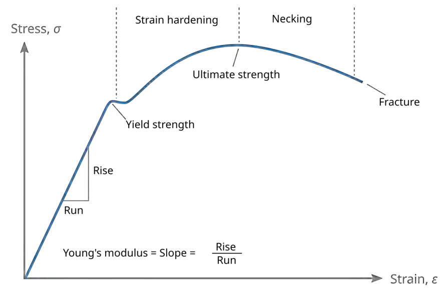
In this thesis, the system under study is knit, a material manufacturing technique, that presents large potential for surface differentiation in order to achieve various spatial effects of the membrane made with knit.

3.1.2 CLASSIFICATION OF MODELS

Models are omnipresent and diverse, appearing in a wide range of contexts and applications. The classification of models provided below offers a useful framework for understanding the various forms and representations that models can take. This framework is essential for appreciating the intricate relationships between model types, their domains of application, and, consequently, their epistemological roles, which is following afterwards. Moreover, the provided framework facilitates the identification of specific model types, ultimately leading to the definition of simulation as a distinct category of models.

Given the various classification schemes available (Winsberg and Harvard 2024; Varenne 2018; Frigg and Hartmann 2021), this section focuses on selection of few that are most relevant to this research. Additionally, the chosen classification help to position the models developed and employed in this thesis within a broader framework of model categorisation.

THEORETICAL MODELS



F 3.2: Stress–strain curve typical of a low-carbon steel.

Theoretical models are abstract frameworks based on mathematical principles and assumptions that describe system behavior. They produce fixed analytical predictions and rely on users to interpret behavior, as they do not inherently simulate dynamics (Downes 1992; Winsberg 2010; Varenne 2018; Winsberg and Harvard 2024). In material science, they predict properties under idealized conditions, such as stress-strain relationships **F**3.2 or thermal conductivity, and provide a foundation for hypothesis formulation and experimental design. For example, Young's modulus, derived from elasticity theory, predicts material deformation under load and serves as a reference for validating experiments or simulations. Theoretical models thus offer simplified yet universal representations of complex phenomena, enabling analytical reasoning and guiding the development of simulation-based approaches. Conceptual models, used in design, may also adopt theoretical characteristics when they abstractly define relationships and constraints to explore how material and form interact, offering frameworks for structured reasoning within creative processes. Thus, theoretical models function as critical tools in the application domain by offering universal, simplified representations of complex phenomena, supporting both analytical reasoning and the development of more detailed simulation-based models.

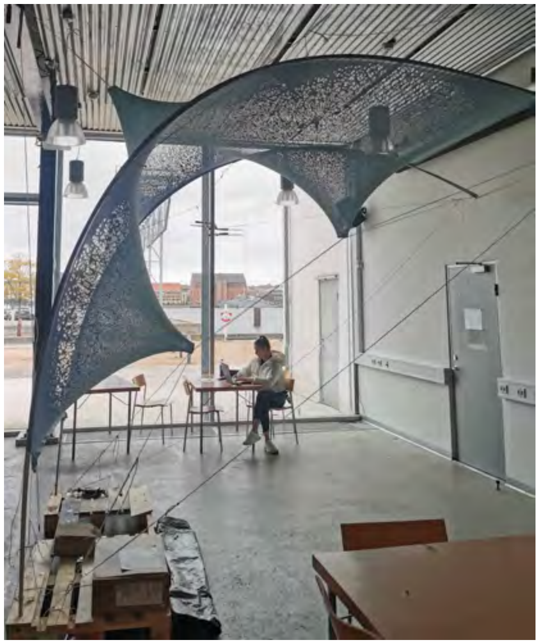
PHYSICAL MODELS


F 3.3: Physical model made of lycra fabric for exploration of membrane novel topologies with compression elements. Pre-studies for Isoropia project at CITA. *Sinke 2017*

In contrast, *concrete* models often take the form of physical objects that naturally exhibit behavior similar to their target system through their inherent materiality and intrinsic dynamics. These concrete models can be categorized into analogical and scaled models. Analogical models are typically found and employed as analogies to represent the target system, while scaled models are deliberately constructed to replicate specific aspects of the target system at a smaller or larger scale (Winsberg and Harvard 2024).

As discussed earlier in the State of Art, physical modelling has been instrumental in understanding material behavior and the structural forms of tensile membrane structures. Analogical models, such as soap bubbles or nets, are frequently used in physical modelling to explore minimal surface structures in structural engineering and architecture. These materials naturally minimize surface tension, leading to equilibrium configurations that align with the principles of minimal energy states required for structural optimization. The analogous physical modelling practices emphasise a direct interaction with material properties, serving as an early form of *simulation*, where the experimentation and observation drove the design decisions. These practices can be understood as an exploration of "computable functions" in a physical realm (Kotnik 2010).

A scaled mock-up, constructed using materials similar to the target architectural structure, exemplifies a deliberately constructed concrete model. Such scaled models enable engineers and architects to analyze stress distribution and deformation under load conditions, mimicking the behavior of the full-scale structure. The physical response of the scaled model reflects the characteristics of the actual structure due to the proportional similarity in material properties and structural design. In architectural applications, these mock-ups are often built at a 1:1 scale, referred to as prototypes, which provide critical insights into material performance, assembly, and design feasibility.

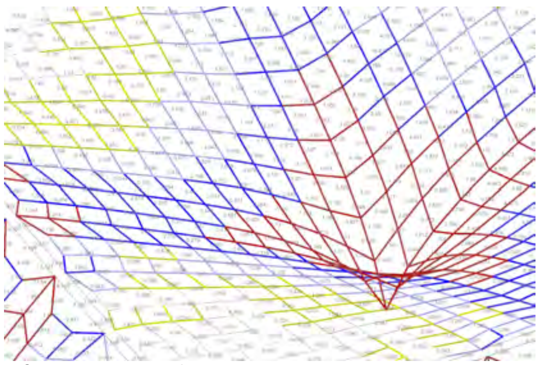


F 3.4: Prototyping at scale: Tensile membrane unit for the Zoirotia project at CITA, demonstrating advancements in the Fabrication Model. *Photo Seskas 2021*

This thesis employs both analogical and scaled concrete models. For design exploration, scaled-down physical models made from lycra fabrics are used to simulate the behavior of tensile systems. Additionally, 1:1 knitted prototypes, fabricated using digital CNC machines, are developed to integrate the features and properties of the final architectural elements. These full-scale prototypes not only validate the design intent but also provide a tangible means of testing the material performance, structural behavior, and assembly processes of tensile knitted membranes. The dual use of analogical and scaled models thus underscores their versatility in bridging conceptual design and real-world implementation.

DATA, DIGITAL, COMPUTATIONAL, SIMULATION MODELS AND FORM-FINDING

The data models, on the other hand, are essentially summaries of information collected from various sources. Their purpose is to condense and organize this information into a structured form, often stored in spreadsheets or databases for statistical analysis (Parker and Winsberg 2018; Winsberg and Harvard 2024). The information in data models can be represented in a wide range of formats; however, the numerical representation facilitates data manipulation, sorting, and analysis. An example of a data model could be a list of axial stress values experienced by a structure across its elements.



F 3.5: Data model of axial stress values in each mesh member, during structural analysis within Design Model of this thesis *Sinke 2022*

The mathematical models aim to integrate mathematical relationships that describe the world and apply them to the target modelled system. These models exist in symbolic form as mathematical equations, either to explain abstract laws or to be implemented in software for numerical solutions. Within this context, computational models are often considered a subset of mathematical models. They come into play when the complexity of the mathematics—such as analytically intractable differential equations—prevents solutions through traditional methods. These models rely on computation to simulate behaviours or make predictions (Winsberg 2010). For instance, finite element analysis (FEA) is a computational model used in engineering to predict how materials behave under mechanical loads. Computational models often compare their results to data models to assess whether the simulation outputs align with existing empirical knowledge or adhere to recognized standards.

From the perspective of a model's dynamism, models can be classified as static or dynamic. Static models represent a single moment in time, while dynamic models capture how a system evolves. This distinction introduces the concept of simulation, which is the process of using a model to run experiments by manipulating variables and observing the system's behavior over time. Unlike static representations, simulations dynamically engage with the model, enabling scientists to test hypotheses and predict how systems will respond to various inputs and conditions (Winsberg 2010). This dynamic process relies heavily on computational power, especially for complex systems too intricate to solve analytically, thus defining simulations as dynamic computational models.

$$F = \frac{E \cdot A}{L} \cdot x$$

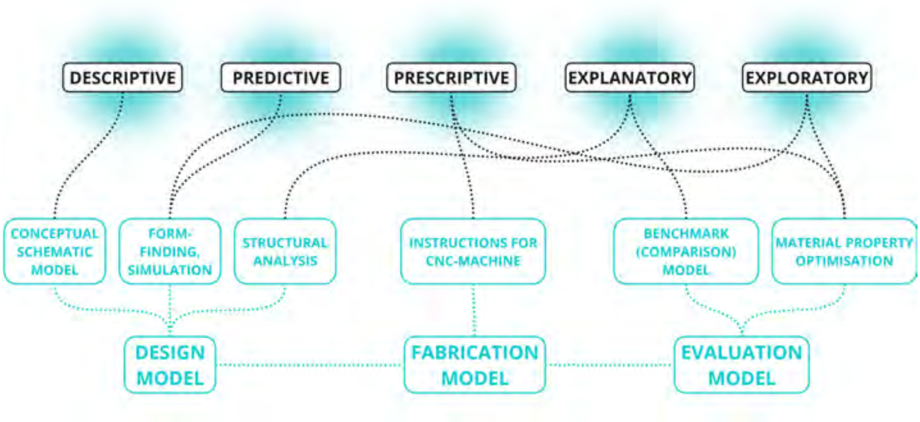
F 3.6: Axial force equation, where F is the axial force [N], E - Young Modulus [MPa], A is the cross-section area [mm2], L is the current length [m and x is the extension [m]. This equation is behind the K2Engineering component of BarOutput, used to calculate the stress anf force distribution in the form-found digital mesh

To compare, while theoretical models tend to be more abstract and produce fixed analytical predictions without the need for computational experimentation, computational models focus on creating programmatic representations of systems. These are designed to run dynamically, enabling the real-time manipulation of variables and the observation of outcomes. This often occurs through iterative processes and numerical approximations. With the advent of computers, models also became digital, created in silico (Vallverdu 2014). This development has led to the visualization of computational models in digital software, such as FEA models in Sofistik, used by engineers, or parametric models in Grasshopper, employed by architects.

The term digital model refers specifically to models represented and processed in digital form, meaning they are built, stored, and manipulated using digital computer technology. A digital model can be computational, but it also encompasses any digitally constructed or stored representation. It is important to emphasize that, while all computational models used today are digital, not all digital models are computational in the sense of running simulations.

It is important to clarify the distinction between the terms *simulation* and *form-finding*, as both are integral to engineering and spatial design and will frequently appear throughout this thesis. **Form-finding** is a *generative* process used to determine optimal shapes for structures based on material and force interactions. It does not begin with a predefined shape but instead *discovers* a geometry that emerges through equilibrium conditions and constraints. **Simulation**, by contrast, is an *analytical* tool used to study and predict the behavior of a system under specific conditions. It involves modelling known properties and inputs to examine how a material or structure responds to external forces.

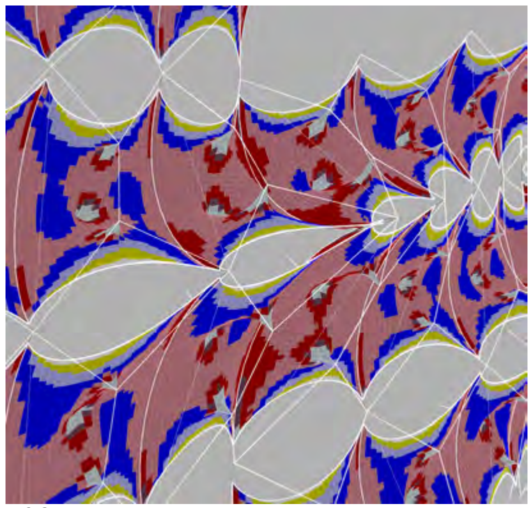
TYPES AND ROLES OF MODELS IN THIS THESIS



F 3.7: Different types of models in this thesis. *Sinke 2024*

At the core of this PhD project, simulation serves as a critical *mediation tool* between the design and fabrication processes, with a particular focus on the material system of differentiated CNC-knitted membranes. This involves the creation of various digital models that reflect and support these processes. These models, primarily computational and simulation-based, have distinct roles and are structured differently to fulfill their purposes. From the perspective of a simulation model's purpose, various types can be identified, including *descriptive*, *predictive*, *prescriptive*, *explanatory*, and *exploratory* models. This classification aids in navigating the potential functions of models and guides decisions in their construction and application.

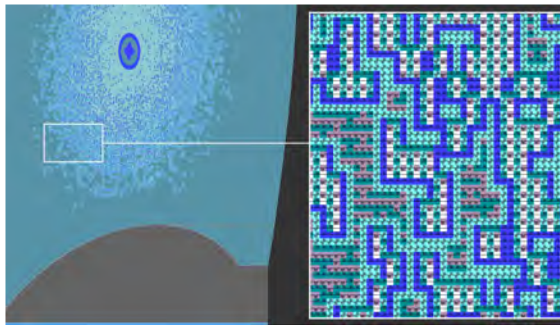
Descriptive models aim to replicate and describe a system's existing behavior without forecasting future states or outcomes. Simulation in general at its heart a descriptive modelling technique (Rossetti 2015). These models are focused on capturing and representing the current or past behavior or status of a system. For instance, in the context of this thesis, the conceptual model within the *Design* Model in this thesis capture the initial design intent through schematic diagram, in order to describe the structural and material system before the dynamic form-finding. Additionally, a simulation replicating the stress distribution in a physical tensile membrane under specific load conditions, without suggesting future changes, serves as a descriptive model as well. The *Evaluation* Model of this thesis operates descriptively when comparing the digitally simulated and physical behaviours of CNC-knitted membranes to validate the accuracy of predictions.



F 3.8: Explanatory-descriptive model, showing axial stress distribution in membrane. *Sinke 2023*

Predictive models are designed to forecast future states or outcomes of a system based on input data or defined conditions (Vallverdu 2014). These models are particularly useful for anticipating how a system will respond to changes or external forces. For example, in *Design* Model of this thesis, integrated form-finding simulations predict how differentiated knitted membranes will deform or behave under specific environmental loads, guiding material differentiation decisions during the design process.

Prescriptive models go beyond prediction by recommending optimal solutions to achieve specific objectives (Roy and Oberkampf 2010). These models are often associated with optimization tasks, suggesting the best course of action while considering system constraints. In manufacturing, prescriptive models play a critical role by generating machine-readable instructions for digital rapid prototyping. For instance, a prescriptive simulation might recommend specific adjustments to the density, and thereby arrangement of stitches in CNC-knitted membrane patterns to optimize material efficiency and tensile strength **F**3.9. The *Fabrication* Model in this thesis integrates prescriptive elements when translating simulation outputs into instructions for industrial knitting machine. These instructions ensure the desired structural or aesthetic properties are achieved while addressing the practical demands of the manufacturing process.



F 3.9: Prescriptive fabrication model outcome - bmp-instructions for the industrial knitting machine. *Sinke 2022*

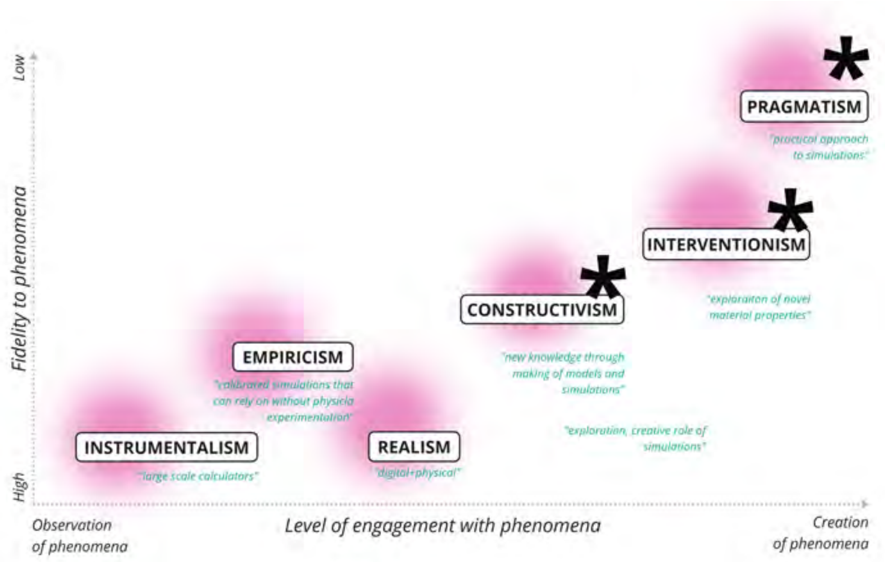
Explanatory models focus on providing insights into why and how certain behaviours or outcomes occur within a system (Vallverdu 2014; Weirich 2011). They aim to reveal the underlying mechanisms driving the observed phenomena. For example, an explanatory model might simulate how local stress concentrations in a knitted structure arise due to variations in material density or knit pattern. This type of simulation can aid in understanding how specific design decisions influence structural performance, bridging the gap between *Design* and *Evaluation* Models.

Exploratory models, on the other hand, are valuable in situations of uncertainty or incomplete knowledge (Kwakkel and Pruyt 2012). These models simulate multiple scenarios, often under varying assumptions, to uncover potential behaviours and outcomes. In this thesis, exploratory simulations play a role in the iterative refinement of *Design* and *Fabrication* Models, allowing for the testing of different material configurations or production parameters to explore their effects on the final architectural element. Within *Evaluation* Model, the exploration occur to find the optimal material stiffness solution.

While these models serve distinct purposes, their functions often overlap. A single model may describe existing behavior, predict future states, offer explanations, or explore various scenarios, depending on the system's complexity and the goals of the analysis. In this thesis, the Design, Fabrication, and Evaluation Models, introduced further in detail in the second half of chapter, demonstrate this *multifunctionality*, acting as mediators between different stages of the digital design processes, where simulations enable iterative refinement and seamless transitions between virtual and physical realms.

3.1.3 EPISTEMOLOGICAL PERSPECTIVES ON SIMULATION

The roles and values of simulations and models vary across disciplines, deeply influenced by their epistemological underpinnings and the specific applications they serve. The preceding classification of models established a foundational frame-



F 3.10: Epistemological perspectives on simulation role in inferring knowledge. *Sinke 2024*

work, categorizing models into theoretical, physical, data, digital, computational, and simulation models. These classifications are not merely distinctions in form and application but also inform the understanding of their epistemological roles in different domains. In the philosophy of science, the roles and values of simulation and model-making have been shaped by several key perspectives: instrumentalism, empiricism, realism, and constructivism, interventionism, pragmatism **F**3.10. This section explores these perspectives—rooted in the philosophy of science—and examines how they interpret the knowledge-generating potential of simulations within the broader contexts of science, engineering, and design. These perspectives provide distinct insights into how simulations contribute to knowledge, interwoven with the previously presented model classifications and the disciplines in which they are employed, demonstrating their intricate relationships.

The introduced epistemological perspectives offer a unique lens through which the role of simulations in science, engineering, and design can be understood. By linking these perspectives with specific model types, this discussion underscores the dynamic interplay between theoretical constructs, computational processes, and physical artefacts. This nuanced understanding not only highlights the varied roles simulations play across disciplines but also informs the methodological approach of this thesis. Here, simulations and computational tools are employed not only for their instrumental computational capabilities, such as solving equations or validating material behavior but also as exploratory tools. These tools facilitate the discovery of novel material gradings for differentiated CNC-knitted membranes, pushing beyond predefined frameworks to enable the systematic investigation of complex material behaviours and their spatial differentiation. This dual role underscores the creative and investigative potential of simulations within the broader context of material design and fabrication.

INSTRUMENTALISM:
SIMULATIONS AS LARGE CALCULATORS

From an *instrumentalist* perspective, simulations are primarily viewed as tools for solving complex computational problems within predefined frameworks. This perspective aligns closely with theoretical models, which often rely on abstract mathematical formulations to predict behavior. In fields like engineering, where computational models—such as finite element analysis (FEA)—are used to simulate stress distributions, the instrumentalist view emphasizes the utilitarian role of simulations as "large-scale calculators." They extend mathematical techniques but are not seen as generating new theoretical insights (Humphreys 2009; Winsberg 2010).

EMPIRICISM:
SIMULATIONS AS PROXIES FOR PHYSICAL EXPERIMENTS

The *empiricists* see the simulations as capable of producing an empirical knowledge, treating them as the *proxies for the physical experiments*. In this view, simulations are akin to laboratory experiments, used to test the theories and predict the behavior of complex systems. By mimicking the real-world phenomena, simulations allow the researchers to experiment on these systems in a controlled, computational environment. This perspective is particularly valuable in cases where the direct physical experimentation is difficult or impossible, such as in meteorology or planetary sciences. The simulations in this perspective, therefore, are seen as stand-ins for the real-world systems, facilitating the study of behaviours that are otherwise inaccessible (Boge 2019; Parker 2008; Cartwright 1983; Symons and Alvarado 2019). In case of engineering domain, the calibrated FEA model permit to predic the structural behavior of the modelled structure, withouht necessitating to build it prior to that. But this only works if the simulation is reliable, calibrated, which closely relate to realism approach .

REALISM:
SIMULATIONS AS CREDIBLE REPRESENTATIONS OF REALITY

Realists advocate for the interpretation of simulations as reliable representations of reality, contingent on rigorous validation processes. This perspective finds strong relevance in computational and simulation models used in science and design, where empirical data integration is critical. This philosophy laid the groundwork for modern scientific methodology, placing a strong emphasis on *observation*, *experimentation*, and *scepticism* in the pursuit of knowledge (Tolk et al. 2023; Brown 1994; Winsberg 2010; Winsberg 2013; Vallverdu 2014; Esfeld and Lam 2010). Here, the realists perspective aligns closely with the experimental nature of creative activities in the design practice, where the digital simulations are often validated and refined through the physical prototyping and the material testing. This iterative process not only strengthens the reliability of simulation results, but also bridges the gap between the abstract digital models and the tangible real-world outcomes, thereby supporting the view that simulations can serve as credible representations of the material behavior in design exploration.

CONSTRUCTIVISM: SIMULATIONS AS CREATIVE AND EXPLORATORY TOOLS

The constructivist perspective highlights the *creative* and *exploratory* potential of simulations, viewing them as tools for generating new knowledge rather than merely representing existing phenomena. Unlike in science, where simulations often serve as virtual experiments to study pre-existing, independent phenomena defined by general laws and theories, in design, the very notion of phenomena is reinterpreted. In scientific contexts, phenomena are systematically explained and predicted through deductive reasoning based on established principles (Valsiner 2019). However, in design, phenomena are not static or pre-defined entities waiting to be uncovered but emerge dynamically through iterative acts of making, experimentation, and interaction with materials, forms, and fabrication techniques.

This shift toward inductive reasoning underscores the experimental and contextual nature of knowledge in design, where material behavior becomes a phenomenon in its own right, actively shaping design decisions. Simulations in design, therefore, are not limited to validating or representing known behaviours but play a important role in material exploration and creative synthesis, transforming abstract concepts into tangible artefacts (Kotnik 2011). Through the iterative feedback loop between model-making—both physical and digital—simulations enable designers to test hypotheses, explore scenarios, and uncover novel material gradings or forms.

Simulations permit to explore the scenarios that may not be directly accessible or observable through the physical experimentation. From this viewpoint, simulations are not merely the computational tools, but are actively involved in the *construction of knowledge* through an iterative development and the manipulation of models and their variables. As a result, the focus is less on the simulation's correspondence to an existing reality and more on its capacity to reveal the new patterns and relationships through the systematic exploration and testing of simulations (Winsberg 2010; Barberousse and Vorms 2013). This perspective sees the simulations as occupying a distinct methodological space that combines the elements of both theory and experimentation. They are not purely the theoretical constructs, nor do they serve as the traditional experiments; rather, they function as a hybrid activity that bridges these two modes of inquiry together (Rohrlich 1989; Odenbaugh 2011). This aligns with the generative aspects of digital and computational models, particularly in computational design. By manipulating variables and exploring emergent behaviours, simulations facilitate the discovery of novel patterns and relationships. For example, parametric models in Grasshopper enable architects to iteratively explore complex forms and material behaviours, embodying the constructivist approach to knowledge construction.

3.1.4 SIMULATION'S ROLE IN MEDIATION BETWEEN DESIGN & FABRICATION

This thesis addresses three interrelated challenges central to its modelling approach: discovering material differentiation, translating design into machine instructions, and calibrating form-finding processes under material uncertainties. Each challenge demands a nuanced integration of simulations and modelling techniques to bridge the gap between theoretical constructs and practical applications. Underpinning this approach is an epistemological framework that builds upon constructivist, interventionist, and pragmatist views of simulation. The following subsections explore how these epistemological perspectives inform the way simulations are leveraged to address the three core challenges, shaping the methodology that underpins this research.

PHILOSOPHY ON SIMULATION'S ROLE IN MATERIAL DIFFERENTIATION: INTERVENTIONISM

In the philosophy of simulation, the problem of material differentiation is linked to the discussions on how the simulations interact with the physical properties and inform material behavior. The critical question revolves around the epistemic role of simulations in *shaping the material characteristics*: are the simulations simply the *representations* of the material properties, or do they actively *define* and *manipulate* them? A relevant framework for this discussion is provided by the constructivist and **interventionist** perspectives. The constructivists, as outlined earlier, argue that the simulations are not just the predictive or representative tools, they rather actively participate in constructing of knowledge about a system (Alvarado 2020). Interventionists expand on this, by considering that simulations acts as agents of causation, where the changes to input parameters, such as the material properties or boundary conditions, directly lead to the different material behaviours or configurations (Alvarado 2023). This perspective views the simulations as tools for understanding the causal relationships, examining how the manipulation of one part of a system alters the outcome (Woodward 2004). Within this framework, the simulation explores counterfactual scenarios — the situations that did not occur but could have occurred — allowing the variables to be adjusted to observe their impact on the system as a whole.

PHILOSOPHY ON DESIGN AND FABRICATION MODEL'S INCOMPATIBILITY

From the constructivists perspective, Winsberg notes that the simulations often involve directly incompatible models, when they are built for the specific purposes, leading to the tensions in integrating the results across different contexts (Winsberg 2010). This is particularly relevant in design related domain where the conceptual and fabrication models are represented and function differently. However, this does not diminish the value of these models; rather, it highlights the complex nature of capturing the real-world phenomena through the multiple, purpose-built approaches that may initially appear conflicting. Morrison argues that these inconsistencies are fundamental for representing the complex systems. Different models can yield conflicting yet complementary insights, each reflecting a different facet of a multifaceted reality (Morisson 2015).

In this thesis, design and fabrication processes are contained within the corresponding distinct models, where the simulation and computational tools bond these distinct models and translate the format and representation deviations through algorithms that ensure the smooth flow of data.

PHILOSOPHY ON SIMULATION PRECISION AND PRAGMATIC APPROACH IN SIMULATIONS

The interconnectivity of the models in the complex simulations, as well as the complexity of the modelled phenomena often results in certain parameters that are difficult to fully comprehend, leading to the issue of models accuracy and precision. Addressing these issues involves the managing of *uncertainty*. Winsberg emphasizes that balancing of approximations appropriately allows the simulations to succeed in providing the adequate results for the specific purposes, even if the underlying model is not universally perfect (Winsberg 2010). Grim, similarly, points out that the simulations must strike a balance between the similarity and the distortion in their correspondence with the real-world phenomena (Grim et al. 2013). Success lies in approximating the reality without oversimplification or overcomplication, through the approach of tailoring the models in order to manage the uncertainty, while maintaining coherence across interconnected models.

Philosophically, this balancing act aligns with the *pragmatic* views on simulations, which is an addition to the list of epistemic perspectives on simulations, presented earlier in section 3.1.3. The pragmatic approach focuses on the outcomes, the exploration, and the flexibility of the models. The pragmatic simulations are not intended to be the perfect or universally applicable solutions, but are viewed as the problem-solving tools, designed for the specific and practical purposes (Brister 2023). Their value lies in their actionability — guiding the decisions under the uncertainty rather than producing absolute truths. In this context, simulations serve as *provisional tools* that enhance the practical value of material-driven research.

In this thesis, the question of accuracy and tolerance in simulation and computational models is highly relevant. The flexible nature of knitted materials, with their stiffness properties being highly anisotropic and dynamic, introduces certain tolerances and approximations in digital modelling. This thesis seeks to navigate these challenges to determine what level of deviation is acceptable for reliable and meaningful results.

FROM EPISTEMOLOGY TO METHODOLOGY

The epistemological perspectives introduced above provide a unique lens for understanding the role of simulations in science, engineering, and design. By linking these perspectives to specific model types, this discussion highlights the dynamic interplay between theoretical constructs, computational processes, and physical artefacts. This understanding not only reveals the diverse roles simulations play across disciplines but also shapes the methodological approach of this thesis.

Simulations and computational tools are employed here not only for their instrumental capabilities—such as solving equations or validating material behavior—but also as exploratory tools. These tools enable the discovery of novel material gradings for differentiated CNC-knitted membranes, pushing beyond predefined frameworks to systematically investigate complex material behaviours and their spatial differentiation. This dual role emphasizes the creative and investigative potential of simulations within the broader context of material design and fabrication, laying the groundwork for a discussion on research methodologies across scientific and creative disciplines in the following section.

3.2 RESEARCH METHODS IN SCIENCE, ENGINEERING AND DESIGN

Building on the discussion of epistemological perspectives in using modelling and simulation practices, used diversely in various professional disciplines, it is important address their *exact methodological approaches* in order to extract the relevant practices for this Phd research. The section outlines two methodological approaches—Research-by-Simulation (RbS) and Research-by-Design (RbD)—as complementary instruments for integrating simulation, design, and physical experimentation. The RbS method is presented from the lens of ground framework developed in scientific fields, while additionally supported by simulation workflows from world of structural engineering of tensile membranes. The RbD method, on the other hand, is presented from the perspective of importance of design thinking and physical prototyping as the mode of acquiring new knowledge and development of design.

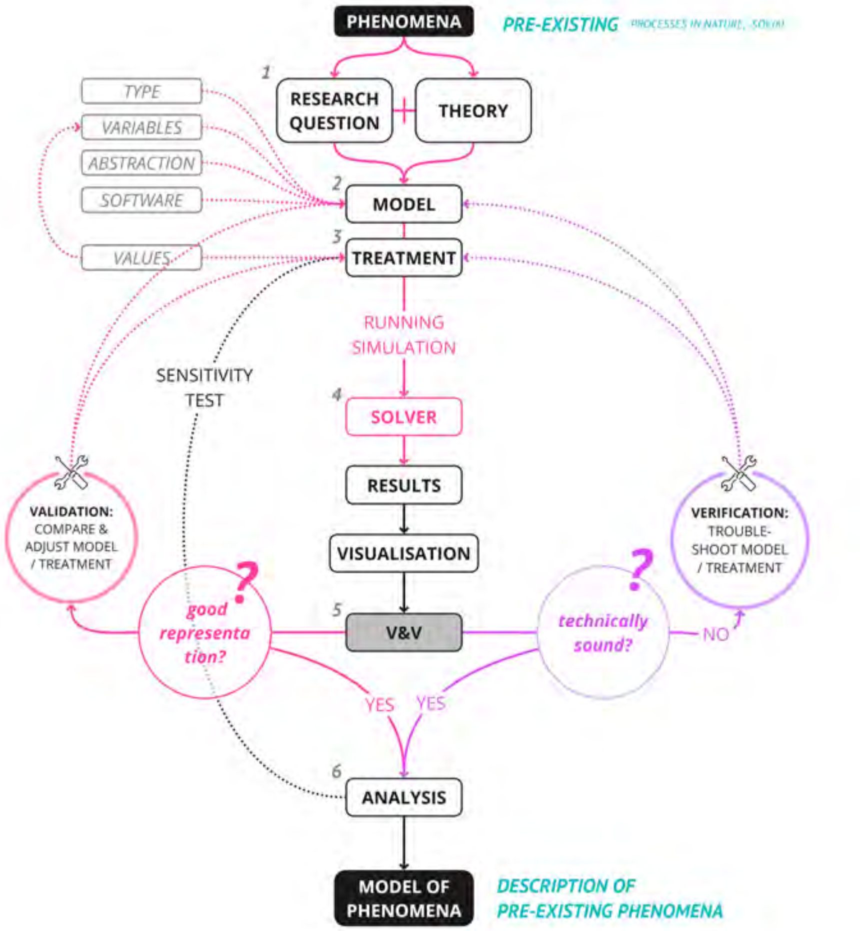
This two methodologies lay a foundation for introduction of a combined methodology, employed in this thesis, which enhance the importance of joining the computational digital design with integrated simulation and the physical prototyping, which informs and refines one another, by establishing a dynamic feedback loop between the digital and tangible realms. There, the synergy between the physical and the digital explorations joins the methodological aspects from the field of simulation (Research-by-Simulation, RbS) and design (Research-by-Design, RbD) into a combined methodology of Research-by-Design&Simulation (RbS+RbD), where the digital modelling, simulation and physical prototyping act as as main modes of research, permitting design exploration, comprehension of knit material system behavior and industrial fabrication constraints posed by the industrial knitting machines, all together leading to creation of the novel textile material system of differentiated knit, tailored for an architectural application.

3.2.1 RESEARCH-BY-SIMULATION (RBS) FROM SCIENTIFIC DOMAIN

Having established and understood the distinct roles of simulations and models in the design and science, it is important to explore the exact *methods* used to construct the digital simulations. This section first explores the method of simulation construction as understood in the scientific domain, following a structured approach of translating the phenomena into theory and subsequently into models for generating the simulations, and how these yield the extraction of new meaningful knowledge.

There the focus will shift to how these methods can be adapted and expanded within the design field, leading to the foundation for methodological discussion around the physical prototyping, unfolded in the subsequent section, representing Research-by-Design methodology.

In scientific domains, simulations and computational models serve as primary tools for investigating, analyzing, and predicting the behavior of complex systems or phenomena, thereby facilitating the generation of new knowledge. This underpins the definition of the **Research-by-Simulation (RbS)** methodology, which is commonly employed in fields such as computer science, physics, biology, medicine, materials science, and social sciences. Within these disciplines, researchers develop simulation models to replicate real-world conditions, enabling the exploration of scenarios that may be impractical, costly, or impossible to study through traditional experimental methods. The RbS methodology involves defining the processes through which digital models and simulations are constructed, validated and applied in order to meet its initial predictive purposes. This methodology integrate the theoretical foundations, model development stages, simulation execution, and validation against the empirical or experimental outcomes (Winsberg 2010; Arnold 2019; Juan M. Durán 2020). By iteratively refining these models, simulations provide



F 3.11: Research-by-Simulation Methodology from scientific domain, focusing on simulation of pre-existing phenomena. *Sinke 2024*, based on literature review.

valuable insights into system behaviours, performance, and outcomes, contributing significantly to research advancements.

This section examines the simulation methodology framework introduced by Winsberg 2010, which has been synthesized from multiple authoritative sources in the field of philosophy and simulation (Lenhard 2007; Frigg and Reiss 2009; Dowling 1999; Parker 2010) While Winsberg provides a foundational structure for understanding the methodological steps of simulation creation, this thesis expands upon his framework by incorporating additional details and refinements. These enhancements are based on insights from other notable works, including Robinson's practical approaches to simulation modelling (Robinson 2004), studies on verification and validation by Sargent 2010; Roache 2009; Rider 2019; Beisbart 2019, and Roy's analysis of scientific computing methodologies (Roy and Oberkampf 2010). By integrating these diverse perspectives, this section provides a comprehensive view of simulation methodology, grounded in Winsberg's theoretical framework and enriched by practical and technical insights from the broader literature, including Vallverdu 2014; Juan Manuel Durán 2018; Juan M. Durán 2020.

The Research-by-Simulation (RbS) methodology is outlined through step-by-step actions and considerations necessary for creating a simulation model. These steps, informed by Yin's Introduction to Modeling and Simulation Techniques (Yin and McKay 2018), expand Winsberg's foundational framework into an instruction-like format through steps (S1-S6). By combining Winsberg's and Yin's terminologies, a unified RbS methodology is presented in **F**3.11, serving as a guide to the key simulation stages presented in this section. Presented workflow is moving from *Phenomena*, as something the simulation aims to represent, towards the *Model of Phenomena* - a complete simulation, representing the original phenomena of interest.

SIMULATION WORKFLOW

S1. RESEARCH QUESTION AND THEORETICAL BASIS

The RbS process starts with a clear research question and theoretical framework (**F**3.11). The research question defines what aspects of a system need modeling, while the theoretical framework provides scientific principles to underpin the model. For instance, physics-based theories may guide representation strategies such as discrete or continuum methods. However, theory informs but does not entirely determine the model, allowing space for abstraction (Winsberg 2010).

S2. MODEL CONSTRUCTION

Model construction involves abstracting the real-world system into a mathematical or computational framework. Key considerations include:

- **Model Type:** The type —conceptual, mathematical, computational, or physical—shapes representation methods and focuses on precision or dynamic behavior based on the model's purpose.
- **Variables:** Variables represent system characteristics or elements (e.g., temperature, force, length of mesh spring etc.) and allow adjustments to study the resultant effects onto the system.
- **Abstraction:** Simplifying complex systems focuses on relevant aspects, balancing resolution with computational constraints (Morrison and Morgan 1999). Winsberg highlights *physical intuition* as a heuristic tool for determining essential model features (Winsberg 2010).
- **Tools and Software:** Selecting compatible tools bridges conceptual and computational aspects, ensuring technical requirements and user expertise align with the model's objectives.

S3. MODEL'S SPECIFICATION: THE TREATMENT

Model specification, or "Treatment", refines the model by assigning *values* to *variables*, defining conditions, material properties, and external forces, guided by theoretical or empirical data (Winsberg 2010). These parameters determine the model's structure and behavior, ensuring its ability to replicate real-world phenomena. Effective parameter selection ensures alignment with the model's purpose. For example, stiffness and force distribution influence deformation in structural simulations, while viscosity and flow rates are vital for fluid dynamics. Poor parameter choices can lead to deviations from expected behavior (Roy and Oberkampf 2010). The Treatment phase transforms an abstract model into a functional tool, capable of delivering accurate predictions and insights into real-world phenomena (Rider 2019).

S4. RUNNING THE MODEL: THE SOLVER

With the model and parameters in place, the Solver executes the simulation to analyze the system's behavior. The Solver resolves equations and generates results, often as large datasets. Visualization transforms data into accessible forms, enabling interpretation. Winsberg describes this as creating a "Model of Phenomena", which refines understanding of the modelled system and guides further simulations iterations (Winsberg 2010).

S5. VERIFICATION AND VALIDATION (V&V)

In Winsberg's framework, the *verification* and the *validation* (V&V) are two critical activities in evaluating the simulation model's functionality and accuracy.

VERIFICATION is defined by Roy and Oberkampf 2010 as the *"the process of determining, whether or not the output of the simulation approximates the true solutions to the differential equations of the original model, questioning whether the model is technically correct"*. Verification ensures the simulation outputs align with the model's equations, confirming technical correctness through systematic troubleshooting. The troubleshooting involves identifying, diagnosing, and resolving issues that occur during the development and execution of the simulation model. These issues can range from the software bugs and the numerical instabilities to the convergence problems, incorrect parameter settings, the misuse of data structures, and the faulty visualizations. Troubleshooting acts as a crucial "debugging" phase (Roy and Oberkampf 2010), ensuring internal consistency and trust in the model's behavior (Roache 2009).

Troubleshooting follows a systematic sequence. It starts by identifying the problem, such as unrealistic outputs, crashes, or anomalous behavior. Experience and physical intuition are crucial at this stage. The next step is to diagnose the cause, investigating issues like incorrect parameters, boundary conditions, numerical instabilities, or coding errors. After diagnosis, the issue is isolated by testing individual components or simplifying the model to pinpoint the malfunction. Once identified, the error is corrected by adjusting parameters, refining algorithms, improving mesh quality, or optimizing code. Finally, the model is re-tested to ensure the solution works and no new issues arise. This process establishes internal consistency, building trust in the model before validation and further analysis.

VALIDATION is defined by Roy and Oberkampf 2010 as *"the process of determining, whether or not the chosen model is a good enough representation of the real-world system for the purpose of the simulation, questioning how precise is the model"*. Validation in simulation ensures the model accurately represents real-world phenomena by comparing outcomes to empirical data, experimental results, or theoretical predictions. This step verifies that appropriate equations and parameters replicate the system's behavior reliably, critical for decision-making or predictive applications. Common techniques include benchmarking, testing models against known cases, and calibration, fine-tuning parameters to align with observed data. A validated model builds confidence for further analysis and informed decision-making. (Roy and Oberkampf 2010).

Despite their theoretical distinction, verification and validation often work in tandem. Verification focuses on the technical correctness of the simulation, ensuring that outputs align with the mathematical foundations of the model. Validation, on the other hand, assesses the precision of the model in representing real-world systems. Together, they converge in practice, blending theoretical rigor, empirical data, mathematical precision, and physical intuition to enhance the simulation's fidelity and reliability (Winsberg 2010). This interplay ensures the effectiveness of simulations throughout their development and application.

S6. INTERPRETATION AND ANALYSIS: EXTRACTING THE INSIGHTS FROM THE SIMULATION

The final phase of the simulation focuses on extracting and interpreting data from verified and validated models. This step ensures findings align with simulation objectives and generates computational representations of real-world behaviours, often called "models of phenomena" (Winsberg 2010). Data interpretation involves identifying patterns, trends, and relationships, often requiring advanced visualization techniques to clarify complex outputs like stress distributions or time-series data (Roy and Oberkampf 2010). Sensitivity analysis further examines how input variations impact outcomes, revealing influential factors and refining understanding. This process solidifies confidence in the model's robustness and its capacity to inform predictions (Sargent 2010).

In summary, the text above highlights the instrumental role of simulation methodologies derived from scientific fields while *questioning their direct applicability to design contexts*. The Research-by-Simulation (RbS) methodology although offers a systematic framework for structuring simulations, prioritizing prediction of behavior of complex systems, accuracy and internal consistency by grounding models in theoretical and empirical foundations, however lacks the explicit directions on integration of fabrication processes — an essential component in design disciplines, particularly within the context of this thesis. The bottom-up approach of scientific RbS often overlooks the iterative interplay between digital simulations and physical production that is central to design practices, that are inherently exploratory, iterative and focusing on material behavior and the *creation of novel objects*. As a result, they require more adaptable approaches to simulation construction that diverge from pure traditional scientific methods of RbS.

3.2.2 RESEARCH-BY-SIMULATION (RBS(F)) FROM ENGINEERING DOMAIN

In contrast, the structural engineering domain, situated between science and design, engage with artificial created things (Simon 1988) and therefore incorporates simulation workflows, addressing address structural behavior and fabrication constraints. This methodology is located within the RbS framework, however is abbreviated in this text as RbS*(f)*, linking its relation to *fabrication* of things. For instance, **form-finding** methodology detailed by Knippers et al. (2011) exemplifies the hybrid approach of joining simulation and manufacturing. This methodology integrates material properties, structural analysis, and fabrication considerations within an iterative workflow, where digital simulations and physical processes inform one another. Such methods demonstrate the potential for bridging the systematic rigor of bottom-up simulation framework of RbS with the top-down requirements of design-driven production. The workflow for designing membrane structures, as outlined by Knippers, integrates both form and structural behavior, emphasizing the interplay between geometry, material properties, and loadbearing efficiency. The process aligns closely with iterative scientific methods but extends into the practical considerations of fabrication and construction. The detailed steps of the method are presented below through the sequence of steps (S), while graphically reflected in **F**3.12.The diagram is redrawn exactly from the original drawing from book *"Construction Manual for Polymers + Membranes"*, where the numbering of steps and the description of steps is synthesized by this thesis author understanding of the process described in the book.

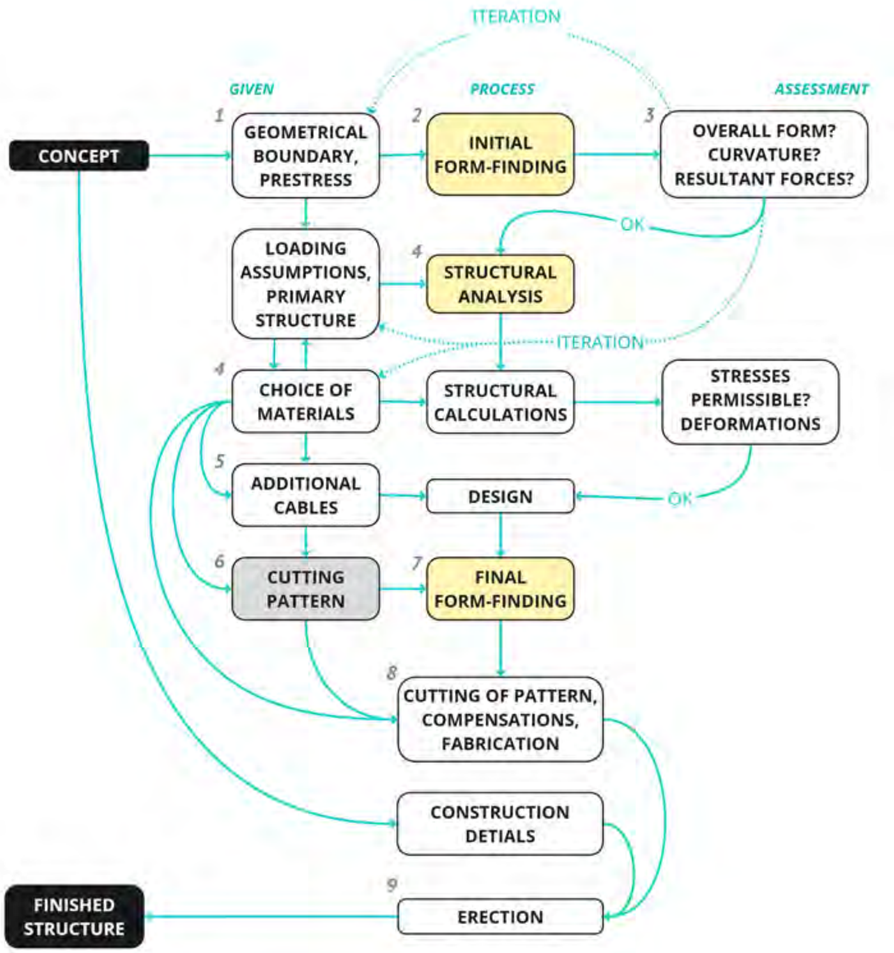
FORM-FINDING WORKFLOW FOR MEMBRANES

S1: BOUNDARY CONDITIONS AND INITIAL GEOMETRY The *first* step involves defining the boundary conditions, including the placement of fixed points, perimeter edges, and preliminary geometric constraints for the membrane. This phase establishes the spatial framework within which the membrane operates, ensuring compatibility with intended load paths and material behavior. Additionally, this step ensures unobstructed flow beneath the structure, addressing functional and spatial considerations.

S2: INITIAL FORM-FINDING The *second* step focuses on initial form-finding, where numerical and experimental methods such as finite element analysis, force density techniques, or dynamic relaxation are applied. These methods determine an equilibrium geometry under prescribed pre-stress conditions. The objective is to achieve a stable state of equilibrium, aligning the membrane's geometry with its boundary constraints, material properties, and anticipated load distributions.

S3: ITERATIVE REFINEMENT OF FORM The *third* step introduces iterative refinement to optimize the equilibrium geometry. Parameters such as prestress distribution, curvature, and support configurations are adjusted to enhance the form's stability and efficiency. Practical considerations are integrated at this stage, including responses to wind, snow, and live loads, ensuring the membrane maintains both structural integrity and serviceability under real-world conditions.

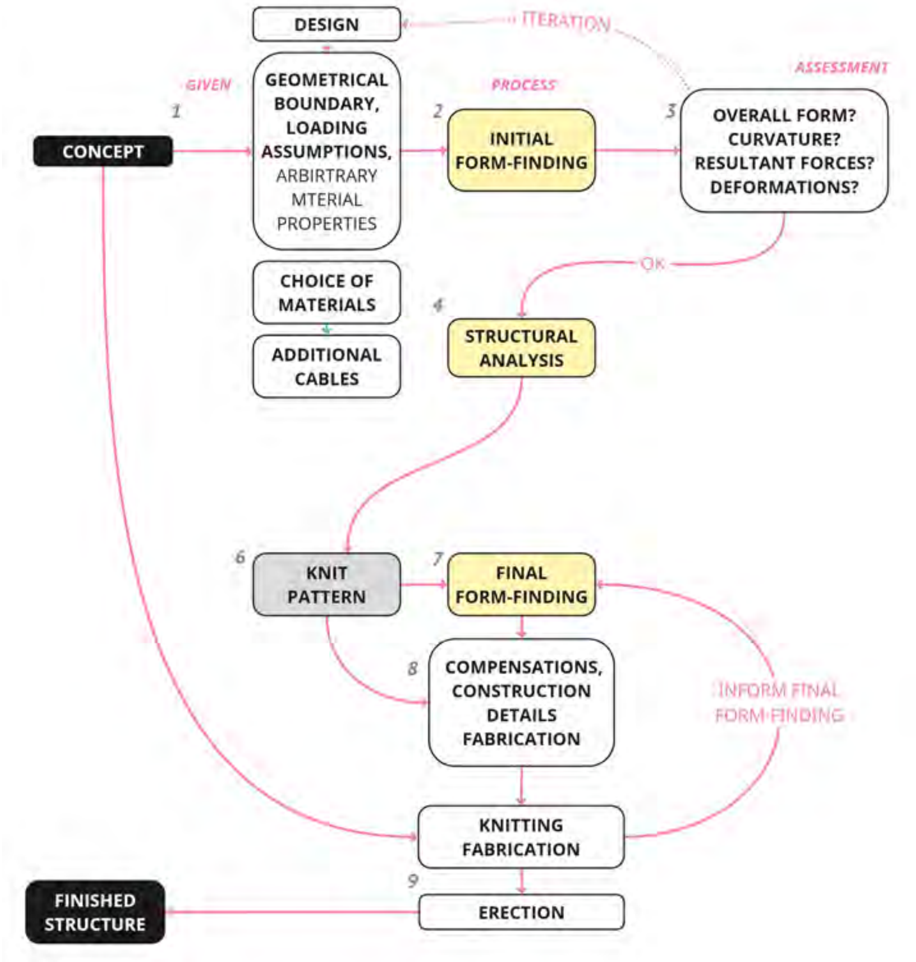
S4: STRUCTURAL ANALYSIS AND MATERIAL SELECTION In the *fourth* step, the refined geometry undergoes detailed structural analysis to validate its loadbearing capacity. Simultaneously, material selection is conducted to ensure tensile strength, elasticity, and durability align with the membrane's operational demands. This process guarantees the membrane can endure environmental stresses without significant deformation or failure.



F 3.12: Iterative form-finding for conventional membrane structures. Sinke 2024 redrawn from *Knippers et al 2011*

S5: INTEGRATION OF RIDGE AND VALLEY CABLES Where additional stiffness or deformation control is required, ridge and valley cables are incorporated into the membrane during the *fifth* step. These elements subdivide the membrane into zones, providing additional support and addressing potential issues such as water pooling or material flutter. This step is particularly crucial for large-span membranes or designs subject to dynamic environmental loads.

S6: CUTTING PATTERN The *sixth* step involves designing the cutting pattern for the three-dimensional surface based on inputs from structural analysis and material selection. This ensures alignment with both structural considerations and the intended aesthetic of the membrane, as seams become visually prominent when illuminated from underneath. The cutting pattern accounts for material stretch, curvature compensation, and seam orientation. Strategic alignment of cutting lines with principal curvatures minimizes distortion and enhances structural performance.



F 3.13: Correlation of form-finding process in this thesis in relation to RbS(f) methodology by *Knippers et al 2011* from structural engineering

S7: FINAL-FORM FINDING The *seventh* step involves final form-finding, which integrates the refined membrane properties, including material selection, cutting pattern orientation, and cable integration. This ensures a cohesive and optimized final design, balancing aesthetic and functional requirements.

S8: FABRICATION AND PRESTRESSING Fabrication begins with translating the cutting patterns into physical components, ensuring precise seam alignment. The three-dimensional membrane patches are planarized into outlines suitable for CNC cutting, which executes the cutting of woven laminated cloth. The patches are then welded or sewn together to create the final membrane.

S9: ERECTION ON SITE The final step involves erecting and tensioning the membrane in situ. During erection, the membrane is prestressed—either mechanically or pneumatically—to achieve its designed curvature and stiffness. This process requires meticulous planning to avoid damage, such as tearing during prestressing, while also considering material relaxation and long-term creep behavior. Detailed plans account for site-specific conditions, including weather, terrain, and accessibility. Incremental adjustments during this phase ensure the membrane attains its intended geometry and stress distribution, culminating in a fully realized structure that meets both design and structural performance objectives.

This structured workflow bridges computational rigor and practical application, emphasizing iterative adjustments to ensure equilibrium, efficiency, and aesthetic coherence of membranes. The methodology serves as a complementary framework to scientific RbS by addressing aspects of fabrication and assembly, which are critical for the integration of simulation into design workflows.

Additionally, structural engineering method for form-finding demonstrate a *dual* nature, encompassing both *bottom-up* and *top-down* approaches of design, highlighted by the State of Art chapter as crucial for design and fabrication of differentiated CNC-knitted membranes. This duality is integral to achieving equilibrium between material-driven behaviours and overarching design goals. The top-down approach in form-finding begin with a pre-defined global intent, such as a geometric target boundary and location of supports, and further refine the material properties or configurations to align with these objectives. Conversely, the bottom-up approaches in form-finding start with the material properties and localized forces, allowing the global form to emerge naturally from these interactions. In practice, these approaches often work in tandem: a designer might envision a pavilion's general shape (top-down) and then iteratively refine it based on local material and force behaviours (bottom-up). These method reveal how design targets and intrinsic material behaviours inform each other, reflecting both bottom-up and top-down perspectives.

This dynamic relationship between bottom-up and top-down strategies is particularly relevant to architectural tensile knits, as they are introduced by this thesis as a special class of membrane materials. However, the inherent properties of knit, such as dynamic behavior of surface rearrangement, as result of heterogeneity of stitches organised into patterns, often dictate its macro-scale behavior, aligning with bottom-up methodologies. Simultaneously, the global design intent, such as a desired shape or performance criteria, guides the configuration of the knit structure, aligning with top-down approaches. This interplay highlights the importance of *form-finding as a method* for simulation within this thesis, particularly its certain aspects of structural analysis initial modelling methods of tensile structures prior to simulation. There, the term *simulation*, however is also used within this thesis to describe the analytical processes as part of form-finding.

In its entirety, this engineering RbS(f) methodology although requires adjustments to work effectively with knitted membranes. Structural engineering methods are tailored primarily for fabrication strategies of cut patterns of woven membranes, where material performance is secondary to geometric considerations. Knitted membranes, by contrast, demand the integration of material performance and detailing as a fundamental part of the design process, preceding fabrication, simultaneously integrating the material properties of surface composition into fabrication instructions. The anisotropic behavior of knits and their ability to adapt material density across a surface necessitate a more integrated approach, where the material configuration is inseparable from the design. The integration of structural analysis earlier in the design process would enhance its effect to knitted membranes. If in structural engineering, analysis typically acts as a post-action on pre-designed forms, validating their performance with the minor changes to the initial design, in the context of knits, embedding of structural analysis into the early design stages would allow for a more seamless interplay between design, material behavior, and performance and fabrication, fostering closer links between the global membrane shape and its local material composition.

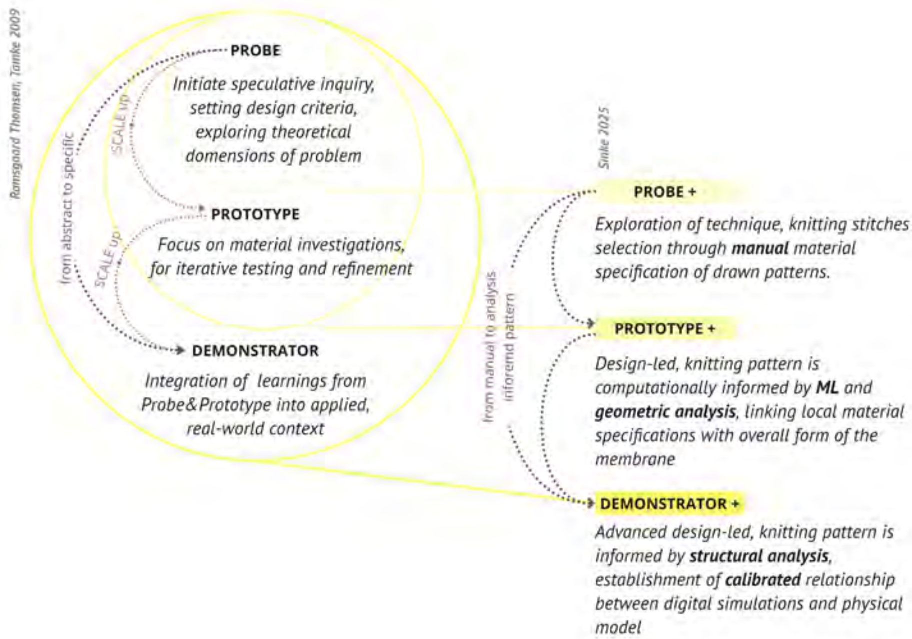
The design flow presented in this thesis demonstrates how digital form-finding can support the development of membrane structures—from conceptualisation to realisation. While conventional workflows, such as those used for tensioned membranes, rely on a form-finding process tailored for cut-pattern generation and largely assume homogeneous material behaviour, this approach is not directly transferable to differentiated CNC-knitted membranes. Instead, the design framework of this thesis adapts the logic of a two-stage form-finding process **F**3.13: the first stage (analogous to step 2 in conventional workflow presented above) estimates topology without considering material properties, guiding initial shape generation and structural analysis. The equivalent of the cutting pattern stage (step 6) is reinterpreted here as a process of differentiating the membrane—"cutting" it into regions of distinct mechanical properties. A second form-finding stage (step 7) then incorporates these differentiated properties to refine the geometry. Unlike stiff woven membranes, which benefit from established material models, knitted membranes present a high degree of anisotropy, non-linear behaviour, and local heterogeneity. This complexity precludes a straightforward predictive approach. The thesis therefore introduces a framework where form-finding and structural analysis guide the discovery of novel patterns for knitted membranes, while simulation of material grading is iteratively tuned against physical prototypes.

The following section introduces the Research-by-Design (RbD) methodology, emphasizing how it complements and extends the insights gained from simulations by grounding them in *physical prototyping* and *hands-on experimentation*.

3.2.3 RESEARCH-BY-DESIGN (RBD) FROM CREATIVE DOMAINS

Within the creative design fields, the **Research by Design (RbD)** is a methodology that emphasizes the design as a primary means of inquiry, where the creation of the physical artefacts serves as both an investigative and the knowledge-generation tool (Frayling 1993; Ramsgaard Thomsen and Tamke 2009). There, through the design processes, supported by physical making the complex phenomenon of material behavior is explored, tested, and understood by creating of *tangible* objects and artefacts, that are essential for generating the insights, as they provide tangible evidence and feedback throughout the design process (Ramsgaard Thomsen and Tamke 2016).

Research by Design (RbD) methodology aligns closely with Donald Schön's idea of *reflection-in-action* (Schoen 1992), a process where practitioners actively engage with and reflect on the situations they encounter, treating them as dynamic and evolving. In the context of RbD, designing and making are not merely technical processes but also forms of inquiry that lead to new knowledge and understanding. There, the practitioner responds to the materials and constraints of the design process, which, in turn, "talks back," presenting new challenges and insights and driving thedesign process forward. Schön emphasizes that in professional design practice, *knowing* emerges from *action*—an embodied, tacit understanding developed through the act of making and reflecting. For example, when a designer tests



F 3.14: RbD methodology, centered around design of physical prototypes. Ramsgaard Thomsen 2009 definiiton of Probes, Prototypes and Demonstrator, supplemented by Sinke 2024 definition as seen in this thesis

a material system or explores the geometry of a tensile structure, they engage in cycles of making, observing, and refining. This process generates insights that could not have been predicted without direct engagement with the artefacts and their behaviours. He underscores the importance of engaging with the "messy, indeterminate zones of practice," which traditional technical rationality often overlooks.

Herbert Simon and Nigel Cross both highlight the foundational principles of RbD methodology such as creativity, synthesis, and problem-solving. Simon characterizes design as "concerned with how things ought to be,"opposing it to the scinetific domain that primarily deal with "how things are", thereby emphasizing the normative nature of creating novel artefacts through goal-directed processes (Simon 1969). Similarly, Nigel Cross underscores the distinctiveness of design thinking, marked by solution-focused approaches rather than analytical problem exploration (Cross 2006). Cross identifies abductive reasoning as central to design—an iterative, hypothesis-driven process that connects functional goals with physical artefacts.

Within the context of tensile textile-based systems of knit, this reflective dialogue becomes particularly critical. The complexity and unpredictability of these systems demand an iterative and responsive methodology where every prototype informs and reshapes the next stage of the investigation. By doing so, RbD transcends traditional boundaries of research, becoming not only a mean to solve design problems but also a mode of generating and validating knowledge within the creative design disciplines.

In the context of this thesis, these ideas underpin the methodological approach, emphasizing that the iterative feedback loops between digital simulations and physical artefacts are not just mechanisms for achieving precision but also opportunities for discovering novel design strategies and material compositions.

PROBE, PROTOTYPE AND DEMONSTRATOR

Unlike the rigorous simulation based methodologies of RbS, RbD is not offering the specific steps or instructions, but rather highlighting the importance of tripartite framework of *Probe, Prototype, and Demonstrator* are key components, introduced by Ramsgaard Thomsen and Tamke 2009, that allow to practically navigate the RbD methodology. In there *Probes* initiate speculative inquiry, setting design criteria and exploring theoretical dimensions of a problem, *Prototypes* focus on material investigations, allowing iterative testing and refinement of artefacts in response to defined criteria, while *Demonstrators* integrate these learnings into applied, real-world contexts, bridging conceptual and practical realms.

Alike Ramsgaard Thomsen and Tamke 2009, these modes are viewed in this thesis as sequential and iterative components, that build up the complexity of architectural investigation. However, within this PhD research, which primarily focuses on discovery of novel material gradings, the definitions of Probe, Prototype and Demonstrator are slightly reintroduced with the focus on strategies for material creation and differentiation. Further down in the chapter they are given a more nuanced definition tailored to the specific challenges and opportunities of knits, informed by the evolution of material differentiation complexity.

COMPUTATIONAL THINKING

The advent and wider accessibility of digital tools to architects has transformed traditional design thinking into computational thinking. In this context, computational design not only integrates parametric modelling and algorithmic processes but also enables seamless interaction between digital simulations and physical prototyping. As noted by Ramsgaard Thomsen and Tamke 2009, this shift bridges the divide between representation and making, as numerically driven fabrication tools like CNC machines and 3D printers translate abstract digital models into precise physical artefacts. This thesis explores these computational advancements within the context of textile knitted systems, which are highly mathematical structures characterized by their complex, anisotropic behavior. These systems demand an understanding that extends beyond physical experimentation, requiring computational tools for precise simulation, analysis, and material composition manipulation. The integration of computation allows for deeper engagement with the material systems of knit, steering its complexity, simultaneously getting better control at it. By fostering iterative experimentation, both digital and physical, that combines creative intuition with algorithmic precision, enriching the overall architectural design process and facilitate their accurate manufacturing on industrial CNC-knitting machines.

3.3 HYBRID METHODOLOGY: RESEARCH-BY-SIMULATION & DESIGN

In this PhD thesis, the complexity of integrating design and manufacturing becomes particularly evident when working with differentiated CNC-knitted membranes, produced through digitally driven processes on industrial knitting machines.

These membranes represent a distinct category within membrane architecture, exhibiting anisotropic material behavior shaped by both localized material differentiation and the global shape of the design. Unlike conventional homogeneous membranes, differentiated CNC-knits possess varied material properties that influence their expansion and overall structural performance. The challenge lies not only in simulating these behaviours but also in aligning them with the constraints and capabilities of the manufacturing process. The integration of material properties and performance into the design process thus poses significant challenges for modelling and simulation but could also unlock new design possibilities (Ramsgaard Thomsen 2020). This thesis seeks to identify a suitable methodological approach to address these challenges.

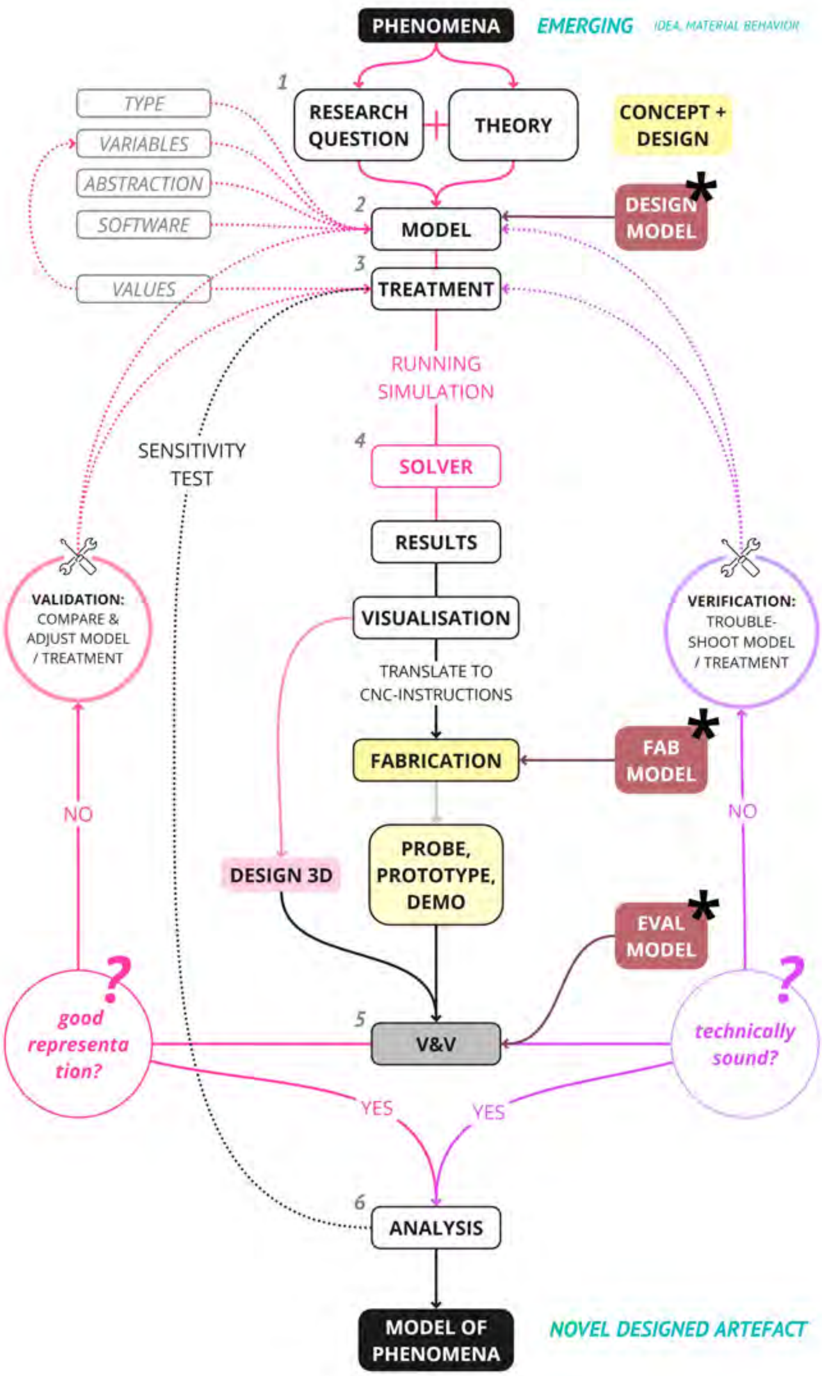
3.3.1 LEVERAGING THE BENEFITS OF BOTH

Leveraging the strengths of both Research-by-Simulation (RbS) and Research-by-Design (RbD) methodologies, this PhD thesis adopts a synthesised methodology: Research-by-Simulation & Design (RbS + RbD) **F**3.15. This synthesis enables the discovery of novel knowledge through combined experimental work, centred on the development of digital models and simulations that guide the design and production of textile artefacts, while simultaneously being refined and informed by these artefacts.

The "*predictive*" RbS methods, rooted in the scientific domain and reliant on digital simulation as a core research tool, are intertwined with the "*exploratory*" RbD methodology, which is supported by hands-on physical prototyping.

One of the key strengths of scientific RbS lies in its emphasis on continuous refinement, resonating with the iterative nature of the design process and making the methodologies compatible. The predictive power of RbS provides invaluable insights into material behavior, enabling exploration in uncharted design territories. Its rigorous structural approach benefits complex design processes that rely on inter-scalar modelling and cross-disciplinary collaborations, as demonstrated in this thesis. However, RbS alone is insufficient to fully address the manufacturing processes of physical artefacts. Conversely, RbD, rooted in creative disciplines, emphasizes a hands-on, exploratory, and iterative approach to engaging with material behavior, fabrication techniques, and design constraints. While RbD facilitates the creation of physical prototypes and demonstrators—allowing for contextualised design exploration—these artefacts also play a crucial role in validating and verifying simulations created using the scientific RbS methodology. This ensures that both design and fabrication processes are rigorously tested against real-world material performance.

By combining RbS and RbD, this thesis establishes a robust and flexible framework that integrates the strengths of both methodologies. It marries the predictive precision of simulation with hands-on physical exploration to achieve both scientific and design-oriented breakthroughs. Additionally, it incorporates the methodology of membrane design, supported by form-finding and structural simulation analysis, adapted from RbS(f) in the engineering domain. This combined methodology enables the adoption and steering of computation, simulation, and digital manufacturing to gain greater control over the potential of differentiated knit materials. It links local material differentiation with global structural and performance demands, thus uniting form and matter. This dual approach deepens the exploration of design possibilities, extending beyond the limitations of purely physical experimentation by incorporating insights at the micro-scale of materials—insights that are not visible



F 3.15: RbS + RbD combined methodology to the naked eye but can be captured through simulation. For instance, in this thesis, simulations reveal design opportunities related to material grading by providing insights from structural analysis that would otherwise remain inaccessible through physical methods alone.

Together, these methodologies provide the tools necessary to explore potential design outcomes, refine them based on material behavior, and ultimately manufacture innovative textile objects.

This synthesised methodology integrates the *rigorous framework* of scientific RbS as a guide for simulation construction, applied across the *digital models* developed in this thesis. The simulation and form-finding aspects of RbS(f) contribute to establishing design and simulation models, while RbD focuses on prototyping and incorporating fabrication processes into the framework. This integrated approach ensures that both the overall design and material performance are thoroughly considered and aligned.

As the design process advances, the physical artefacts become increasingly refined, incorporating more detailed material properties and aligning them more thoroughly with design principles. Concurrently, the digital models and simulations grow in complexity, continuously adjusted to meet contextual demands and research requirements. They also improve in accuracy, predicting the behavior of designed artefacts with differentiated material properties. In this interplay, the RbS, RbS(f), and RbD frameworks complement one another. The physical artefacts and digital models serve as tools for exploring research questions, establishing and testing methodologies, and providing platforms for evaluation.

3.3.2 DIGITAL DESIGN CHAIN AS METHOD OF RBS+RBD

The use of computational simulation tools combined with rapid digital prototyping is integral to the methodology of *Digital Design Chain (DDC)*, introduced earlier in the State of Art chapter. In a DDC network, multiple linked digital models integrate various scales and aspects of complex material systems, design processes, and fabrication workflows, fostering a seamless dialogue between these interconnected processes. A growing body of research highlights the significance of integrating DDC workflows to address complex, real-world challenges through the design of novel structural systems, innovative materials, and advancements in digital manufacturing processes (Hensel and Sunguroglu Hensel 2013). This approach enables creative exploration while maintaining technical and performance-driven rigor.

Moreover, simulations integrated into the DDC are pivotal in performance-oriented design processes, where they facilitate the optimization of environmental, structural, and material performance, bridging the gap between conceptual exploration and technical precision (Hensel and Sunguroglu Hensel 2013). By employing design as a method of problem-solving, simulations validate and refine design decisions, making both processes indispensable for innovation in architecture, engineering, and design (Dorst 2015). Digital tools and simulations have thus become transformative in the way designers think and generate new forms, positioning simulation not only as a tool for validation but also as a driver for novel ideas (Ramsgaard Thomsen and Tamke 2013a; Oxman 2017a; Oxman 2017b).

In this thesis, the methodology situates itself within the broader domain of computational design and aligns with DDC principles by proposing a custom Digital Design Chain tailored specifically for differentiated CNC-knitted membranes. This chain consists of three interconnected digital models, which collectively guide the design, fabrication, and evaluation processes.

3.3.3 EXPANDED DIGITAL DESIGN CHAIN: THREE MODELS, FOUR PROTOTYPES

The methodological framework of this PhD builds upon existing DDC practices within architectural knit research, as introduced in State of Art and illustrated in **F**2.38. Addressing the critical limitations of these practices, this research advances the design-to-fabrication process into an Expanded Digital Design Chain tailored for differentiated CNC-knits, applied as tensile membranes. This chain includes a network of three digital models: the **Design Model**, the **Fabrication Model**, and the **Evaluation Model**. Together, these models create a comprehensive framework that integrates simulation, manufacturing, and performance validation, ensuring alignment between digital and physical domains **F**3.17. The development and outcomes of these models are further supported and validated by four physical prototypes: **KnitVault, KnitVault ML, Zoirotia,** and **GraCe**, where each serves as experimental artefacts, bridging the digital and physical and facilitating iterative refinement of design, material performance, manufacturing techniques and calibration of digital models.

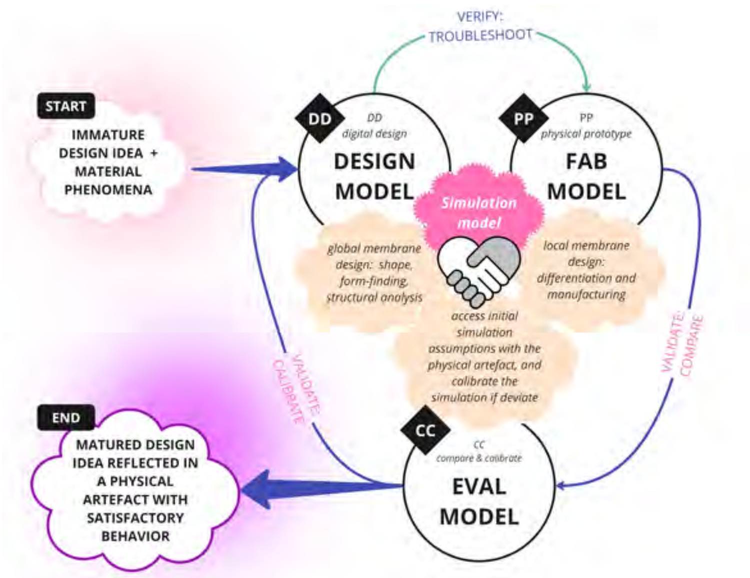
DIGITAL MODELS AS THE FRAMEWORK OF DESIGN PROCESS (RBS)

In this thesis, the digital models form the *framework* for a *design-to-fabrication-to-evaluation* workflow, employed to explore differentiated knit as architectural material. Each model has a distinct purpose, while remaining closely interconnected with the other two through data flow, as illustrated in **F**3.16. Together, they establish a complex yet cohesive design process. This framework leverages the inherent expansion properties of knitted materials to achieve the desired three-dimensionality, offering a unified approach for predicting material behavior via form-finding, analyse material internal processes with simulation analysis, ensuring fabrication precision through detailed material specifications, and enabling post-validation for improved accuracy.

The **Design Model** focuses primarily on the global spatial design of tensile membranes, operating at the macro-scale. Here, the schematic conceptual model defines boundaries, constraints, and material properties, while the Form-Finding Kangaroo Solver activates these settings, running simulations to explore feasible forms and configurations.

The **Fabrication Model** operates at the meso-scale, translating local material specifications into stitch distributions informed by the global design and structural analysis from the Design Model. This model addresses the inherent incompatibilities between design and fabrication environments, including spatial, metric, and resolution disparities. By emphasizing inter-scalar and interdisciplinary considerations, the Fabrication Model ensures minimal distortion and data loss throughout the design-to-fabrication workflow.

The third, **Evaluation** model works back at the macro scale, supporting the precision of Design Model through simulation validation and calibration. It describes the differences between the digital model and resulting physical prototypes, by evaluating the deviation through *benchmarking validation*, and addressing the *calibration*



F 3.16: Digital Design Chain in CNC-knit design: Diagram of co-dependence, sequence and hierarchy of models within this thesis

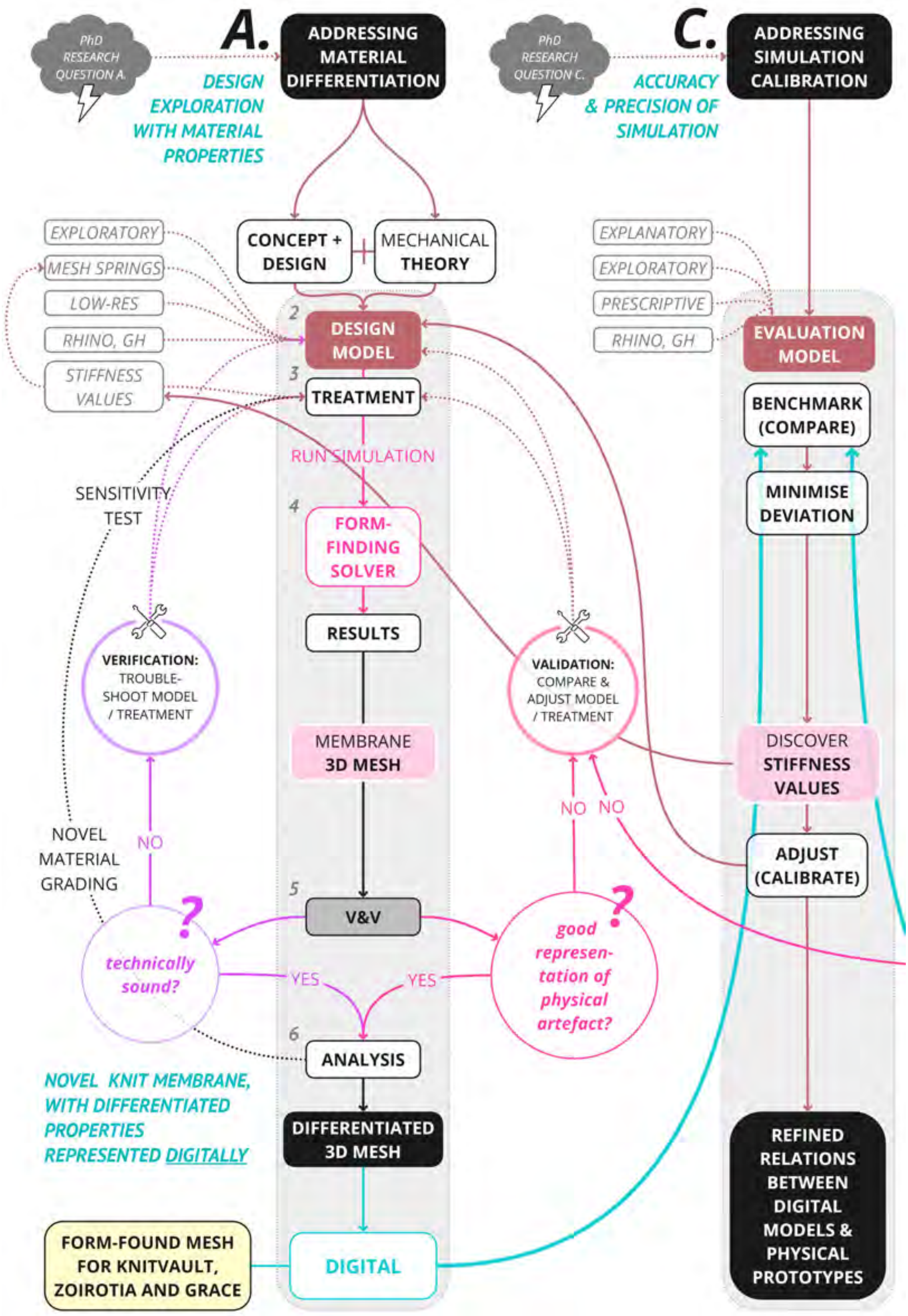
through optimisation, by discovering right stiffness values, that are fed into the material properties component of the Design Model, thereby minimising the distortion and improving the quality of initial simulation. It addresses the challenges of simulating the behaviour of differentiated membranes by refining the unknown stiffness values and integrating these discoveries back into the design's model simulation. This iterative feedback mechanism ensures that the digital simulations accurately reflect the physical properties of the differentiated membranes, enhancing both the simulation predictive accuracy and reliability throughout the design-to-fabrication workflow.

Supported by simulation and computational processes, these three models constitute a robust and expanded Digital Design Chain, specifically tailored for the design and manufacturing of CNC-knitted differentiated membranes. This chain is not limited to a specific membrane topology but is designed to ensure reliability and adaptability across various topological design situations, with a focus on the relationships between form and matter.

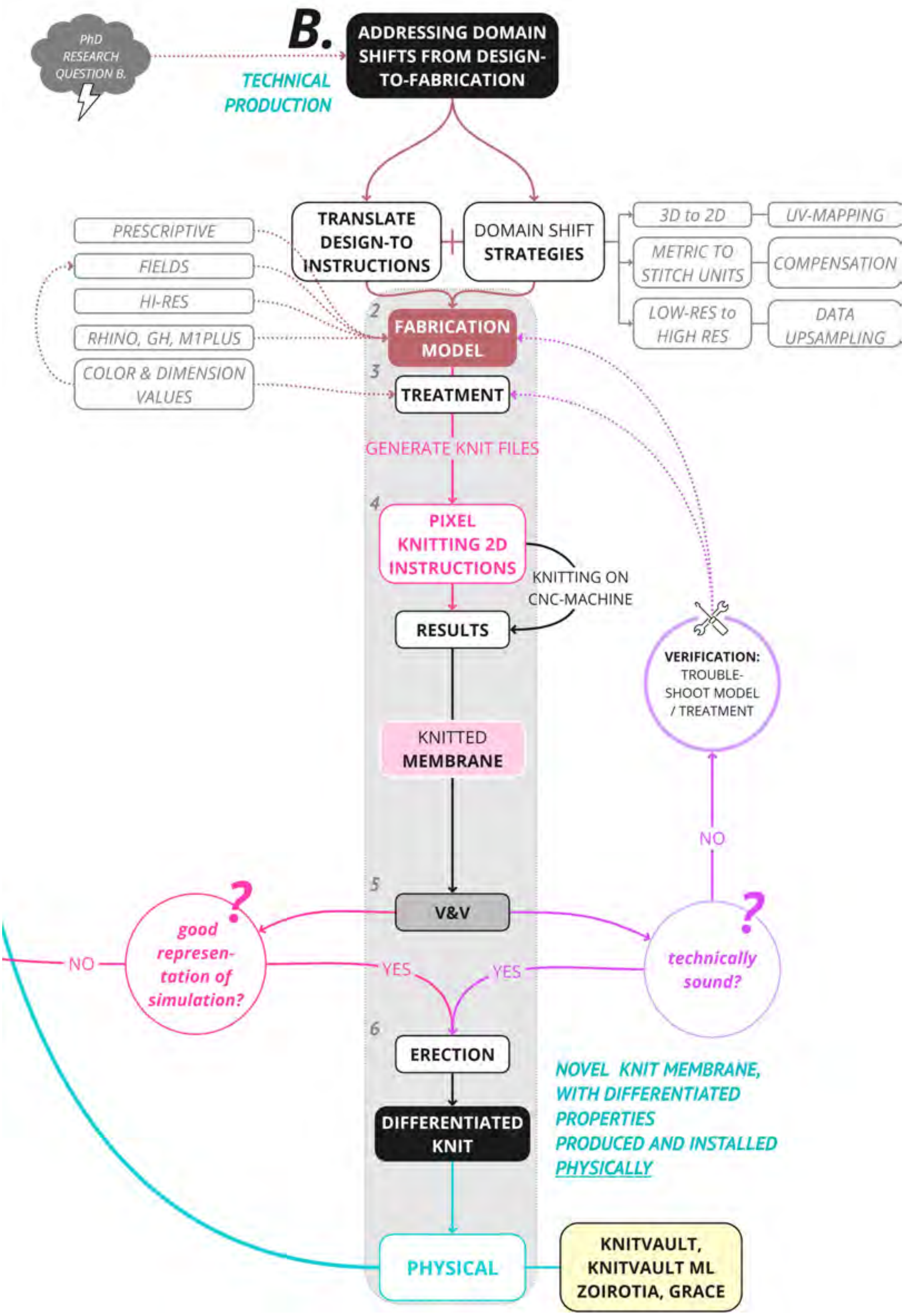
RBS STRUCTURE OF DIGITAL MODELS

A more detailed description of each digital model is presented in the following Experiments chapter and related scientific publications, included there. The introductory remarks below are provided to assist the thesis reader in navigating the flow diagrams and descriptions, that follow.

The individual description of the digital models follows the scientific RbS methodology, adhering to a step-by-step phasing approach in which each phase is specifically adapted to the context of individual models. This structured approach ensures alignment among the three digital models and organizes the data flow across them, emphasizing their interconnections. The Design and Fabrication Models adhere more distinctly to the RbS framework as they function as generative



F 3.17: Digital Models as framework of DDC in this thesis


PhD RESEARCH QUESTION B.
B.
ADDRESSING DOMAIN SHIFTS FROM DESIGN-TO-FABRICATION
TECHNICAL PRODUCTION
TRANSLATE DESIGN-TO INSTRUCTIONS
DOMAIN SHIFT STRATEGIES
3D to 2D
UV-MAPPING
METRIC TO STITCH UNITS
COMPENSATION
LOW-RES to HIGH RES
DATA UPSAMPLING
PRESCRIPTIVE
FIELDS
HI-RES
RHINO, GH, M1PLUS
COLOR & DIMENSION VALUES
2
FABRICATION MODEL
3
TREATMENT
GENERATE KNIT FILES
4
PIXEL KNITTING 2D INSTRUCTIONS
KNITTING ON CNC-MACHINE
RESULTS
VERIFICATION: TROUBLE-SHOOT MODEL / TREATMENT
KNITTED MEMBRANE
NO
5
V&V
good represen-tation of simulation?
technically sound?
NO
YES
YES
6
ERECTION
DIFFERENTIATED KNIT
NOVEL KNIT MEMBRANE, WITH DIFFERENTIATED PROPERTIES PRODUCED AND INSTALLED PHYSICALLY
PHYSICAL
KNITVAULT, KNITVAULT ML ZOIROTIA, GRACE

models that produce new data. In contrast, the Evaluation Model serves as a validation model, operating between the two and requiring a slightly modified structure to accommodate its role.

Within each model, the process begins with the goal of representing or addressing specific phenomena and progresses toward the development of a *Model of Phenomena*, as defined in the scientific RbS flow. Each model has a distinct purpose, a set of inputs, and a unique *target* representing its desired outcomes (Winsberg and Harvard 2024). For example, in the Design Model, the target is a *Digital 3D Simulation* resulting from form-finding. In the Fabrication Model, the target is a physically tangible knitted membrane produced on an industrial CNC-machine. In the Evaluation Model, the joint target is a *Calibrated Digital Simulation* and a *Performing Physical Artefact*.

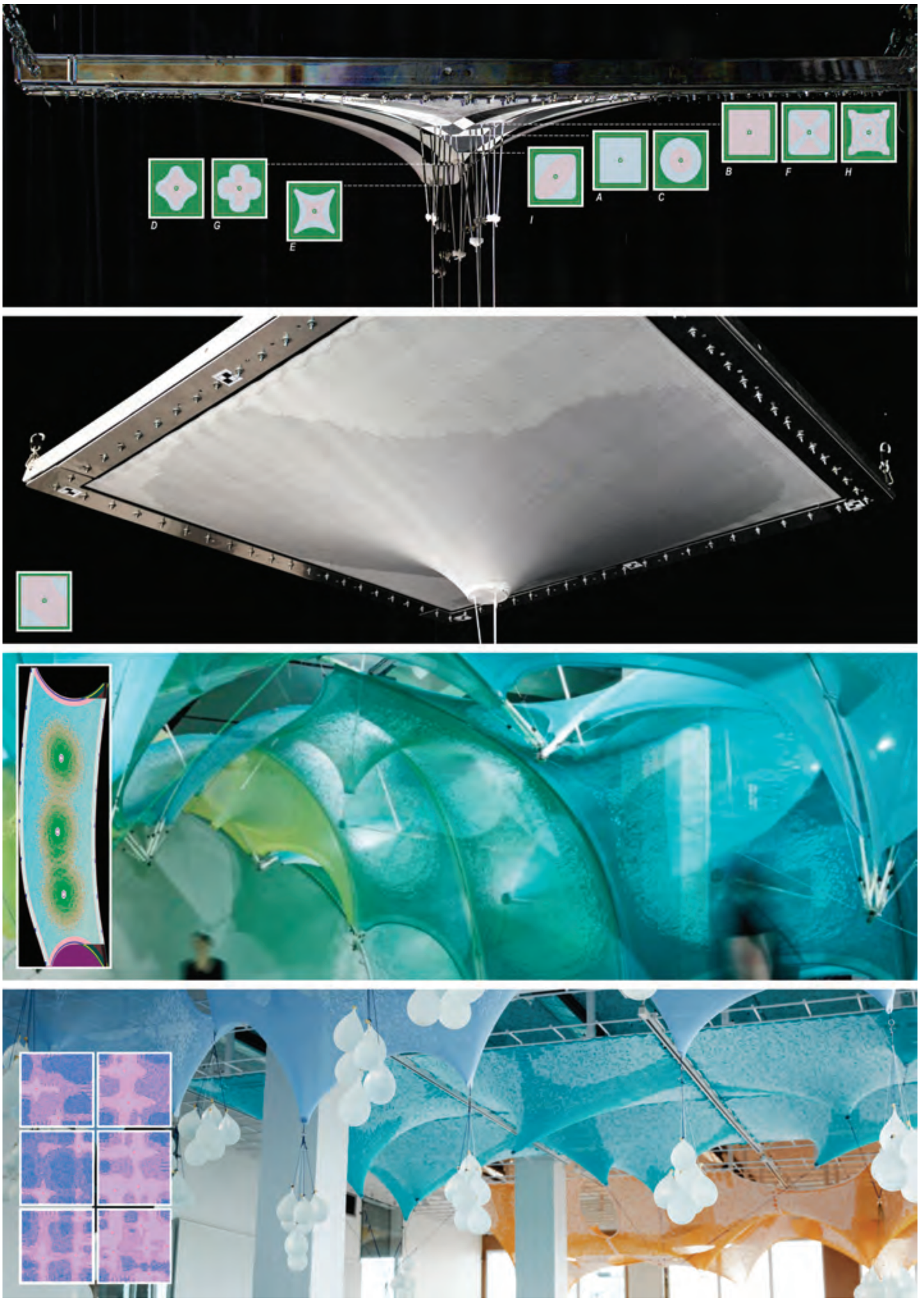
Each of the three models is examined through the lens of its *Research Question* and the *Theory* that informs it, detailing how the model is constructed and the considerations required during its *Treatment* phase to ensure clear model specifications. While the *Treatment* phase is a consistent component of both the Design and Fabrication Models, its function differs. In the Design Model, the Treatment phase involves defining the mesh membrane properties, whereas, in the Fabrication Model, it consists of computational algorithms that address domain shifts between design and fabrication, ensuring smooth transitions. The primary role of the Treatment phase is to prepare each model for its respective Solver: a form-finding simulation in the Design Model and the auto-generation of knitting files in the Fabrication Model. Finally, the Results produced by each model are analyzed in terms of their contribution to and influence on the other models, ensuring a cohesive and iterative workflow.

PHYSICAL PROTOTYPES AS OUTCOMES AND VALIDATORS OF DIGITAL MODELS (RBD)

In this thesis methodology, physical prototypes play a critical role not only as outcomes of the design process but also in the development of each individual digital model. This approach facilitates the development of physical models through the gradual layering of design intents and increasing complexity. It incorporates new rule-based features into the digital models while yielding higher-complexity physical outcomes, incrementally linking closer the form and matter of knitted membranes. The physical prototypes, specifically defined as *probe*, *prototype*, and *demonstrator*, are collectively referred to as the experimental projects — *KnitVault, KnitVault ML, Zoirotia,* and *GraCe*.

The development of these projects redefines the concepts of probes, prototypes, and demonstrators in relation to Thomsen's framework Ramsgaard Thomsen and Tamke 2009, as detailed below and in **F**3.14. In this thesis probe, prototype, and demonstrator collectively contribute to the advancement of local material differentiation strategies, evolving from a bottom-up, manual approach to a top-down, computationally informed methodology guided by simulation analysis **F**3.18.

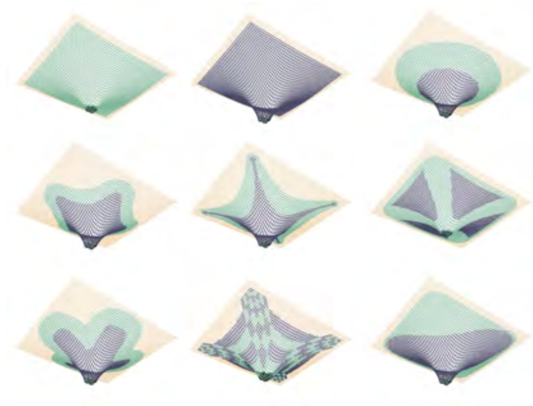
F 3.19: KnitVault surface knit pattern. *Sinke 2019*



F 3.18: Physical models in this thesis. Top to bottom: KnitValut, KnitVault ML, Zoirotia and GraCe

PROBE

The Probe captures material behaviours by engaging with the CNC-knitting process, providing a tactile and empirical foundation for understanding material responses. In this thesis, the Probe is defined as a small-scale textile membrane surface that facilitates the observation of material behavior in relation to the chosen yarn, machine settings, knit stitch selection, and their arrangement into patterns. The Probe marks the beginning of the research journey by establishing the relationship between local material differentiation and the global form of a membrane, testing the hypothesis that differentiation in a knitted membrane surface can control the three-dimensionality of tensioned membranes. The initial aim is to explore these relationships in a bottom-up manner by linking manually defined surface knit patterns to the resulting depth, as determined through systematic testing on a tension rig. The probe in this thesis is therefore re-defined as:



F 3.20: KnitVault digital simulation. *Sinke 2019*

+ **PROBE** - An early material exploratory activity aimed at understanding the manufacturing technique of industrial knitting and its impact on material behavior, particularly in establishing the relationships between pattern configurations and the behavior of tensioned textiles. This is accomplished through a manual design approach, where the "drawn" pattern configurations define the zonation of differentiated knit properties.

KNITVAULT The first experiment, KnitVault probe, investigates how manually generated surface patterns influence the shape of tensioned fabric. The patterns are manually designed and tested using a setup where a square textile panel is clamped around its perimeter to a metal rig (1.20m x 1.20m) and loaded with a consistent weight of 15 kg at the center **F**3.21, where further documented by laser scanning. This setup results in cone-like three-dimensional canopies, each with varying depths depending on the knitting pattern. The pattern design exploration, driven by the author's physical intuition, focuses on achieving cone-like geometries with minimal wrinkling, thereby studying the relationship between pattern design and the depth of the resulting cone. The patterns, which resemble geometrical symmetrical forms, aim to assess how variations in design impact the depth of the stretched fabric.

The choice of yarn and stitch selection is informed by the author's prior experience with the Isoropia project, where stitches such as *pique* and *piquet lacoste* demonstrated distinct strain (elongation) properties. Dyneema® yarn, known for its

F 3.21: KnitVault tension testing rig. *Sinke 2019* high tenacity, was selected for its ability to provide structural integrity to the surface while allowing the investigation of membrane three-dimensionality to focus on the knit pattern rather than the inherent properties of the yarn itself.

The KnitVault probe establishes the foundation of the expanded RbS+RbD methodology by setting up both the Design and Fabrication Models, which integrate manual material differentiation into a design-to-production workflow. It also lays the technical groundwork for the industrial manufacturing of architecturally differentiated CNC-knits using STOLL knitting machines—a novel system for the author, who had previously worked with ShimaSeiki. The successful production of these probes demonstrates the project's ability to bridge manual design exploration with industrial fabrication processes, regardless of the manufacturing system used.

Furthermore, this experiment initiated the development of the Evaluation Model, expanding the workflow into a design-to-fabrication-to-evaluation process. This model compares the outcomes of both the Design and Fabrication Models to identify deviations between physical and digital results, leading to early efforts in simulation optimization and calibration. The manual pattern exploration conducted in this phase serves as the foundation for more complex pattern definition strategies, which are further explored in subsequent **Prototypes**.

PROTOTYPES & DEMONSTRATORS

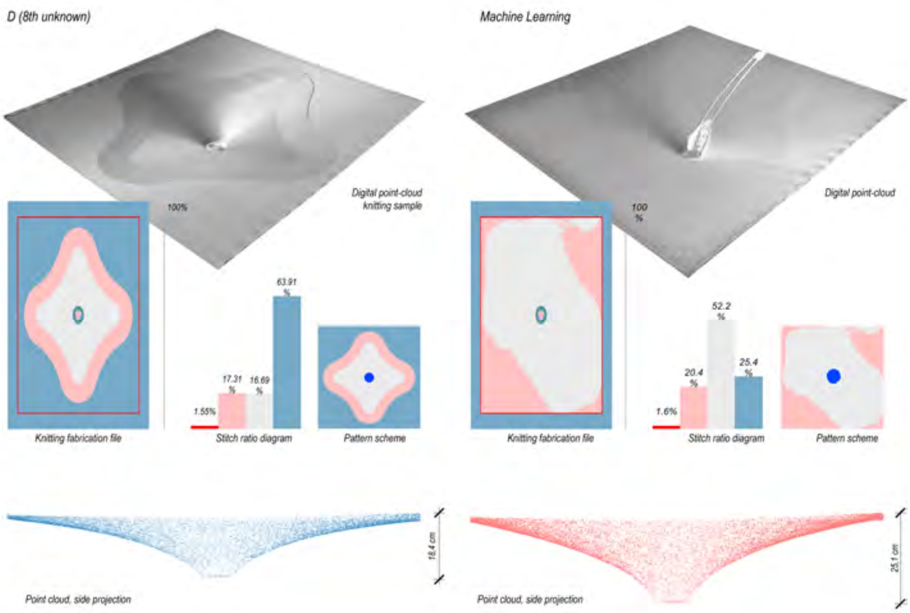
The definition of *Prototype* and *Demonstrator* in this thesis follows the perspective of material differentiation, unfolding in relation to modes of knit pattern-making. Prototypes and Demonstrators are therefore understood as *application-led* and *computationally-informed* design investigations. They transition from bottom-up, manually predetermined pattern explorations to a more controlled, top-down approach, where the global form informs the patterns through computational tools and structural form-finding analysis.

The *Prototype* represents the initial attempts to reverse the material differentiation strategy by using the membrane shape and its deformation under tension as input for local material differentiation. This is achieved through shape geometry analysis and machine learning techniques. The Prototype aims to establish the relationship between the pattern and the overall membrane shape, following a top-down approach where the global form informs local material differentiations. This process fosters an early dialogue between *form and matter*.

The *Demonstrator*, in contrast, presents a more advanced approach by employing structural analysis for material specification, linking shape and matter more closely. This approach directs force distribution flows through local pattern configurations, resulting in enhanced surface curvatures and expressions. The Demonstrator also serves as a platform for calibrating relationships between the overall membrane shape and its local material differentiations. By minimizing deviations between the initial design and its realization in tangible membranes, it uses computationally driven optimizations to uncover previously unknown digital properties of knit, and as a result tune the digital simulation. As such, in this thesis, the *Prototype* and *Demonstrator* are defined as:

+ **PROTOTYPE** - Design-led, knitting pattern is computationally informed by ML and geometric analysis, linking local material specifications with overall form of the membrane.

+ **DEMONSTRATOR** - Advanced design-led, knitting pattern is informed by structural analysis, establishment of calibrated relationship between digital simulations and physical model.



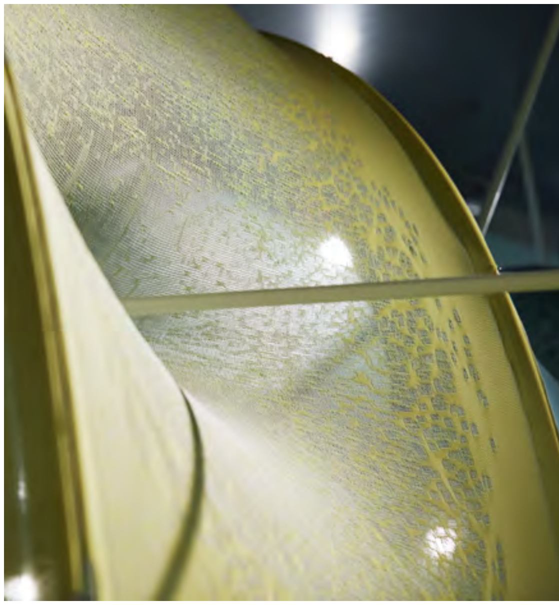
F 3.22: KnitVault ML knitted membrane compared to the membrane with manually defined pattern D from KnitVault experiment. *Sinke 2020*

KNITVAULT ML The second experiment, the prototype **KnitVault ML** *(ML - Machine Learning)* transitions from the manual definition of material specifications to a machine learning methodology as a tool for exploring potential surface patterns based on the target 3D form of the membrane. This experiment builds on data from the probe *KnitVault*, correlating the resulting depths of the stretched membranes with the manually drawn surface patterns. The aim is to establish links between the patterns and the global resulting shape, investigating alternative approaches to parametric workflows for generating knit specifications based on target performance—in this case, the depth.

This experiment is conducted in collaboration with Sebastian Gatz, a colleague from CITA, who supported the setup of machine learning data training based on the data from the *KnitVault* probe, provided by the author of this thesis. The author's role focuses on ensuring the integration of the novel machine-learned surface pattern into the fabrication workflow, its realization at an external CNC-knitting manufacturing facility, and the subsequent installation of the resulting membrane in the metal rig for performance evaluation. A more detailed description of the process is provided in the following chapter.

ZOIROTIA The third experiment, **Zoirotia** *(from greek, "vivid")*, presents a large-scale tensile installation where the local differentiation of knit is driven by simulation input. A geometric analysis conducted on the digitally form-found shape acts as a guide for steering material specification **F**3.23. Here, the exploration of patterns moves beyond the manual assignment used in the Probe and examines how the 3D *form* of the membrane influences the 2D pattern distribution, which in turn mutually supports the membrane's formation into that *form*.

The stitch selection for this project is guided by the need to explore distinct strain properties of the knitted surface compared to the previously used *pique* and *piquet lacoste*. For this, the double jacquard knit technique is employed, which exhibits visibly different elongation properties due to the strategic application of dropstitch across the pattern. Additionally, the double jacquard technique allows for the exploration of multiple dimensions of surface differentiation, offering control not only over the surface's structural strain performance but also over the color distribution as an additional layer of material specification. The exploration of color, combined with the high-tenacity performance of technical yarns, was made possible through the use of Serafil sewing thread, which provides exceptional tear resistance and a wide color range. This exploration significantly expands the capabilities of the Design and Fabrication Models while simultaneously revealing their limitations. During this experiment, the Design and Fabrication Models mature, integrating greater detail in both design exploration and fabrication execution.



F 3.23: Prototype of geometrically informed knit material differentiation in Zoirotia project. *Photo A. Ingvartsen*

In a broader context, *Zoirotia* is a commission by ZKM (the Center for Art and Media in Karlsruhe, Germany). It represents an interdisciplinary collaboration among the designer (*CITA*), engineer (*str.ucture GmbH*), and textile producers (*SIA Viola-Stils, Kobleder GmbH, Royal Danish Academy CNC KnitLab*). The project demonstrates remarkable spatial expression, knit differentiation, and scale of application. The structure consists of 88 custom-knitted membrane units, covering 568m^2, each uniquely differentiated for its tensile configuration.

F 3.24: Author of this thesis knitting a patch for Zoirotia project at CITA. *Photo Sinke 2021*

The author's role in this project focuses on design development and the establishment of the design-to-fabrication workflow, which was successfully implemented across multiple fabrication sites in Europe **F**3.24, where the author took initiative in managing manufacturing processes and communicating with textile production partners from Denmark, Latvia, Austria, and Germany. This workflow was developed in close collaboration with Drua Sif Albrechtsen *(Royal Danish Academy CNC KnitLab)*. Through iterative back-and-forth interdisciplinary conversation, the three-dimensional design aspects of differentiated CNC-knits were effectively translated into machine-readable instructions, enabling a seamless fabrication workflow and great level of flexibility, in order to match various machine specification in different production factories. This facilitated the automation of file generation for an unprecedented large-scale production at outsourced knitting manufacturing facilities.

GRACE The fourth experiment, the demonstrator **GraCe** *(from* **GRA***-ded* **CE***-iling)*, is a ceiling panel installation that takes a new direction in simulation-based material differentiation exploration **F**3.25. It incorporates structural analysis conducted on a form-found shape while considering the internal processes occurring within the surface, such as force and stress distributions. Although smaller in scale and requiring less erection effort than the *Zoirotia* prototype, *GraCe* serves as a *demonstrator*, encapsulating the most advanced developments of this thesis research in simulation and material specification. During this experiment, the *Design Model* reaches a more advanced stage, incorporating the most intricate links between form and matter through material differentiation informed by structural analysis, and the *Evaluation Model* is established, improving the precision of simulation and form-finding outcomes.

This project was conducted as part of the author's teaching activities during a two-week workshop with students from the Master's Programme in Computation in Architecture (CiA) at the Royal Danish Academy. The workshop, conducted in collaboration with Drua Sif Albrechtsen as a continuation of interdisciplinary collaboration, aimed to evaluate the robustness of the entire design-to-fabrication-to-evaluation workflow and validate its precision. The digital workflow for GraCe, using the core flow developed for *Zoirotia* project, was well-structured and adapted, allowing students with no prior CNC-knitting experience to successfully translate their design concepts into digital models and physical prototypes using the Academy's in-house CNC-knitting machine, all within a short period. The outcome was three sets of ceiling installations, each exploring different tensile strategy.

F 3.25: GraCe knitted ceiling panels, where the form of textile strain shapes the knitting pattern. *Sinke 2022, Photo A.Ingvartsen*

3.4 RESEARCH TRACKS

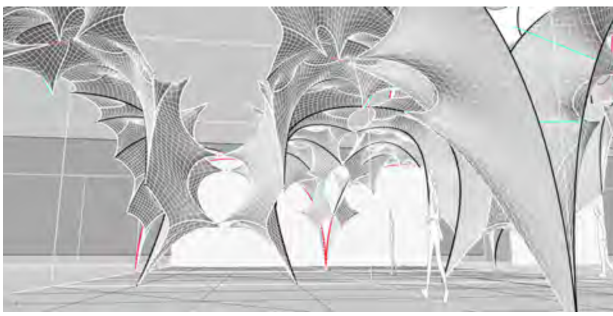
Having established the methodological framework by introducing the network of digital models and physical prototypes earlier in this chapter, this closing section outlines the structure of the following Experimental Chapter, organized into three *Research Tracks* corresponding to the thesis's research questions, digital models and physical prototypes **F**3.26. As this thesis is *by-publication*, each *Research Track* is supported by related publications that document its development and findings. This section provides a roadmap for the research work of this PhD, linking the methodological framework to the practical investigations detailed in the subsequent chapter.

3.4.1 RESEARCH TRACK A: ADDRESSING MATERIAL DIFFERENTIATION

Research Track A, addressing *Research Question A*, focuses on the *Design Model* to explore knit material differentiation in relation to membrane shape targets. Specifically, it investigates the use of simulation and form-finding to connect the global membrane design with its local knit material differentiations, aiming to control the three-dimensionality of the membranes as a target performance.

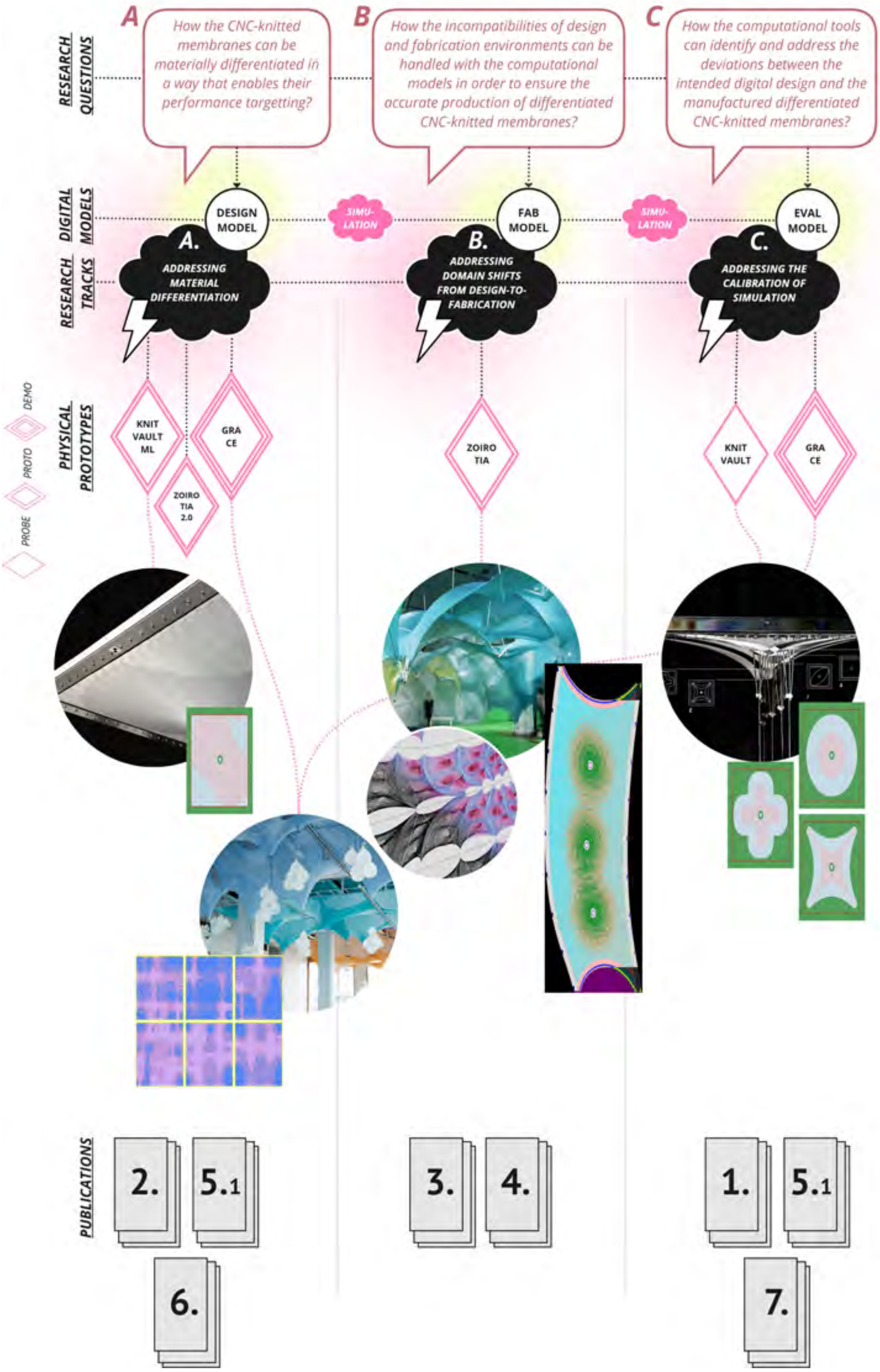
The Design Model evolves through a series of advancements, transitioning incrementally from simplistic, arbitrary manual approaches—such as geometric pattern drawing in the probe *KnitVault* - through alternative attempts to use machine learning in *KnitVault ML* - to a systematic, computationally informed approaches of geometric analysis in *Zoirotia* prototype and structural analysis in *GraCe* demonstrator. eparting from the notion of knit membrane differentiation as isolated surface "decoration," this research track aims to develop a *coherent strategy* where meso-level surface specifications are informed by, and contribute to, macro-level performance design goals. This connection is enabled within the Design Model, supported by simulation's capacity to extract meaningful data from form-finding processes and translate it into innovative approaches for pattern-making.

In this thesis, simulation is conceived as an active platform for shaping the logic of material differentiation in tensile CNC-knitted membranes. It establishes a critical link between the global form — derived from the equilibrium state of a form-found mesh—and the local material patterns, which are based on structural analyses of the mesh. Key information, such as material stretch, displacement, or mesh topology, is translated into strategies for specifying local material properties to achieve the desired behavior, thus positioning simulations as essential design informants. By integrating simulations early in the design process, they shape decision-making by identifying areas for material differentiation linked to the global structural requirements of differentiated strain. This elevates local pattern-making from a superficial operation to a core structural strategy.



F 3.27: Design Exploration of Zoirotia interior space through articulated membrane manipulation to create connections between the structural elements. *Sinke 2021*

Moreover, the computational power of established digital models facilitates parameter space exploration, systematically testing a range of material configurations to predict how localized changes propagate throughout the structure. This capability identifies optimal zones for local differentiation based on the performance criteria of the target membrane shape, establishing a framework where pattern design decisions are directly linked to structural or geometric performance, rather than serving as decorative surface features.



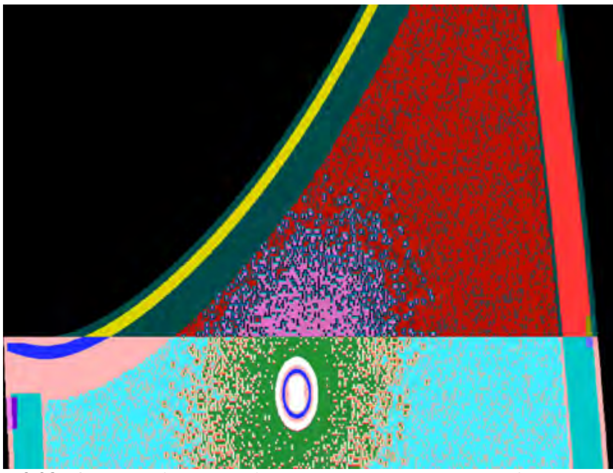
F 3.26: Research Tracks: Research Questions, Digital Models and Physical Prototypes

3.4.2 RESEARCH TRACK B: ADDRESSING DOMAIN SHIFTS FROM DESIGN-TO-FABRICATION

Research Track B, addressing *Research Question B*, focuses on the *Fabrication Model* to tackle domain shifts related to *resolution*, *metric*, and *spatial* differences between design and manufacturing environments. This track ensures the fabrication feasibility of differentiated CNC-knitted membranes within manufacturing constraints and architectural applications. It facilitates the translation of digital designs, represented as 3D meshes, into planar, pixel-based machine instructions that enable the production of physical artefacts with minimal distortion while preserving the original design intent.

The challenge of domain shifts in transitioning from design to production lies in translating global membrane geometries into local material specifications. This complexity is heightened by the models operating across different spatial domains, metric systems, and levels of resolution, resulting in outputs that differ significantly in format and nature. These discrepancies introduce the notion of *incompatible models*, where models cannot be directly integrated due to differences in spatial representations and computational structures. Consequently, the challenge extends beyond navigating between models to reconciling these fundamental differences through computational techniques that bridge these incompatibilities and link the models effectively.

Practically, the incompatibility of the models is addressed through a series of computational sub-models. These sub-models manage the transitions across resolutions, from low to high resolution, and the conversion from 3D configurations to 2D planar instructions. They also handle the shift from metric to stitch-based units, aided by physical preliminary sampling. Additionally, a sub-model defines the compensation factor required to scale down the membrane, ensuring the necessary pre-stress is achieved during membrane installation.



F 3.28: Close up of a bitmap file, containing the instructions for CNC-knitting machine for production of Zoirotia knit graded membranes. *Sinke 2021*

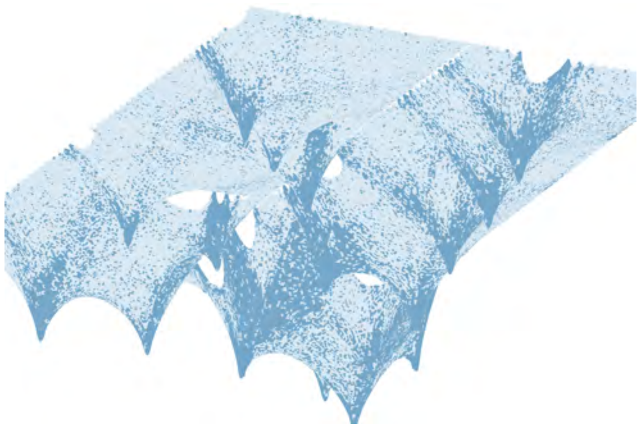
During this research track, the *Fabrication Model* evolves, progressing from the initial design-to-fabrication workflow. It begins with the translation of simpler, manually defined patterns in the probe *KnitVault*, advances to machine learning-generated patterns in the prototype *KnitVault ML*, and culminates in the radical advancements seen in the workflow for the prototype *Zoirotia*. The latter demonstrates the capacity to accommodate a high degree of customization, where highly complex patterns are generated based on the geometric analysis of Zoirotia's intricate tensile units. In the *GraCe* prototype, the workflow is less complex as the membranes are not shaped, however, the translation of structural analysis data is reflected in more intricate local differentiations.

3.4.3 RESEARCH TRACK C: ADDRESSING SIMULATION CALIBRATION

Research Track C, addressing *Research Question C*, focuses on the development of the *Evaluation Model*, which examines and addresses deviations between digital designs and physical artefacts—the outcomes of the *Design* and *Fabrication Models*—through simulation calibration.

The *Evaluation Model* addresses the complexities of interconnected parameters within a network of models, where changes in one model propagate through others, often making the design process highly dependent on aspects further along in the workflow. This raises fundamental questions: How can the design process proceed when critical parameters, such as knit strain and stiffness values, are unknown and interdependent? Where should the design process begin? What should be considered *primary*, and what *secondary*, in the design process? Addressing these questions requires a strategy that can *accommodate uncertainty* while maintaining coherence across interconnected models without hindering the design process. This track seeks to uncover uncertainties in the specification of digital knit material properties using evolutionary algorithms, particularly by discovering stiffness values and employing them to calibrate the *Design Model*, ensuring its accuracy and functionality for further design explorations.

To navigate these challenges, the *Evaluation Model* establishes a closed loop that leverages optimization algorithms to determine material properties, such as stiffness values, and employs model calibration techniques to align digital simulations with physical outcomes. The model advances through calibration exercises, starting with the *KnitVault* probe, which features manually defined knit patterns, and progressing to the demonstrator *GraCe*, which presents a higher complexity of surface grading. This progression allows the exploration of more complex mesh setups for calibration.



F 3.29: Advancements in simulation calibration and representation for differentiated knitted membranes

Genetic optimization provides an automated method for refining parameters while accounting for the complexities and interdependencies among models. By dynamically adjusting key variables in response to evolving model conditions, these algorithms help to address deviations between digital and physical outcomes, ensuring that final configurations align more closely with real-world properties. This flexible approach effectively tackles issues of trust and validation, allowing simulations to adapt and correct themselves as new input emerges. The *Evaluation Model* integrates genetic evolutionary algorithms to discover stiffness values by minimizing geometrical deviations between the digital model and physical recordings of CNC-knitted artefacts, thereby calibrating the *Design Model*'s parameters through multi-objective optimization.

By employing genetic optimization, the model manages the inherent uncertainty in simulations, *balancing approximation with accuracy*. This advanced algorithmic approach provides a *practical* solution to philosophical challenges related to simulation accuracy and functionality. It enables the creation of models that remain effective despite their inherent complexities and uncertainties. These models are seen as practical tools that guide the design and fabrication of differentiated CNC-knitted membranes, incrementally improving throughout the design process by balancing functionality, accuracy, and acceptable levels of deviation.

Chapter IV
EXPERIMENTS

CHAPTER OVERVIEW

Chapter 4: Experiments aims to frame and detail the experimental work conducted in this research within the *hybrid* methodological framework of Research-by-Simulation and Design (RbS+RbD), introduced earlier by the *Methodology* chapter. This chapter 4 is structured around **three Research Tracks**, each addressing a specific **Research Question** and corresponding to the development of a distinct **digital model**. While each Research Track is linked to a particular digital model, physical prototypes are featured across multiple tracks and digital models, serving as examples of specific research developments and acting as validators for the digital models. Given that this thesis is presented as an **article-based submission**, the Experiments chapter consolidates the overarching methodological framework, integrating and contextualizing the research peer-reviewed outputs within a coherent methodological narrative. It highlights and frames the specific technical and conceptual developments published in the included articles, clarifying their methodological significance.

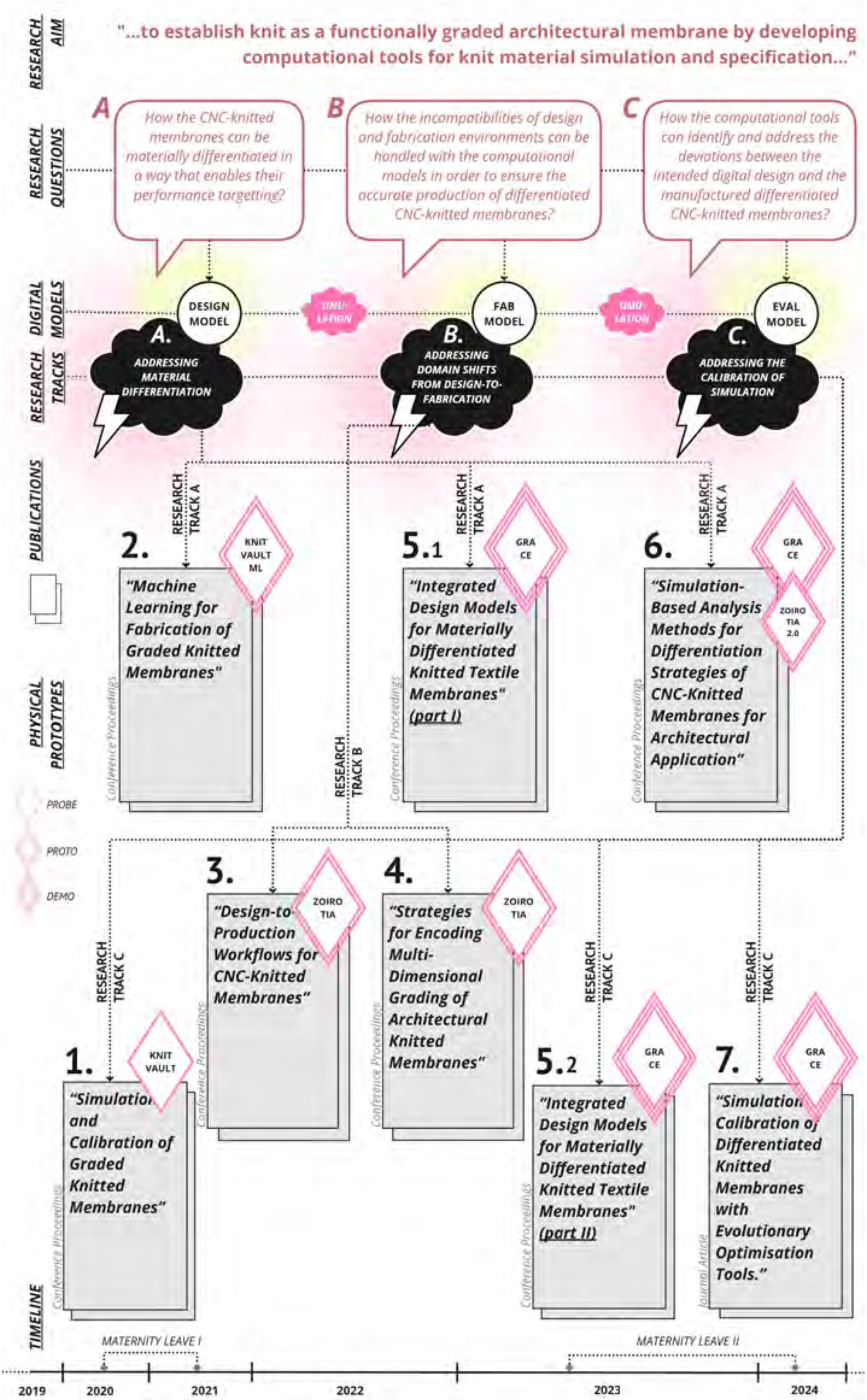
Diagram in **F**4.1, which was introduced earlier in Introduction, is duplicated here again to navigate the framework of three *research questions*, their corresponding *digital models*, and the relevant *publications*, with the mapped physical prototypes across the entire framework. The diagram maps and numbers the articles chronologically by their dissemination year, while in this chapter the publications are presented in the relevant to the narrative order. The publications, appended at the end of each section, are presented in the editing format and language as published.

The chapter is structured into three sections, each corresponding to a distinct Research Track. Within each section, the evolution of digital model development is described, with particular attention to how the digital model, supported with the physical protoypes address the research question it aims to answer.

The first section, **Research Track A**, addresses *Research Question A*, focuses on the *Design Model* to explore knit material differentiation in relation to membrane shape targets. Specifically, it investigates the use of simulation and form-finding to connect the global membrane design with its local knit material differentiations, aiming to control the three-dimensionality of the membranes as a target performance.

The second section, **Research Track B**, addresses the *Research Question B*, through featuring the development of the *Fabrication model*, that addresses the domain shifts inherent to design-to-fabrication workflow of CNC-knitted membranes. The model addresses the three domain shifts: 3d to 2d, metric to stitch based units and low-res to high-res.

The third section, **Research Track C**, addresses the *Research Question C*, through featuring the development of the *Evaluation model*, that addresses the deviations between the digital model and the physical artefact by benchmarking and calibration supported by genetic evolutionary algorithmic tools.



F 4.1: Research scope, mapping the research aim, research questions and the related research activities: articles, digital models and physical prototypes

RESEARCH TRACK A

DIFFERENTIATED KNIT MATERIALITY

4.1 RESEARCH TRACK A: DESIGN MODEL, ADDRESSING KNIT MATERIAL DIFFERENTIATION

Research Track A, addresses **Research Question A**, formulated as *How the CNC-knitted membranes can be materially differentiated in a way that enables their performance targetting?*. This question is explored through the development of a custom digital **Design Model**, which serves as a platform for investigating knit material differentiation in relation to global membrane performance, applied at an architectural scale and context. The section in structured around two subsections, where the first addresses the structure of the Design Model, while the second the methods how the Design Model addresses the knit material differentiation.

In this thesis, local material differentiation is examined by leveraging the potential of knit materials to be graded across multiple dimensions—for both structural performance and visual expression. The structural performance, the primary focus of the research, is controlled through stitch variegation, which allows the material to expand under tension, thereby influencing the controlled strain behavior of the global membrane surface. Meanwhile, visual expression is managed through the differentiation of yarn color, enabling variations in surface chromatic properties and adding an additional layer of design expression. The Design Model integrates multiple dimensions of material grading and prediction of complex knit strain behavior of knit through several interconnected sub-models: the **Concept**, **Simulation** and **Colour** sub-models, where each emerges at specific stages of the Design Model's development. The *Concept* and *Simulation* sub-models jointly support the three-dimensional design and form-finding of tensile membranes by enabling *shape prediction* that accounts for the differentiated surface properties of knit materials. The *Colour* sub-model provides a platform for exploring *colour distribution* across the topological design space of form-found membrane surfaces, as defined by the Simulation Model. The surface colour distribution is not of particular research focus for this thesis and therefore Colour Model will not be presented in this section explicitly, however it will be occasionally referred to as a complementary material differentiation explored during Zoirotia project, while the technical details of Colour Model development can be read in Publication 4, explaining the multi-dimensional design-to-fabrication material specification.

The Design Model addresses structural material differentiation from three perspectives: (1) *manual*, as the initial exploration of hypothesis that differentiation leads to variegated strain, (2) using *analysis techniques* integrated into the Simulation Model and (2) exploring alternative to simulation approach of *machine learning*. The methods are elaborated upon in this section, followed by the detailed descriptions of the structure and functionality of each sub-model.

The development of digital models in this PhD research is carried out within the parametric modelling environment of Grasshopper in Rhino, utilizing both native and custom-scripted components. Grasshopper provides a flexible platform for constructing and manipulating computational and simulation models. These models facilitate spatial exploration and form-finding in Kangaroo2, supported by the structural engineering analysis capabilities of the K2Engineering plug-in. Together, these tools offer a versatile workspace that combines the adaptability of parametric modelling with integrated engineering simulation, enabling the exploration of novel material gradings for knit membranes and their subsequent preparation for fabrication.

At the end of this section, three key **publications—5.1, 6,** and **2** (ordered according to the narrative of this section)—are included as appendices. These publications document the development of material differentiation strategies through technical and methodological advancements in knit differentiation methodologies, incorporating both analytical and machine learning approaches. *Publication 5.1* by Sinke et al. 2023a provides an overview of *geometric and structural analysis techniques*, tested on the knit pattern designs of the GraCe ceiling installation. *Publication 6* by Sinke et al. 2023b *validates* the structural analysis method for identifying novel knit material gradings in more complex geometries, such as Zoirotia. This paper includes a digital preview of how the pattern would appear (Zoirotia 2.0) when applying structural analysis to it. It also highlights the potential of structural analysis for material grading, particularly in supporting non-conventional tensile set up for membranes by eliminating wrinkles through distributed surface strain properties, as demonstrated in the GraCe workshop outcomes. The last, *publication 2* by Sinke Baranovskaya et al. 2021 presents the results of the KnitVault ML experiment, which explores machine learning as an alternative to simulation approach for guiding material specification in relation to target membrane shape. Publications are futher referred in text as **P**.

Additional references to other publications containing aspects relevant to the Design Model are included in this section, although their primary contributions belong to other digital models discussed in the subsequent research tracks. A full list of the papers included in this research track is provided below. The diagram in **F**4.2 presents the Design Model detailed structure, its compound sub-models and the data flow. List of publications, relevant to this section:

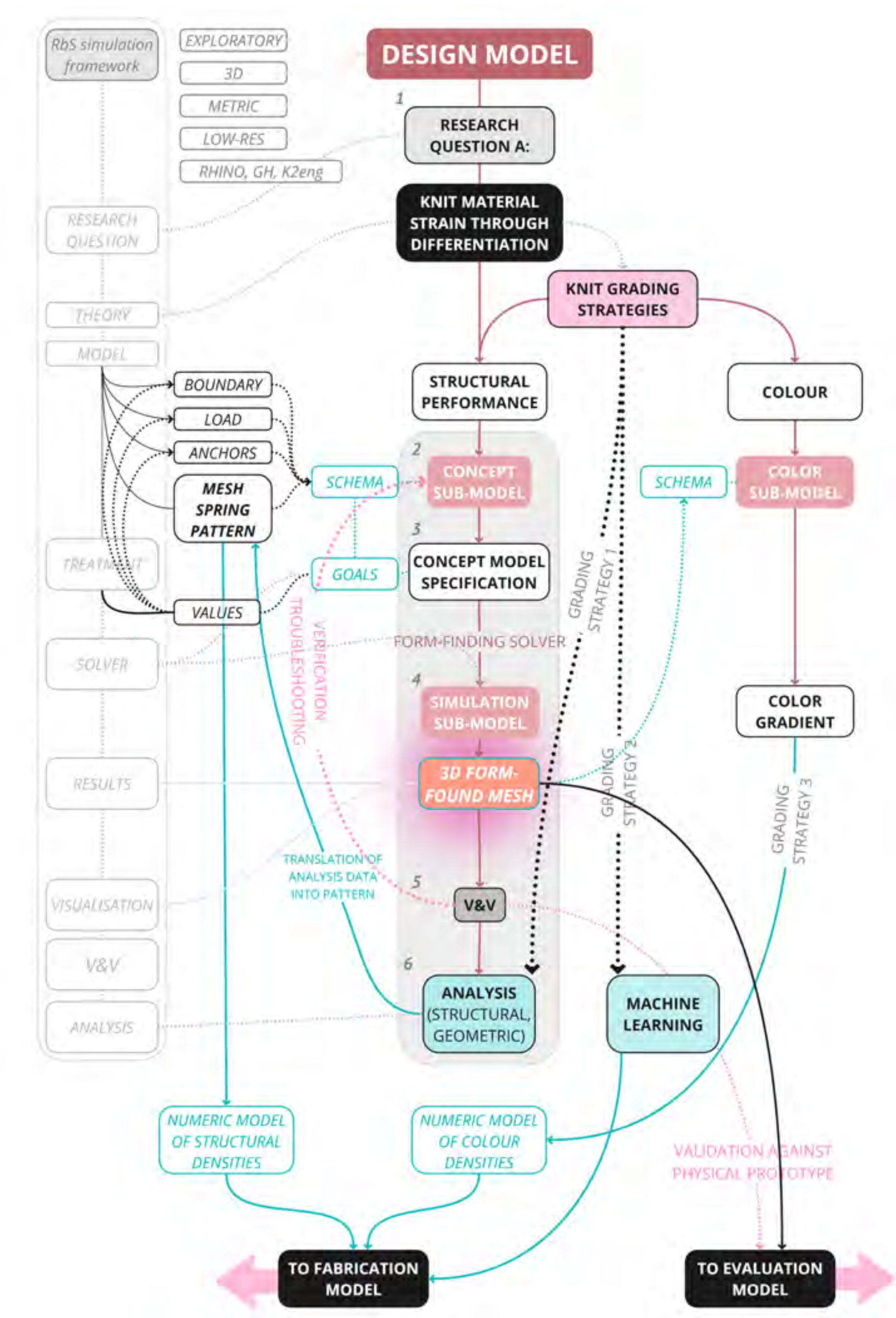
5.1 Sinke, Yuliya, Martin Tamke, and Mette Ramsgaard Thomsen (2023). **Integrated Design Models for Materially Differentiated Knitted Textile Membranes as the Means to Sustainable Material Culture within Membrane Architecture (part I)** In *Sustainable Futures, Leave No One Behind: Proceedings of UIA 2023 Copenhagen World Congress of Architects*. Copenhagen, Denmark: Springer, 2023. p.355-366 (until section 5).

6 Sinke, Yuliya, Martin Tamke, and Mette Ramsgaard Thomsen (2024). **"Simulation-Based Analysis Methods for Differentiation Strategies of CNC-Knitted Membranes for Architectural Application"**. In *Tensinet 2023: Proceedings of Tensinet Symposium. Membrane Architecture: The Seventh Established Building Material.* Nantes, France. p.220-233.

2 Sinke Baranovskaya, Yuliya, Sebastian Gatz, Martin Tamke, and Mette Ramsgaard Thomsen (2020). **Machine Learning for Fabrication of Graded Knitted Membranes**, In CDRF2020: *Proceedings of the 2nd International Conference on Computational Deisgn and Robotic Fabrication*. October 2021. Edited by P.F. Yuan et al. p.309–319.

4.1.1 CONCEPT & SIMULATION SUB-MODELS

Conceptual and Simulation Models are integral components of the Design Model, collectively supporting the spatial design and three-dimensional modelling of tensile knitted membranes with differentiated properties. These two models are



F 4.2: Design Model schematic workflow in relation to RbS framework, representing its compound sub-models: Concept, Simulation and Colour, that offer the space for design exploration, form-finding and analysis. *Sinke 2024* deeply interconnected, forming an inseparable and cohesive entity. Below will be reviewed the structure, role, and relationships of these models.

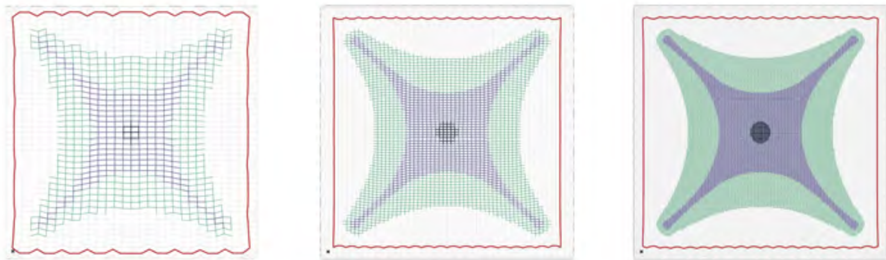
S2. CONCEPT MODEL: SCHEMATIC INPUTS FOR THE FORM-FINDING

The role of the Concept Model is to support the subsequent form-finding process carried out later on by the Simulation Model. Its additional role is to provide a *schematic* input that defines the *model structure* while accounting for the considerations required for form-finding. It functions as a setup space where the *design criteria*—such as the outer shape of the membrane and the methods for activating the textile into a three-dimensional state—are established as a preliminary scheme, often depicted in an abstract manner. Its simplistic representation allows for rapid adjustments, enabling quick design iterations by modifying the membrane typology—whether by redefining the membrane boundary or repositioning hybrid integrated elements.

MESH REPRESENTATION The Concept Model is initially defined by the *boundary* conditions of the membranes, which generate the *meshes* required for the particle-spring-based solver to execute the *form-finding* simulation. In this thesis, quad meshes are employed to represent the knitted membranes. Their dual directionality aligns particularly well with the warp and weft structure of knitted fabrics, making them a natural fit for simulating weft-knitted membranes.

KNIT PATTERN The discretized nature of the mesh enables flexible clustering of its segments for differentiated property assignments, facilitating the introduction of *patterns*. The knitting pattern is defined within the Design Model through the clustering of mesh springs - a linear element of the mesh being defined as the Concept model's **variable**, which can be manipulated and assigned different properties. The definition of the knitting pattern for the membrane surface is conducted schematically using *Graded Fields* — a method that employs a closed curve *outline* as a selection tool to define groups of mesh springs within the model. Graded Fields can be introduced manually, as demonstrated in KnitVault probe through geometrically drawn shapes, or generated automatically with the aid of geometric or structural analysis, as seen in Zoirotia and GraCe installations. The method is detailed in Publication 4 on p.211 (Sinke et al. 2022a) and mentioned in State Of Art in 2.3.3 on p.66.

CONSTRAINS AND ACTIVATION The membranes are *constrained* in space by assigning *anchor points* and *activated* three-dimensionally through the assignment of *load force directions*. For more complex design topologies that involve membrane interaction with active bending support elements, as seen in the hybrid membrane units of Zoirotia and in **F**4.5, the schematic Concept Model incorporates additional temporarily introduced cables. These cables facilitate the three-dimensional activation of the membrane during form-finding by leveraging their ultra-elastic contraction properties (Lienhard et al. 2014). Anchor points, load points, and temporary elastic cables serve as additional variables within the model and are assigned specific properties during the model's specification stage (*Treatment* in RbS).



F 4.3: Resolution and the pattern appearence. From 32x48 to 128x192 mesh subdivision.

RESOLUTION During the setup of the Concept Model, the resolution level is determined by considering the scale of the modelled membrane structure and the degree of surface differentiation required. The architectural scale of the membrane structures in the Design Model sets an appropriate resolution that balances the need for fine material differentiation with the computational efficiency necessary for rapid design iterations.

Since tension in knitted fabrics results in strain regardless of individual loop configurations, capturing intricate loop details is unnecessary, as previously discussed in the State of the Art chapter. Instead, this thesis adopts a *low-resolution* mesh to represent tightly knitted fabrics. This approach strikes a balance between computational cost and the level of detail in the resulting surface differentiation pattern. A mesh resolution that is too low produces a coarse, quad-like pixelated pattern, while a higher resolution smoothens the pattern's appearance **F**4.3.

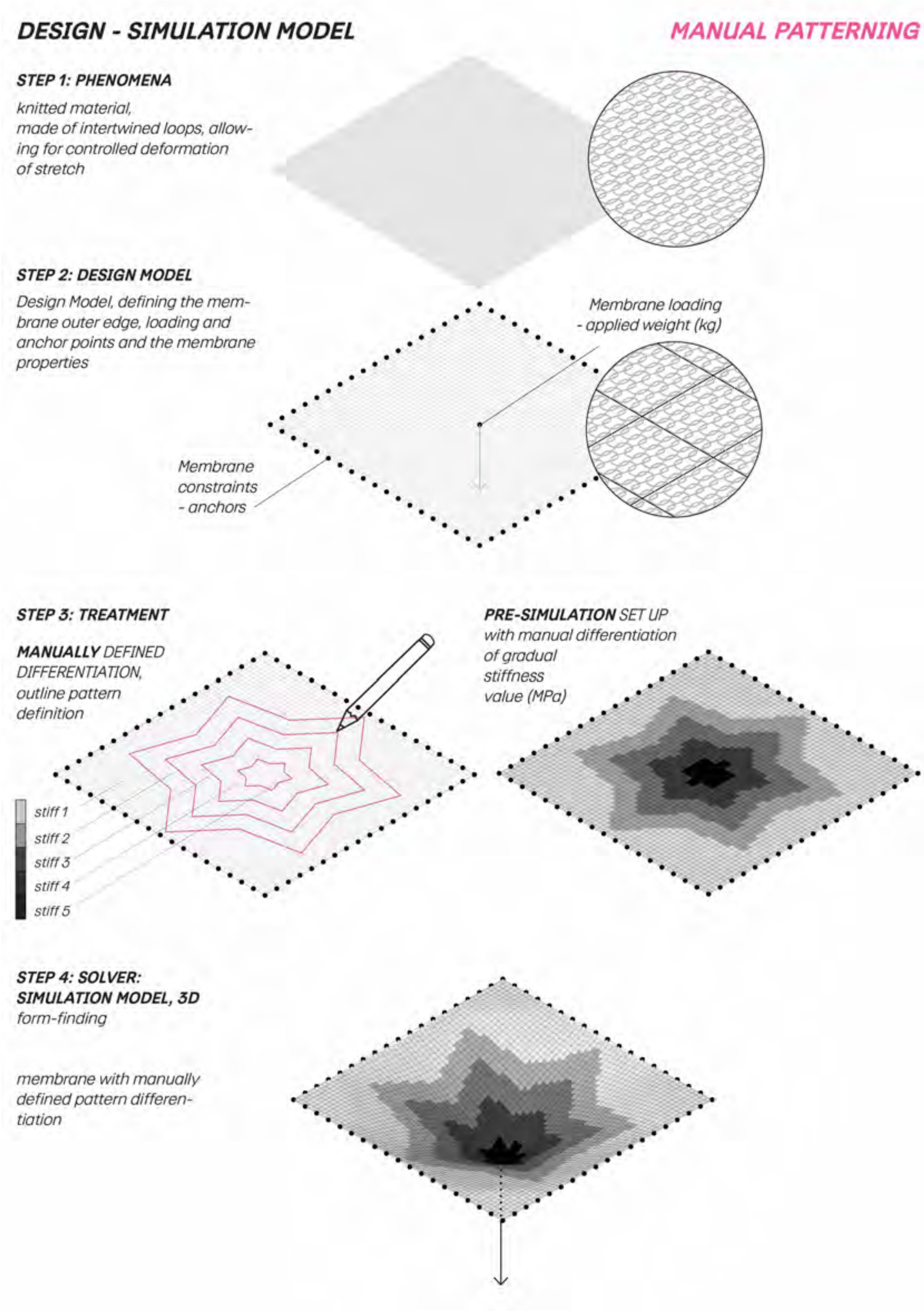
Building on Winsberg's Winsberg 2010 notion of "physical intuition," the meshes are *subdivided* based on the author's experience and expertise in working with knitted fabric simulations. This process envisions that each line of the mesh corresponds to an *n*-number of actual knitted stitches, as depicted in **F**4.4 and **F**4.5.

However, the preliminary resolution is a dynamic parameter that can be adjusted at any stage of the Design Model's development. The use of parametric modelling allows for resolution adjustments whenever it is deemed too low or too high, a process that was continuously applied during the evolution of the Design Model. Striking an optimal balance between mesh resolution and computational efficiency is crucial to creating a model that accurately represents the material system it simulates while also being functional and efficient.

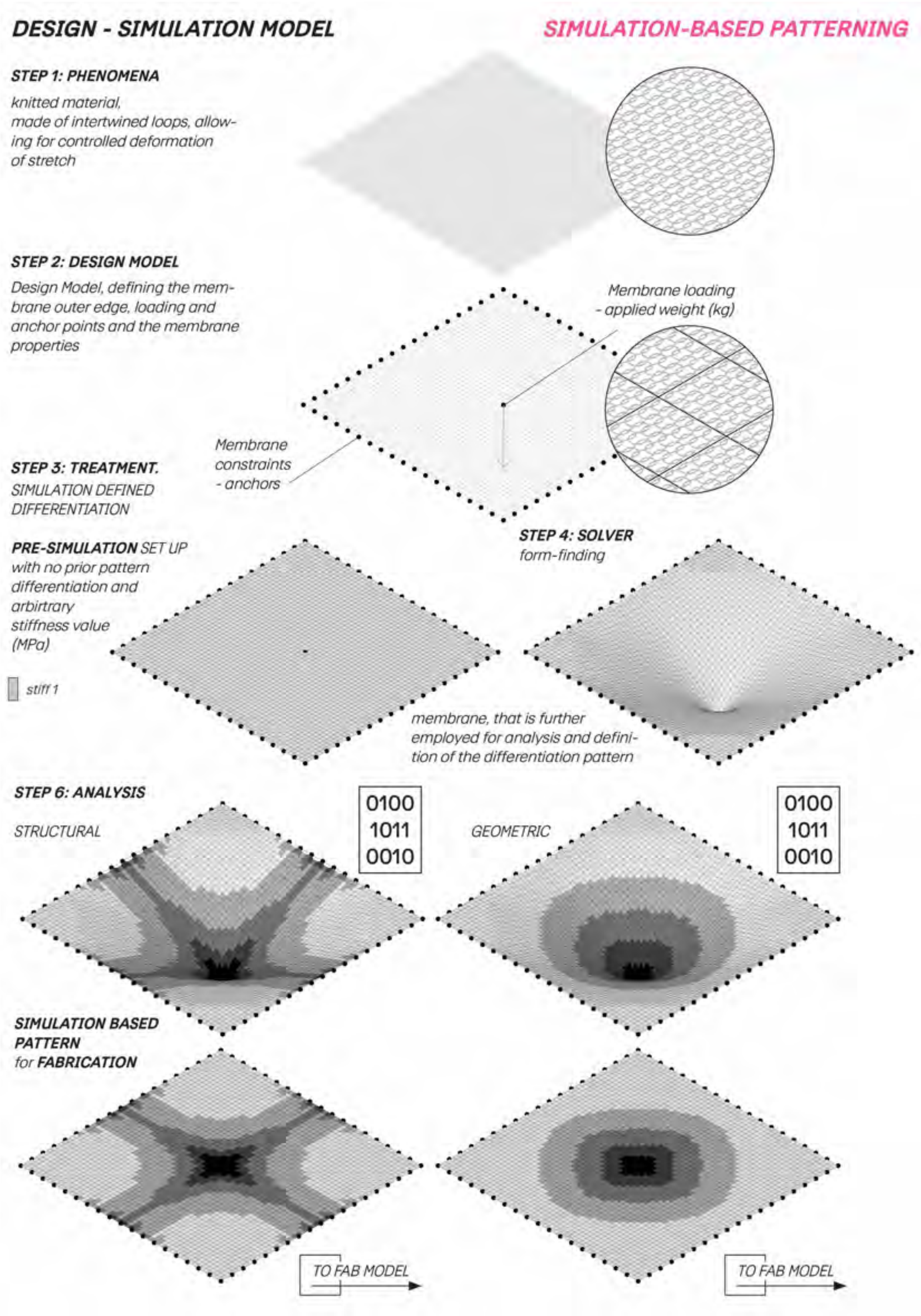
S3. CONCEPT MODEL SPECIFICATION

Once the aforementioned aspects are established and the Concept Model is finalized, it undergoes specification during the Treatment phase. This involves assigning specific numerical **values** to its **variables**, including mesh springs, anchor points, load points, and additional cables. Model specification (referred to as *Treatment* in RbS) is a critical step in preparing the schematic, pre-simulation Conceptual Model for the Solver, transforming it into a fully functional Simulation Model.

GOALS In Kangaroo2 (K2) and K2Engineering (K2Eng), employed for form-finding, the material properties of mesh springs are specified through *Goals*, a set of mathematical constraints or conditions applied to a geometric model, guiding the



F 4.4: Design Model - with manual pattern definition



F 4.5: Design Model - with simulation based pattern definition simulation towards a desired form or behavior. These Goals are packaged within specialized K2 and K2Eng components, enabling the simulation to capture various physical properties and actions, such as forces, elasticity, and bending, making the form-finding process both flexible and dynamic.

The Design Model, which utilizes both K2 and K2Eng goals, highlights distinctions in how mesh spring properties are assigned. In K2, the *Spring-Goal* maintains a specific rest length for each spring to simulate elastic properties and achieve the desired stiffness. In contrast, K2Eng's *Cable-Goal* prioritizes theoretical accuracy by incorporating material properties such as E-modulus (Young's modulus), cross-sectional area, and pre-stress, in line with established engineering principles. Both approaches — Kangaroo2's flexible material form-finding and K2Engineering's precision-driven engineering simulation—are explored in this thesis, providing a robust framework for modelling the differentiated material behaviours of knitted membranes.

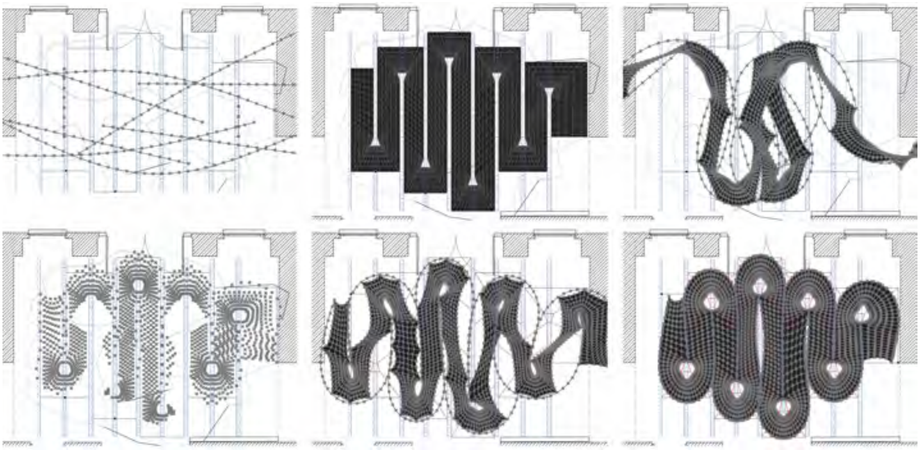
STIFFNESS VALUE CHALLENGE In this PhD research, mesh spring stiffness values are particularly critical within model specification, as these values are initially *unknown* due to the conceptual misalignment between the low-resolution quad mesh and the high density of knitting stitches it represents. While this thesis seeks to determine these values through calibration techniques presented in Research Track C, preliminary arbitrary values are assigned initially to ensure the functionality of the digital Design model.

The specification of other model variables, such as anchors and loads, serves a primarily technical purpose to ensure the Solver's convergence and the model's functionality. Anchor points are weighted to maintain their static positions in space relative to the strength of the assigned loads. While anchor values play a technical role, their distribution across the membrane surface opens opportunities for spatial exploration of the membrane. This distribution influences the redistribution of forces, affecting the generated knit patterns based on structural analysis, as demonstrated in the GraCe experiment presented in **P** 5.1.on p.153 and in **F**4.6.

The combined effect of mesh stiffness values and applied loading strength determines the behavior of the simulated mesh in the digital environment. This interaction is explored in the GraCe ceiling installation, as documented in **P**.5.1. In the digital simulation, homogeneous mesh stiffness values paired with varying applied loads produce deeper membrane shapes in areas subjected to heavier loads, resulting in differentiated membrane strain. Conversely, applying uniform loads across the digital mesh can still achieve differentiated strain by adjusting the material stiffness properties, allowing material differentiation to guide the strain rather than relying solely on variated weights.

F 4.6: Non-conventional membrane tension setup, featuring angled surface tension directions in GraCe ceiling installation. *Photo A. Ingvartsen*

In the physical realization, however, achieving the same three-dimensionality does not necessitate overextending the material capacities through excessive loading. Instead, the same effect can be accomplished by steering material differentiation to carefully control its strain, ensuring the structural integrity of the material while achieving the desired form. This contrast highlights the interplay between load and stiffness as a powerful mechanism in digital simulations and underscores the importance of material differentiation in practical applications.



F 4.7: Initial Model troubleshooting, ensuring the convergence of the Solver. The case study is a digital exercise of designing a ceiling membrane textile structure, taking advantage of knitting technology for continuous extrusion of material

S4. FORM-FINDING SOLVER - THE EMERGENCE OF SIMULATION MODEL

Once the pre-simulation Design Model is fully configured and specified through the *Treatment*, it transitions into the *Solver* phase. Here, the K2 Solver integrates all the parametric goals applied to the pre-simulation Concept model, driving it towards a state of equilibrium by balancing material properties, applied forces, and constraints. Running the Solver generates the *Results*, a comprehensive *data set* that captures multiple types of information simultaneously. This raw output typically consists of numerical values representing the status of various variables over time and space. To extract meaningful insights, the results are reconstructed into a *new model*, enabling key observations through *Visualisation* techniques. During this process, the mesh is rebuilt with new input parameters derived from the form-finding, allowing for a clearer understanding of the model's behavior and its response to the applied conditions. The rendered data produces a digital *Simulation Model* in the form of a *3D form-found mesh*, offering a visual representation of the solved equilibrium state. The Solver phase thus marks a transition point between the Concept Model and the Simulation Model, as the rendered data and its visualisation define the emergence of the latter.

S5. VERIFICATION & VALIDATION (V&V) OF THE DESIGN MODEL

Once the entire design-simulation workflow is established and structured, it must undergo *verification* and *validation* processes. *Verification* focuses on troubleshooting to ensure the model is technically sound, free from errors, and functions correctly. In contrast, *validation* assesses whether the digital model accurately represents the physical artefact. This distinction implies that *verification* primarily occurs within the boundaries of the Design Model and will be outlined further in this section. Validation, however, spans across multiple model domains, involving both the results of the Design Model simulations and the physical artefact produced by the

Fabrication Model, which will be discussed in the next section. Consequently, the discussion on Design Model validation is deferred to the Evaluation Model section later in the chapter, where the digital and physical models are compared, enabling the calibration of the Simulation Model. Below, meanwhile the technical aspects of *verification* are presented.

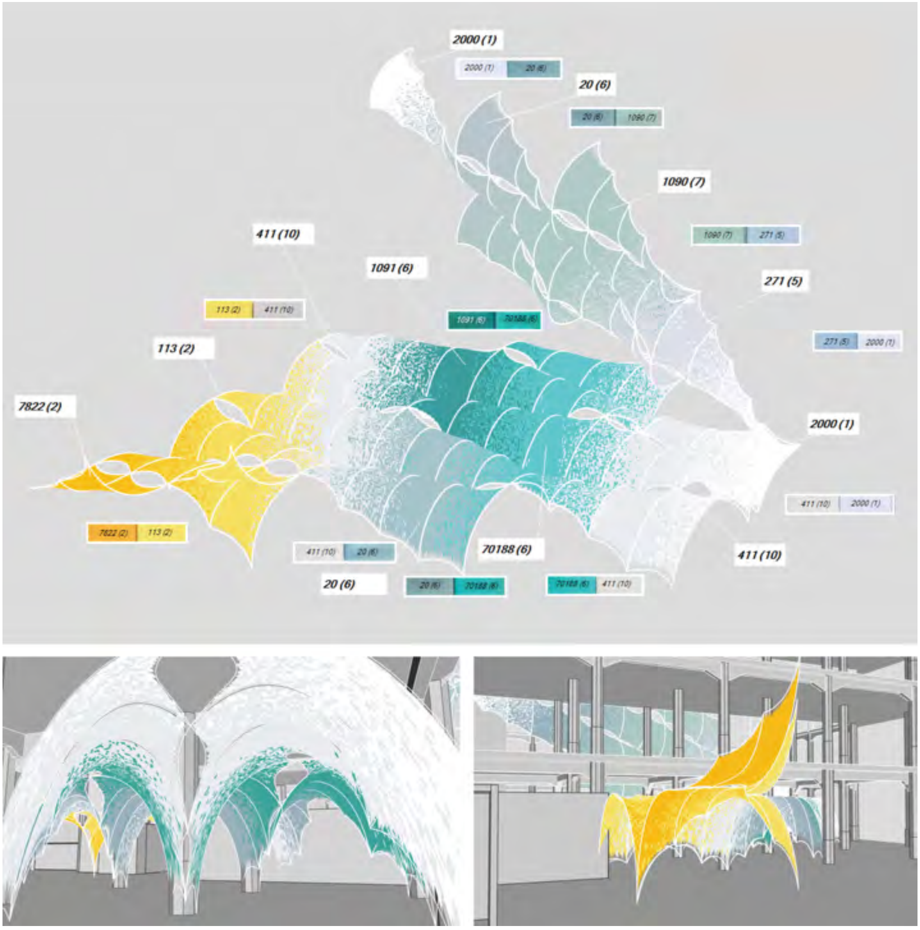
VERIFICATION Given the interconnected nature of data within the Design Model, it is essential to detect and address technical errors early through rigorous troubleshooting to prevent them from impacting subsequent design, simulation, and fabrication stages. Troubleshooting activities for the Design Model primarily focus on model considerations and specifications, following a systematic approach to isolating parameters for targeted problem-solving. Verification of the Design Model, involves several key steps: 1) Checking the placement of constraints and loads relative to the mesh, ensuring proper snapping and the mesh's resistance to applied forces.; 2) Verifying the direction of loading vectors to ensure accurate tension distribution.; 3) Reviewing the data tree structures to confirm correct mesh clustering ensuring appropriate differentiation of material properties into surface patterns. These verification steps ensure that the solver converges correctly and that the model adopts the intended topology. Visualisation techniques play a critical role in this process by presenting output results in a visually observable form. They enable the assessment of the resulting membrane topology, informed by general principles of mechanical theory and physical intuition gained from prior experience, while helping to identify problematic areas when necessary.

Once the model is verified, it is functional but not yet fully accurate, as it still requires calibration against a physical prototype. However, ensuring the entire design workflow operates as a cohesive system, even without complete precision, is crucial. This creates a *working* foundation for subsequent modelling activities related to the fabrication of the physical artefact, which is vital for finalizing the Design Model through calibration processes that enhance its accuracy. Early error detection during the verification phase ensures that the Solver converges to a functional model, laying the groundwork for the development of the Fabrication Model and subsequent stages.

COLOUR MODEL FOR CHROMATIC SURFACE DIFFERENTIATION

In addition to integrating the structural performance of membrane designs, the Design Model addresses the challenge of incorporating an additional layer of material differentiation through yarn material changes, enabling chromatic variation across the surface. An auxiliary Colour Model was developed as part of the large-scale Zoirotia commission, utilizing the outputs of the form-finding 3D meshes for mapping and exploring colour distribution spatially. This achievement allows for the simultaneous differentiation of surface features, enabling the membranes to function structurally, achieve three-dimensional shapes, and convey visual messaging through graded surface colouration.

The Colour Model serves as a schematic conceptual framework for distributing colour across a large network of membranes. It tackles scalar challenges inherent in large-scale designs while ensuring that the surface maintains both its structural and aesthetic integrity. The numeric methods devised to handle colour representation for digital knit manufacturing in the context of low-resolution meshes are discussed in greater detail within the section dedicated to the Fabrication Model later in this



F 4.8: Schematic Colour Model, offering spatial exploration of colour mapping onto the membranes. *Sinke 2021*

chapter and in **P**3 on p.227.

4.1.2 ADDRESSING KNIT MATERIAL DIFFERENTIATION FOR TARGET SHAPE

At this stage of the Design Model's workflow development, the *working* output of the Design Model, in the form of a 3D mesh, contains extensive information that can be extracted for various analytical and computational purposes. The analysis techniques evaluate the *topological* and *structural* features of the membrane's preliminary designs, establishing connections between the mesh topology and structural performance. These insights link back to the mesh spring values, which can subsequently be utilized by the Fabrication Model to translate them into local knit material differentiations, thereby creating a closer relationship between form and matter. Up to this point, unless surface grading is manually defined through zonation, the mesh operates as a homogeneous entity without distinct local properties, functioning primarily as a generic form-finding model that assumes uniform material composition. However, the Design Model incorporates the capability to assign distinct properties, enabling the simulation to represent differentiated material behaviors. This feature facilitates the exploration of material-specific variations and their impact on both the structural performance and visual characteristics of the membrane designs.

As previously discussed in the State of the Art chapter on p.68, this thesis explores an *unconventional* however novel approach to addressing local material differentiation to influence the global shape of the tensioned membrane. This is achieved through *inverted stiffness strategy*, where areas of the membrane experiencing the highest force concentrations are assigned the lowest stiffness values. This approach leads to greater strain in the mesh under applied loads, creating a structural membrane system where the differentiated surface yields more readily to forces. As a result, the membrane undergoes greater expansion and stretching, ultimately achieving a higher degree of three-dimensionality — a characteristic previously identified as advantageous for the structural performance of tensile membranes.

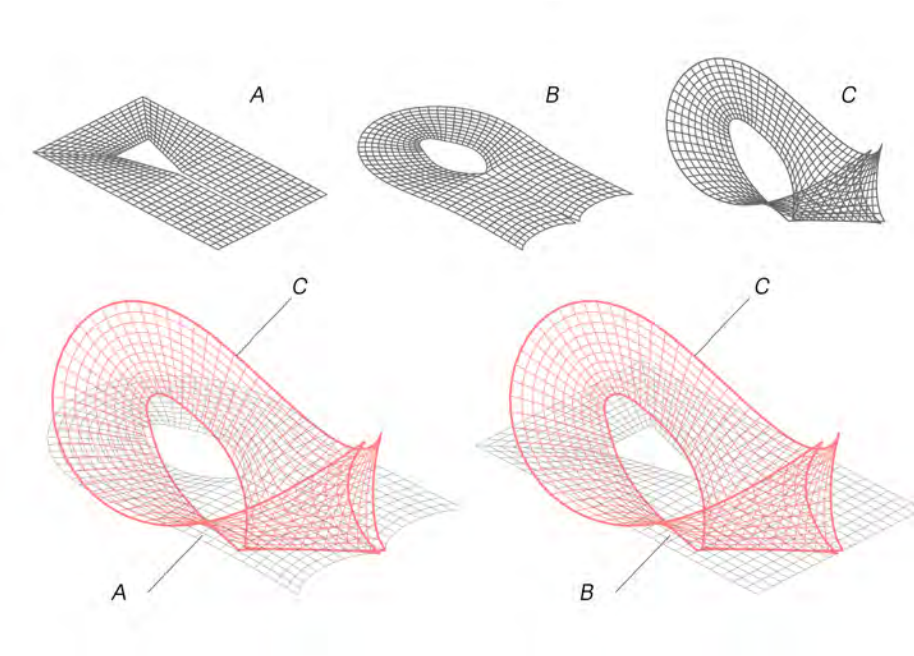
ANALYTICAL TECHNIQUES FOR KNIT MATERIAL DIFFERENTIATION

The analytical techniques integrated into the design workflow to guide controlled material differentiation encompass both *geometrical* and *structural* approaches.

GEOMETRICAL ANALYSIS *Geometrical analysis* extracts the *topological* features of the membrane by comparing the final form-found Simulation Model with an intermediate, pre-stress model. Geometrical analysis is better suited for capturing the physical transformations of the membrane as it transitions through various form-finding stages. By comparing intermediate (B) and final mesh states (C) in **F**4.9, it identifies regions experiencing significant displacement or movement. These areas are assumed to be more structurally active during the membrane's erection and are prioritized for material differentiation to accommodate their higher strain. Geometrical analysis thus focuses on the visual and spatial behavior of the membrane, providing a clear pathway for shaping and patterning based on the observed deformations.

STRUCTURAL ANALYSIS In contrast, structural analysis focuses onto the internal forces and stresses distributed across the membrane, focusing on how the material system responds to applied loads. Rather than comparing mesh stages, structural analysis evaluates the equilibrium state of the form-found model, using K2Engineering outputs to calculate the axial stress and forces acting on individual springs. This method offers a more precise and quantitative understanding of the membrane's structural performance under specific loading conditions. Structural analysis is crucial for identifying stress concentrations, load distribution patterns, and areas where material properties can be strategically adjusted to optimize performance, where the simulation aid to grasp the internal processes inside the material unseen externally.

The technical aspects of structural analysis, including the K2Engineering components used and the equations underlying them, are detailed in **P**6 (p.5 in **P**6) on p.167, while the more detailed methodologies for both analyses are introduced



F 4.9: Methodology for geometrical (middle) and structural (right) analysis through comparison of meshes various stages

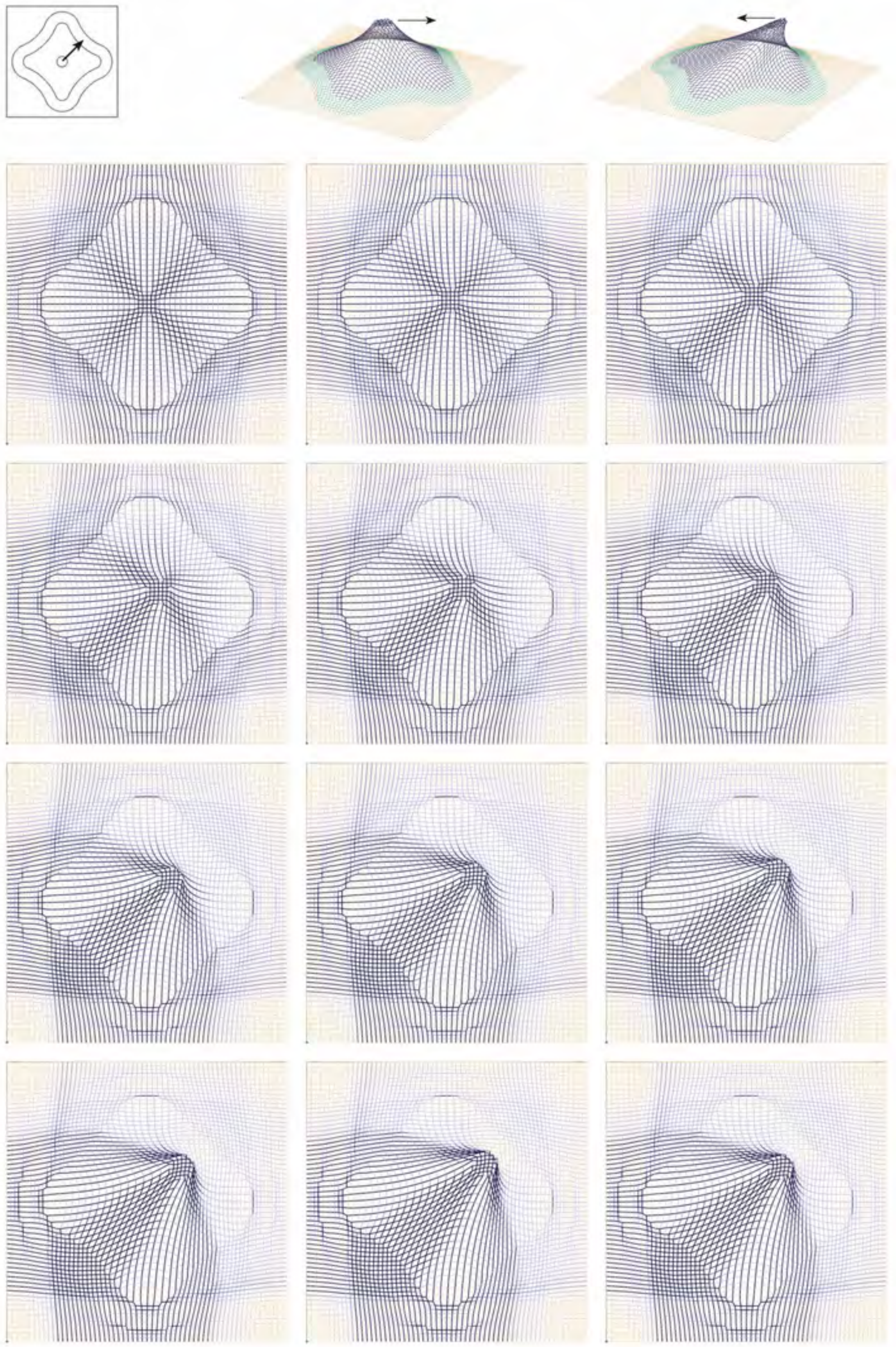
in **P**5.1 (Sinke et al. 2023a). This section, however, focuses on discussing the verification and validation aspects of these analytical techniques.

Geometrical analysis is particularly useful for identifying areas where more elastic or deformable materials should be placed, based on observed deformation patterns. In contrast, structural analysis pinpoints regions that require reinforcement or stiffer materials to handle stress concentrations.

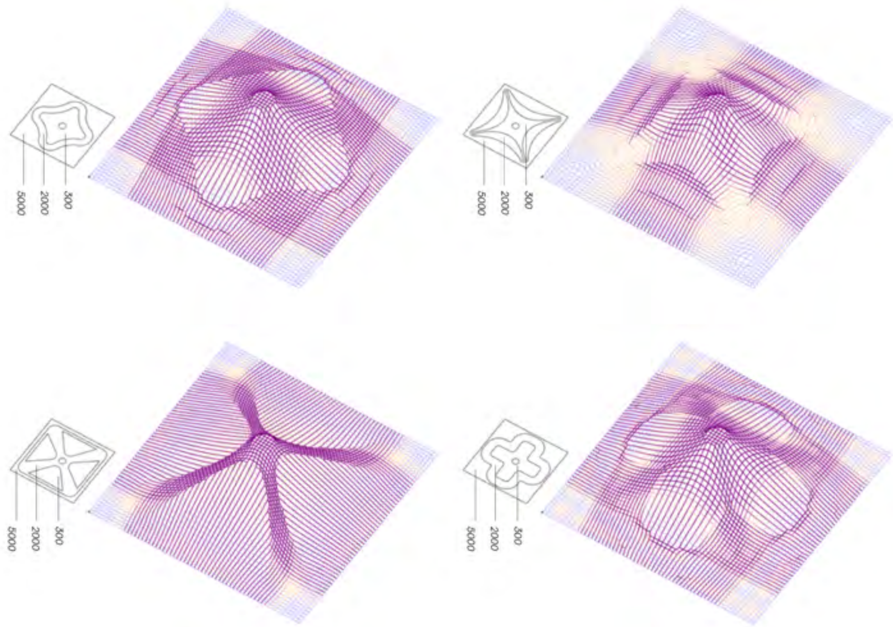
VERIFICATION OF ANALYSIS TECHNIQUES

Since the analysis techniques in the Design Model play a critical role in guiding the development of pattern strategies within the Fabrication Model, verifying these techniques is essential to avoid the propagation of errors. Incorrect data could lead to flawed pattern generation and unexpected textile behavior. Verification addresses issues that may arise, ranging from minor technical problems, which can be resolved through numerical verification and calculation adjustments, to more fundamental concerns about data distribution that challenge the validity of the analysis approach. Ensuring accuracy at this stage safeguards the reliability of the workflow and the performance of the resulting textile system.

The analysis data is visualized by mapping numerical values onto the model variables, such as mesh springs. Validating each analytical approach requires a clear conceptual and theoretical understanding of the underlying processes. An initial assessment to determine whether the analysis requires troubleshooting is performed visually, comparing the outcomes with physical intuition and foundational knowledge in engineering and structural mechanics. Additionally, seeking a second



F 4.10: Responsiveness test on simulation with the following visualisation of forces. *Sinke 2019*



F 4.11: Tension concentration in areas with higher material stiffness. *Sinke 2019*

opinion from experts in engineering can further strengthen the verification process, fostering confidence in the chosen analytical technique and its methodology, as was done in this thesis.

GEOMETRICAL ANALYSIS VERIFICATION. The outputs of the *geometrical* analysis are assessed by observing the visualisation of its data. The spatial displacement aspect used in geometrical analysis can be logically interpreted, with peaks expected around points of applied loads and a gradual dissipation further away from these points. Additionally, minimal surface displacement is anticipated near physically constrained areas of the membrane, such as edges. The validation of geometrical analysis is demonstrated in the "GraCe" square ceiling panels, where distributed weight conditions produce overlapping and merging *circular-like* patterns. Similarly, in the "Zoirotia" installation, the displacement pattern exhibits circular-like clustering around points of membrane tension created by the cable net. These examples confirm the predictive capacity of the geometrical analysis and its alignment with physical expectations.

STRUCTURAL ANALYSIS VERIFICATION. For structural analysis, which involves the calculation of axial forces, a different logic and theoretical framework are required to verify the outputs. According to mechanical theory, forces in textile materials distribute along the shortest path from the points of applied loads to the areas of restriction, such as clamping at static supports. In the case of the square panels of KnitVault or GraCe, with single or multiple points of applied load, the visualisation of force distribution is expected to exhibit a "cross-like" pattern around a single load point. For multiple loading points, the force distribution becomes more complex, with overlapping and merging "crosses" forming intricate patterns. The diagram in **F**4.11 additionally verify the calculation of stress in mesh, as showcasing the concentration of higher tension values in the areas of stiffer mesh properties. An additional layer of robustness in the structural analysis technique is achieved by verifying it against the dynamic response of the membrane during manipulation of its initial topology through changes in the loading vector. For example, in **F**4.10, shifting the loading vector alters the geometry of the cone by moving it off-center, thereby redistributing forces and their visualisation on the mesh in a manner consistent with theoretical expectations. The digital exercise of structural analysis applied to the more complex topology of Zoirotia (**P**6, sec 4.3) further demonstrates that the resulting structurally based patterns adhere closely to the unit's topology.

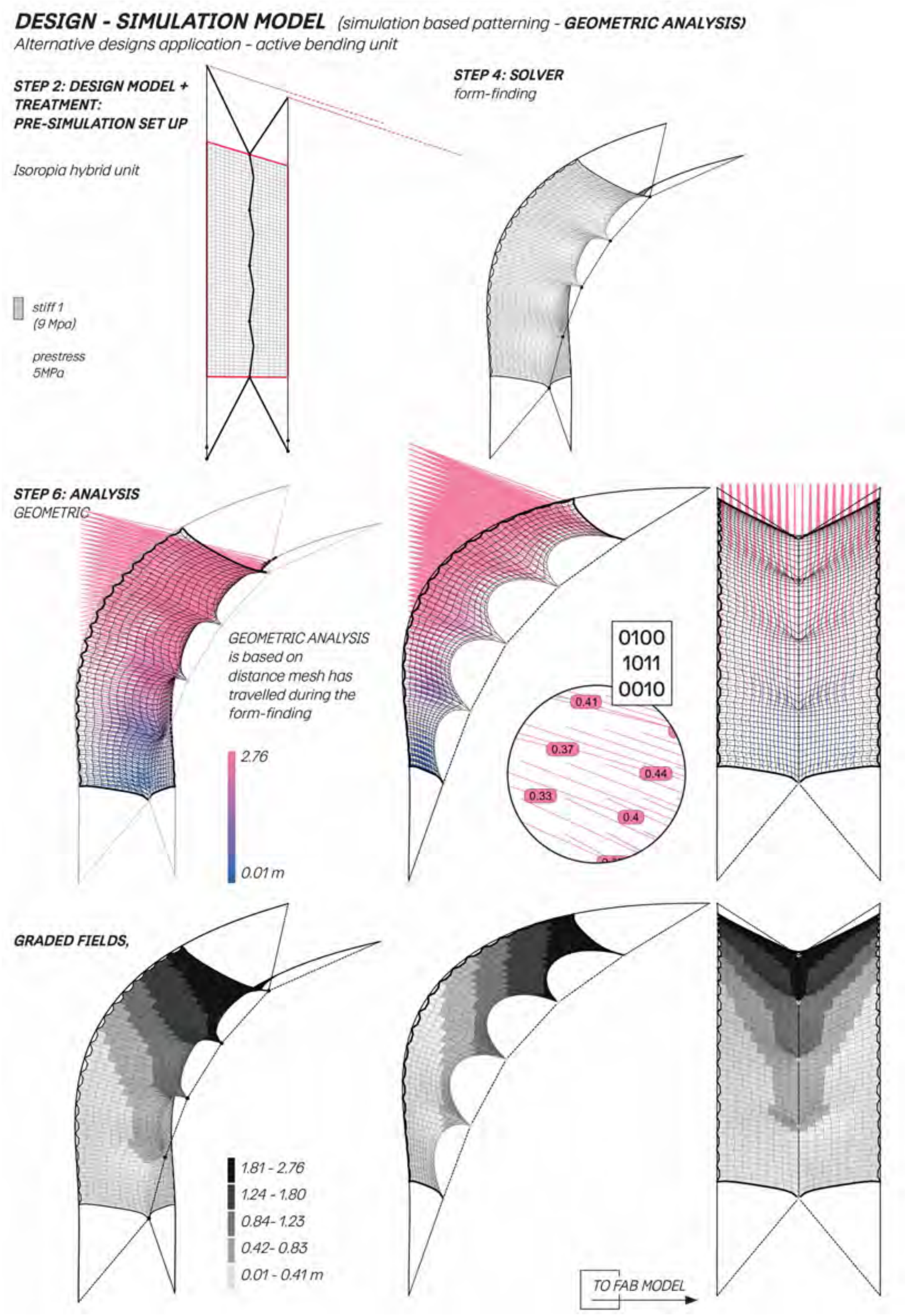
The structural analysis method is further validated by performing the wrinkle-less textile performance tests and observations on the *GraCe* ceiling panels, as detailed in Publication 6 (section 4.2, fig.11). This validation demonstrates the effectiveness of the structural analysis in guiding the local material differentiations based on the global membrane performance, particularly under the unconventional loading conditions with the **angled pulling** directions. For further details regarding both geometric and structural analysis, please refer to **P**5.1 and 6 in this thesis, located on pages 153 and 167.

This section provides additional validation of the analysis techniques by reapplying them to alternative membrane geometries, as presented in the complementary diagrams **F**4.12, **F**4.13, **F**4.14, and **F**4.15. In these examples, the Isoropia-inspired tensile membrane unit, anchored to the ground, exhibits a slightly different knit pattern compared to the circular-like patterns observed in Zoirotia. This variation arises due to differences in the units' activation logic. While the Zoirotia units are tensioned by a cable net from initially bent and prestressed bow elements, the Isoropia unit is bent downward from a vertical position. This bending introduces higher stress at the top of the membrane, as it must bear the effort of pulling the entire unit into the bent configuration.

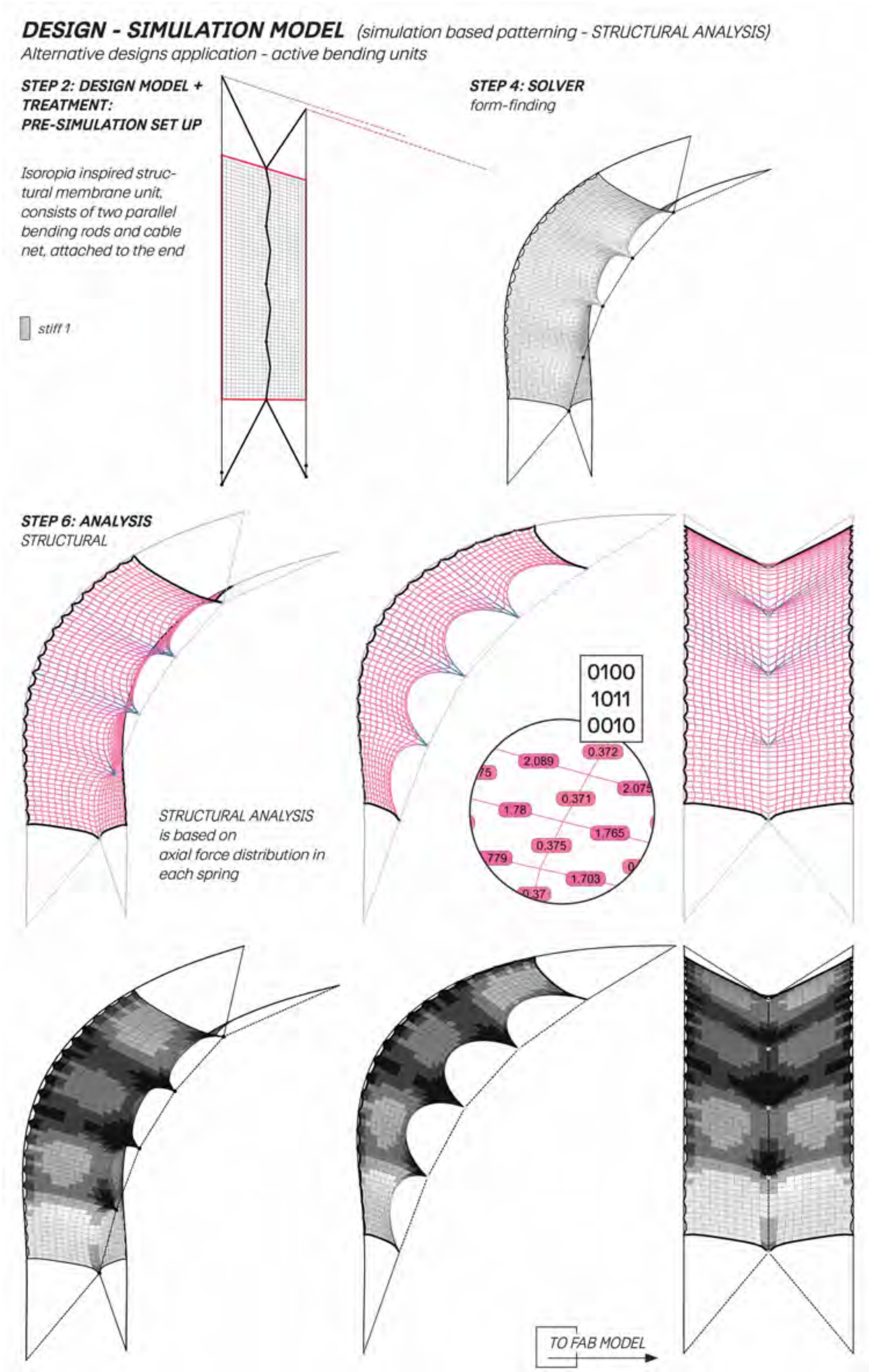
This exploration, conducted purely digitally (without making a physical prototype), validates the functionality of the geometrical analysis approach. It highlights the potential for further research into physically producing these knit patterns and comparing their performance. Additionally, the U-unit illustrated in **F**4.14 demonstrates the successful reapplication of the developed analysis techniques to novel membrane topologies not previously explored in the associated publications.

In summary, integrating analysis within the Design Model is critical for addressing knit material differentiation and answering Research Question A. The analysis establishes a bridge between global membrane forms and local material differentiation by applying logic based on material displacement and the structural response to external forces. This approach enables the generation of novel, computationally derived knitting patterns for material differentiation—patterns that would otherwise remain undiscovered without the use of analysis tools.

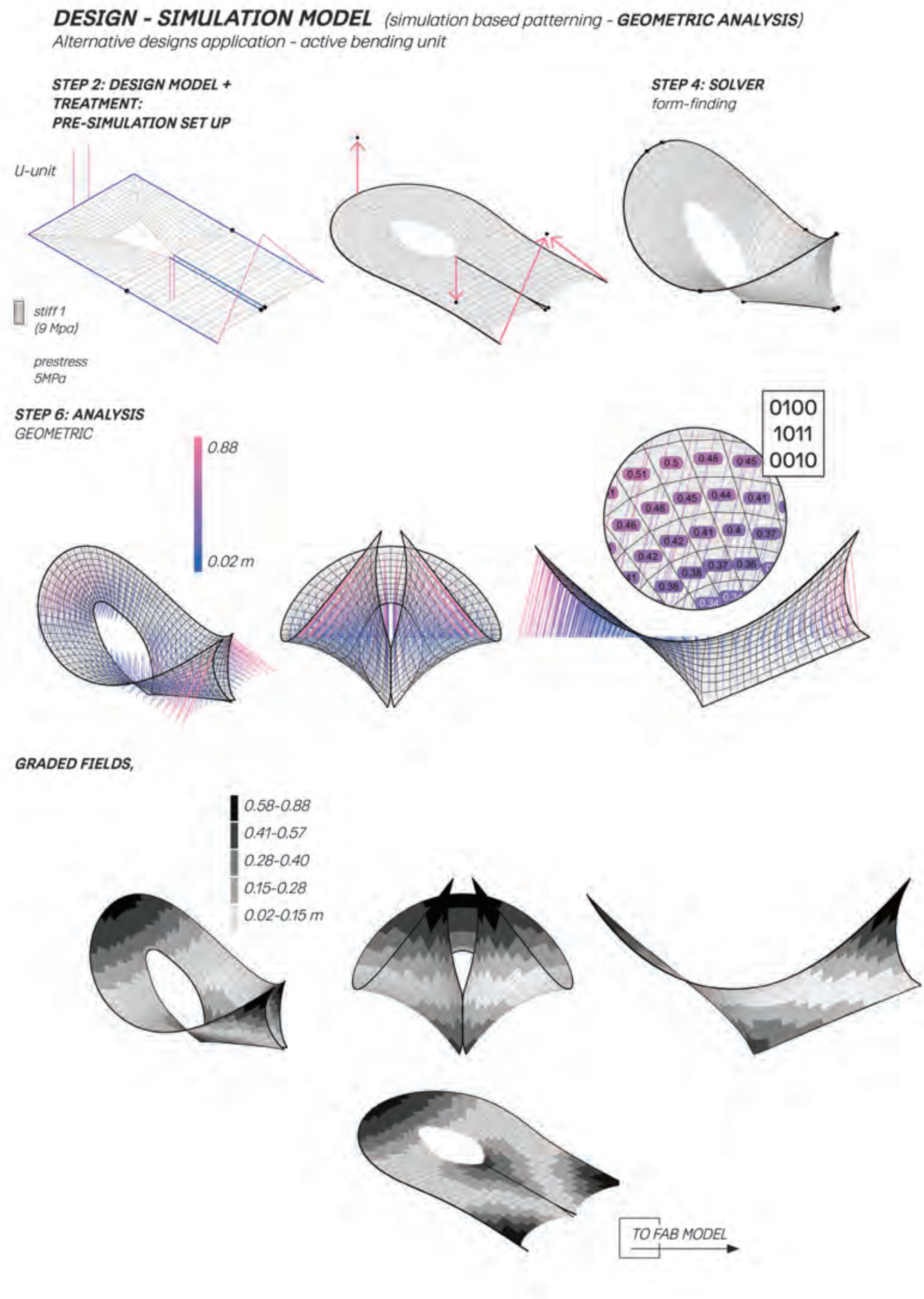
Furthermore, the analysis significantly enhances the epistemological role of *simulation* within the Design Model. It elevates simulation from a purely technical form-finding tool to an exploratory and prescriptive tool capable of introducing novel clusterings within the mesh and, consequently, novel material gradings for knitted fabrics. This digitally refined setup with clustered mesh properties more accurately represents the differentiated characteristics of physical knitted membranes, contributing to a more robust and informed design process.



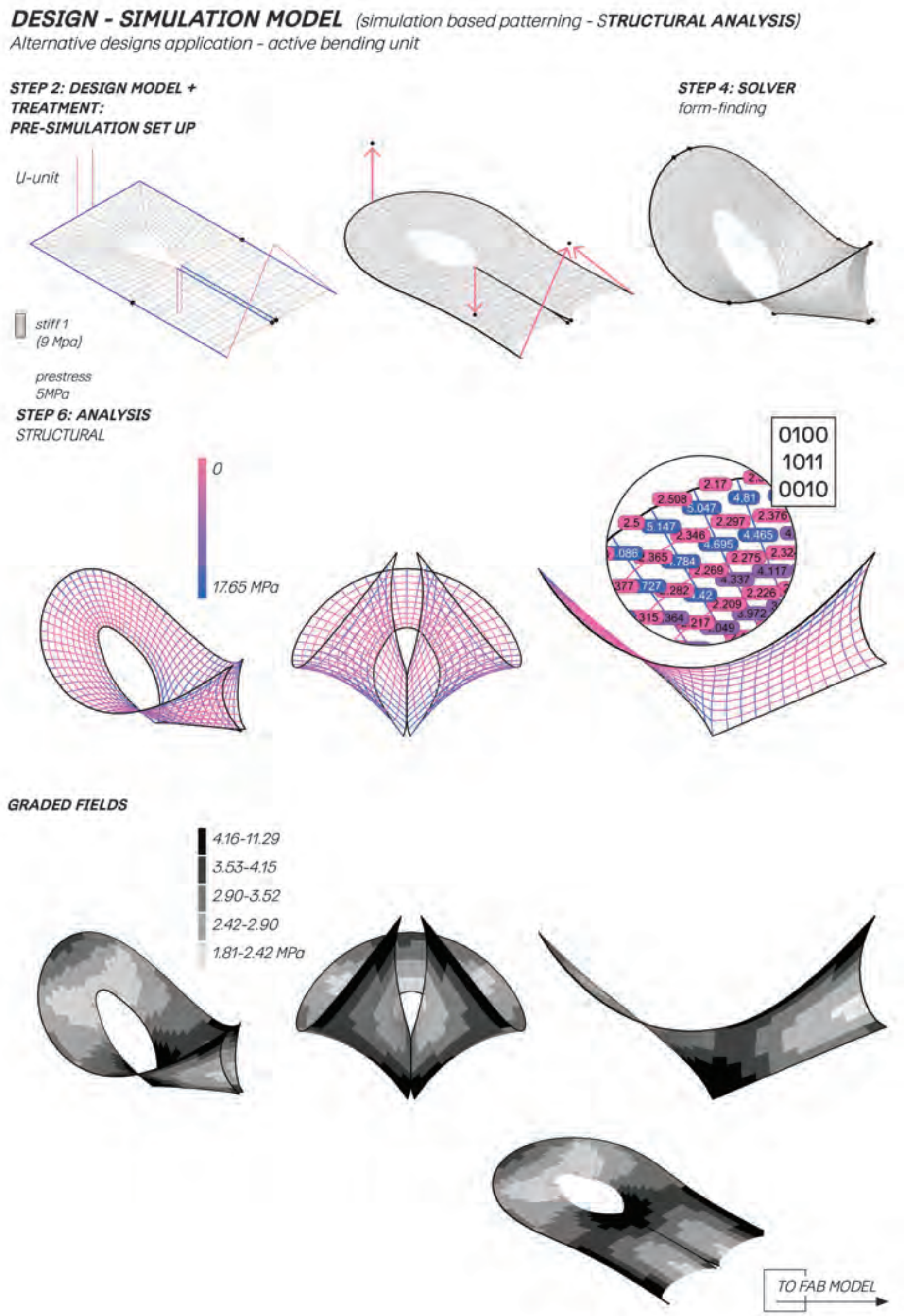
F 4.12: Design Model: Isoropia Hybrid unit. Geometric-based analysis for patterning



F 4.13: Design-Simulation Model, Isoropia Hybrid unit. Structural-based analysis for patterning



F 4.14: Design Model U unit - geometric analysis

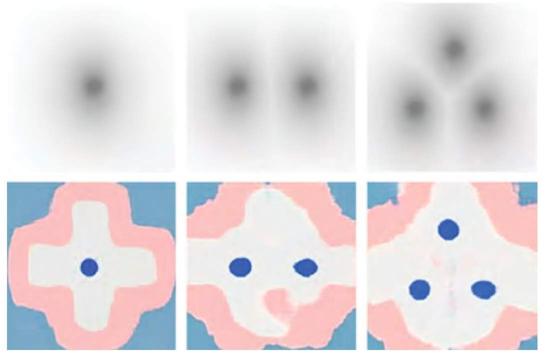


F 4.15: Design Model U unit - structural analysis

MACHINE LEARNING FOR STEERING MATERIAL DIFFERENTIATION

An alternative approach explored in this thesis for addressing material differentiation involves the use of *Machine Learning (ML)*. This approach investigates the discovery of knitting grading patterns based on target membrane shapes, entirely bypassing the three-dimensional parametric digital modelling and simulation process.

Machine learning algorithms operate as complex mathematical models capable of solving unknown systems by learning and mapping relationships between inputs and corresponding outputs derived from real-world results. This exercise is detailed in **P**2 (Sinke Baranovskaya et al. 2021), where a dataset comprising nine physical prototypes serves as the training input. There ML approach establishes links between manually designed surface patterns of KnitVault and their corresponding strain performance, recorded by scanning the physical membranes and translating it into gradient monochrome image representing the depth of stretch under consistent loading conditions. This setup allows the ML algorithm to learn between two pair of images - the knitting pattern and the strain diagram - and potentially generate from these relationships the knitting patterns based on the desired strain performance of the membrane, bypassing traditional simulation workflows.

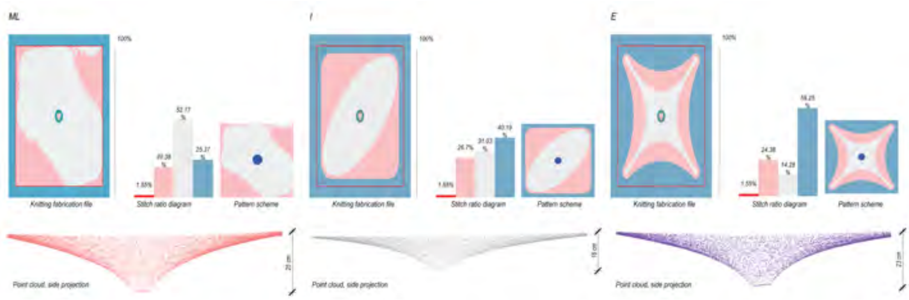


F 4.16: Machine learned patterns based on the novel target strain diagram with three points of stretch. *Sinke, Gatz et al. 2020*

In this exercise, through the learning process, the ML model generates pattern suggestions for a target three-point loading condition. The resulting patterns resemble those derived from geometric circle-like analysis outputs (**P**2, fig.10, p.317) and **F**4.16. The emergence of circle-like pattern topologies can be attributed to the training dataset, which consists of manually designed pattern proposals. However, these proposals were not systematically verified against the global membrane shapes using geometric forms but were intuitively designed following the displacement logic and intuition.

The validation of the ML approach through the production of a physical prototype revealed some deviations from expectations (**F**3.22, p.116), particularly in the differences observed in membrane depth despite using the same target strain diagram. This ambiguity arises from the insufficiently distinct strain differences in the knit stitches, specifically piquet and piquet lacoste, which were used for the knitting pattern. These limited distinctions resulted in less precise outcomes. While this experiment remained a single exercise, it highlighted the need for further research into alternative stitch types with greater variation in strain properties, aiming to achieve more pronounced and visible differences in surface characteristics.

Further exploration of ML techniques could enhance the process by incorporating structurally informed patterns paired with their corresponding physical prototypes. This refinement would enable a more robust verification of structural analysis outputs, providing an ML-based alternative for visualizing and guiding material differentiation. By training on structurally informed input patterns, ML could better respond to the structural behavior of membranes, elevating its potential as a complementary or alternative model for steering material differentiation.



F 4.17: Comparison of membrane performance, with manually designe patterns vs. machine learning derived. *Sinke, Gatz et al. 2020*

DESIGN-TO-FABRICATION TRANSFER

While the simulations and analysis discussed in this chapter provide the tools for exploring the design possibilities of CNC-knitted graded material systems — by predicting and visualizing the behavior and forms of knitted membranes — their true value lies in the real-world application through the manufacturing of the CNC-knitted membranes. Without this step, the simulations remain as theoretical exercises, while the Fabrication Model is essential for bringing the digital designs into life by transforming simulations into the physical outcomes.

This section concluded with the publication appendix, while the the next section introduces the Fabrication Model, which translates these simulations into tangible products by converting the analysis data into the localised material differentiations, represented through the actual knitting instructions, used on the industrial knitting machine. This process involves establishing the connections between the Design and Fabrication Models in order to bridge the domain differences between the digital design exploration and the physical production spaces.

DIFFERENTIATED KNIT MATERIALITY

Publication **5.1**

INTEGRATED DESIGN MODELS FOR MATERIALLY DIFFERENTIATED KNITTED TEXTILE MEMBRANES:

AS MEANS FOR SUSTAINABLE MATERIAL CULTURE WITHIN MEMBRANE ARCHITECTURE

(Part I)

Integrated Design Models for Materially Differentiated Knitted Textile Membranes as the Means to Sustainable Material Culture Within Membrane Architecture

Yuliya Sinke, Mette Ramsgaard Thomsen, and Martin Tamke

Abstract

Material design and production must be rethought in light of limited resources, contributing to UN Sustainable Development Goals, promoting sustainable industrialization and fostering innovation. Currently, building practices rely on composite materials to meet a variety of performance demands, by bonding different materials together. This results in problems of reuse and recycling at the end of life, as they are hard to separate. As an alternative, functionally graded materials (FGMs), such as CNC-knitted membranes, allow the steered intensification of a single material in order to meet multiple performance requirements and ease their further reuse. Current architectural design practice conceptualises matter as homogeneous, while novel FGMs, and knitted architectural materials in particular, require radically different methods and tools for their design and digital representation. Given their extreme heterogeneity, complex material behaviour prediction and additive manufacturing nature, there is currently no ready-to-use software to address these challenges. In order to improve the quality of taken design decisions, better reflect knitted FGMs characteristics and pave the way for more sustainable production using FGMs, it is essential to create integrated design models, considering material heterogeneity, structural performance and fabrication constraints of such materials. In this research, we examine how CNC-knitted membranes, having versatile material structures, can be designed with heterogeneous composition. It is done through the development of custom digital tools that reflect their differentiated structure, analyse tensile performance and perform materially oriented simulation, while taking into account fabrication constraints (figure below). We describe a novel approach to inform the differentiation of knitted membranes by structural analysis and a method for calibrating heterogeneous membrane simulations. By utilising computational tools for structural performance evaluation, Graded Knitted Ceiling panels demonstrate how custom-made bespoke membranes can be materially differentiated and how such designs can then be simulated and calibrated based on the physical results.

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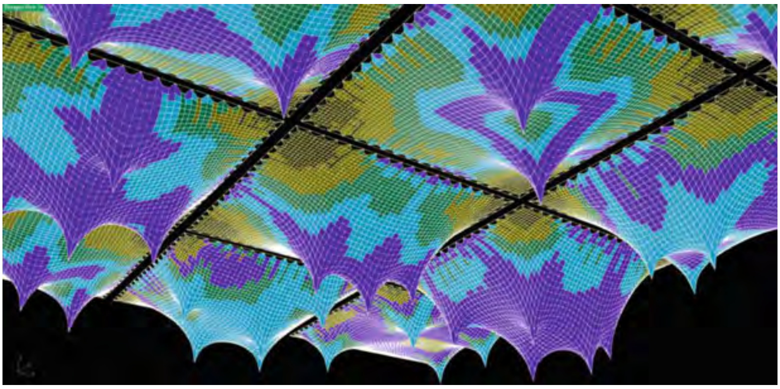
Graphical Abstract

A digital integrated model for graded knitted membranes incorporating aspects of material heterogeneity, digital simulation and fabrication constraints



Keywords

Integrated design models · Simulation of functionally graded materials · CNC-knitted architectural materials · Textile architecture

1 Introduction

1.1 The Scarcity of Resources Incites the Rethinking of Material-Making Culture

Resources scarcity forces us to rethink how materials are designed and made in contemporary design and building culture. This challenge is inciting research into new material practices that optimise resource allocation and reduced waste (Ramsgaard Thomsen et al. 2019a), contributing to the UN Sustainable Goals. Following of these goals ensures responsible production and good use of resources, promoting inclusive and sustainable industrialisation and foster innovation as described in detail in Sustainable Development Goals 12 and 9 (United Nations, Department of Economic and Social Affairs 2015). By moving from the paradigms of standardisation and mass production, these new practices position the making of hyper-specified and functionally graded materials for site- or use specific applications as central means of building smarter with less (Fig. 1). The advent of advanced fabrication techniques, supported by computational technologies, has enabled a differentiated distribution of resources for making novel high-performance materials. Despite these advances, design culture often remains disconnected from truly exploring the material understanding and opportunities for variation and mass-customisation digital fabrication enables.

1.2 The Contemporary Architectural Material Culture of Composites

Architectural material culture can be described through the implementation of technological innovation in the architectural design processes and applications. Today architectural materials and elements are mainly designed and made as *composites*, where several homogeneous matters are fused to achieve multi-functional properties. Despite their benefits for diverse applications, the composite nature of fused homogeneous materials reduces their circular economic value, as they cannot be separated for further recycling.

In lightweight membrane architecture composites are generally comprised of homogeneous woven substrates with a waterproof coating to provide strength and protection from sun and rain. The membrane property variation is achieved by sewing together multiple patches of

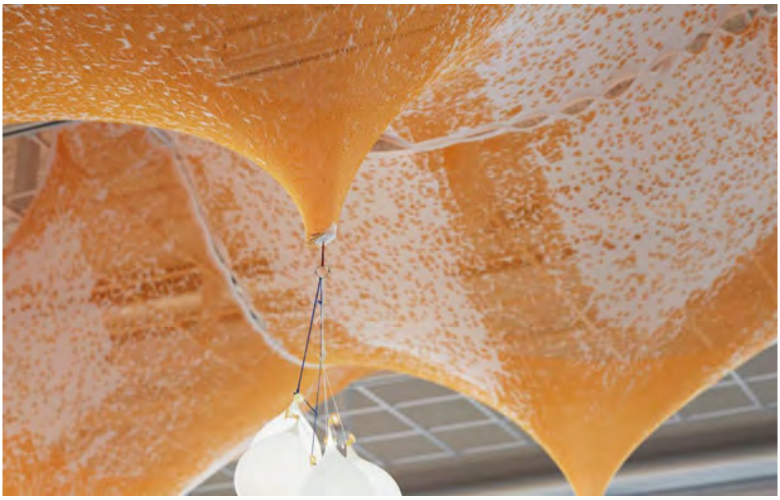


Fig. 1 Functionally graded CNC-knitted membranes use single yarn and are varied in their stretch properties

varying material properties, such as stiffness, fibre direction, transparency or permeability. The practice of pattern cutting and sewing leads to increased resource consumption as well as more waste during production. Furthermore, cut-out patches of conventional membranes can be hardly reused due to their composite structure and overspecified shape. Finally, seams produce undesired accumulations of internal material stresses, thereby reducing structural performance and creating a risk of material failure.

1.3 Future Architectural Material Culture of Functionally Graded Materials

The functionally graded materials (FGMs) are an alternative to composites. They have been the subject of research in material science, chemistry and computer graphics for many decades (Beukers and van Hinte 1998) and today are used in aerospace, nuclear energy, biology, electromagnetism, optics, energy and other fields (Li and Han 2018). The emergence of additive manufacturing, supported by computational interfaces, led to new fabrication processes of digitally controlled material deposition, enabling the production of FGMs of higher grading complexity (Richards and Amos 2014; Grigoriadis 2015). FGMs, therefore, have the advantage of integrating multiple properties and varying densities by grading the application of the same matter. In contrast to composites, FGMs allow the material properties to change continuously throughout the object, eliminating the problem of residual internal stresses and easing their further reuse. With the introduction of material heterogeneities in the design domain, various material advantages can be explored, while material incompatibilities can be alleviated with a gradual material variation (Kou and Tan 2007).

1.4 Knit as a Case of FGMs Within Structural Knitted Membranes

Within this research, CNC-knitted membranes are presented as examples of functionally graded materials in membrane architecture. By developing methods for utilising their heterogeneous compositional nature, they represent the practice of steered performance and reduced material use. The additive fabrication process of knit manufacturing offers opportunities to control membrane composition by strategic allocation of various stitches. Here, the membranes achieve their required three-dimensionality through material expansion, allowing geometrical deformation with reduced material use and less fabrication complexity in comparison to, e.g. 3D knitted textiles. Additionally, the homogeneous resource composition of continuous single yarn intertwined into various fibre configurations makes it suitable for recycling as no other additives are present and yarn can be simply unravelled back to the spool. This technology allows for scaling up and erect architectural structures, made with knit.

Tensile structures made with knit introduce a novel class of materially optimised structural membranes, expressing alternative to conventional woven membranes aesthetics. It has been demonstrated by experimental research projects on large-scale textile structures, where the membrane is employed structurally and materially graded (Deleuran et al. 2015; Ramsgaard Thomsen et al. 2019a; Sinke et al. 2022a, b) (Fig. 2).

FGMs can radically expand the material performances, as demonstrated in Isoropia, where more expandable stitch types are introduced in the areas where the membrane is required to stretch more. However, the heterogeneous nature of these membranes possess an unsolved challenge of predicting material behavior, which means that tools for a finer control of design and performance prediction of materially differentiated CNC-knitted membranes is necessary. Existing tools for design and manufacture of knitted materials are geared towards the garment industry, while architecture applications present another set of design, modelling and tolerance demands.

This paper contributes to the development of an integrated design model for materially differentiated knitted textile membranes. This is able to incorporate required demands of structural performance, the scale of application, and the fabrication limitations through the stages of conceptual design, structural and geometric analysis, materially informed simulation, and a direct link to digital manufacturing on industrial knitting machines. Using the methods and processes discovered in the presented research, we rethink the design of structural knitted membranes at the stitch level and propose new ways for working with heterogeneous custom-made materials in order to develop sustainable material cultures for membrane architecture and spatial design in general (Fig. 3).

Further a novel approach on how to inform the differentiation of knitted membranes by structural analysis and a method for heterogeneous membrane simulation calibration are presented. Mentioned findings are described, using a case study of *Graded Knitted Ceiling*—medium-scale installations, each made of 6 CNC-knitted differentiated panels. They were designed, fabricated and installed during the workshop for students of CiA Computation in Architecture Master Studio at Royal Danish Academy as a part of design workflow assessment and further development and evaluation of material grading and simulation prediction tools.

Fig. 2 Large-scale structures, employing CNC-knitted textile as a structural membrane. Left to right: Hybrid Tower 2016, Isoropia 2018, Zoirotia 2021. Authored by CITA—Center for IT and Architecture, Royal Danish Academy, Copenhagen, Denmark

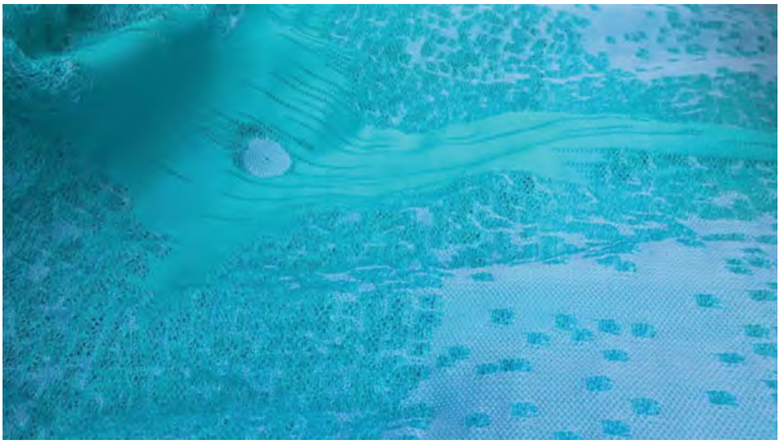


Fig. 3 Close-up of the rich surface modulation of the CNC-knitted membranes through the variation of stitch composition

2 Textile Simulation Practices and Modelling of FGMs

2.1 Simulation in Membrane Design—FEM and Engineering Software

In conventional membrane architecture the canopy shape determines its structural performance. The simulations allow engineers to accurately assess how the membrane shape needs to be adjusted in order to achieve a stable three-dimensional membrane structure, that is able to accommodate different external forces, such as wind, snow and seismic loads. This enables engineers to design safer and more efficient membrane structures.

The membrane behaviour is described using partial differential equations in order to handle large-scale membrane geometries with differentiated loading setups. Due to the fact that there is no exact analytical solution to solve these equations (Chen and Hearle 2009), FEM (finite-element method) was developed. In FEM, the investigated surface is discretised into smaller elements (mesh segments), with a known finite size, where the node intersections are solved analytically (Kyosev 2012). As the nodes are shared between the elements, solving the equation is easier since the result should be the same for all linear elements meeting at the same node. A linear element is regarded as a mass spring, where the tension force of one segment is defined as a linear elastic force.

This method found its wide application within the structural engineering discipline being integrated into commercially available computer-aided engineering (*CAE*) software like Sofistik (www.sofistik.com), EASY.Form (Ströbel and Singer 2005), CADISI (TechNet GmbH), Formfinder and WinTess (Sastre 1992), where each is a stand-alone program with a focus on form-finding and simulation of woven-based structural membranes. In spite of their overall benefits over manual calculations, these software require engineering skills, thus reducing their accessibility to architects, who are trained to work in *CAD*-based (computer-aided design) programs like Rhino, VectorWorks, Sketchup or 3DMax.

2.2 Homogeneous Boundary Models Versus Material Heterogeneous Models

In current design practice multiple modeling environments are employed and several models are constructed. These include CAD (computer-aided design) models for design, CAE (computer-aided engineering) models for structurl evaluation and CAM (computer aided manufacturing) models for fabrication. Architectural design practice is bound to its means of representation. Today the dominant way to represent and model architecture is today digital, using homogeneous boundary models in conventional CAD-modelling enviroments. Here, the focus is on the geometrical representation of the designed object, described by the boundaries in available CAD software. When considering the variety of CAD software, architects and designers have at their disposal, there is a hierarchical distinction between boundaries and properties, shapes and composition (Tsamis 2013). Most of past and present CAD systems are based on the premise of material homogeneities. Designed objects are represented as uniform matter, defined by boundaries, modelled in 3D-Euclidean space (Requicha 1980). These lack the integration of material composition and structural performance. As a result, they fail to accurately represent material complexity of graded materials and hinder exploration of material possibilities for variation and mass-customization that digital fabrication can enable. Engineering softwares simulate object performance and propose its composition, however are rarely useful for design as aimed for structural evaluation rather than morphological exploration.

2.3 Challenges of Using Homogeneous Models When Designing Heterogeneous Materials

Knitted structural membranes occupy a new branch within membrane architecture as they represent radically different capacities if compared to conventional homogeneous membranes. The capacity of controlled stretch of graded CNC-knitted membranes defines their behaviour and shall be taken into account early on during the design process.

The separation of design process into several disconnected environments leads to the decoupling of design from material properties and fabrication constraints, thereby reducing the quality of design solutions, as each iteration and adjustment is cumbersome, slow to make and therefore avoided. Such approach demotivates design production improvements and hinders the opportunity to create sustainable material practices in architectural design. In order to improve the quality of taken design decisions, and better reflect knitted membranes heterogeneities. It is essential to create integrated design models. This would pave the way for more sustainable manufacturing and more efficient design processes.

2.4 Digital Design Chain Paradigm for Knits—Integrated Digital Design, Analysis, Simulation and Fabrication

The design of FGMs involves interdisciplinary knowledge and therefore integrated *CAX*-based (computer-aided technologies, *CAD* + *CAE* + *CAM*) design is envisaged as one of the promising directions for the future (Nayak and Armani 2022). A way to create a workflow between multiple codependent models of a designed object is presented in the paradigm of the digital design chain (Dohmen and Rüdenauer 2007). In this paradigm, several models coexist in the same or tightly interconnected environments, all cross impacting one another. This guarantees minimal or even no data loss when transferring from model to model. Here morphological design, structural evaluation through simulation, material grading and planning for digital fabrication happens simultaneously.

Analysis of structural performance and manufacturing specification integration in the design environment empowers collaboration between professionals and eliminates the possibility of mistakes (Bechthold 2008). It helps to bridge each separate field, enhance interoperability and facilitate design tool integration into the entire process from idea to making.

As a final evaluation of a mature design, the simulation is commonly performed at the end of the design chain to complete the necessary structural documentation. Backward design changes are avoided and made only in cases of severe problems. By incorporating material heterogeneity through materially oriented simulation, it becomes active in the design explorative journey. Here the simulation is a part of extensive design tuning for improved performances. For materially differentiated designs, simulation plays an essential role in evaluating material capacities and performances, which in turn is tightly connected to their manufacturing. When integrated into a design environment and used iteratively, simulation allows to introduce material heterogeneities, test of complex material behaviour exposed to different conditions and skim through the design options. Here, the simulation plays a crucial role in creating a property representational model, where it contributes to the exploration and creation of design possibilities (Ramsgaard Thomsen 2016). This can be especially relevant for CNC knits, where the material grading defines their behavior and shall be taken into account early on in the design process.

Given the novelty of CNC-knitted membranes as architectural materials, reflected in their extreme heterogeneity, dynamic shape, scaling challenges during fabrication, complex material behaviour prediction and additive manufacturing, there is currently no ready-to-use software to address these challenges. To solve this problem, researchers investigate the development of dedicated models that would cover the entire design chain for knitted structural membrane design, from conceptual design to structural analysis and material simulation, as well as the preparation of manufacturing files.

2.5 Environments for Differentiated Simulation of Graded Knits

The achievements of state-of-art digital simulations of materially graded knitted structures have been boosted by the concurrent development of design and modelling environments, supplemented with parametric tools, allowing architects and designers to construct heterogeneous material models. The software Rhinoceros (Robert McNeel & Associates 1980) with its embedded platform for parametric modelling Grasshopper (David Rutten 2007) has gained enormous popularity and created a wide community, actively contributing to custom open source plug-in development, oriented towards particular tasks. A physics-based Kangaroo plug-in (Piker 2013) for Grasshopper makes it possible to simulate real-world materials and objects, engaging an intuitive sense of the material world, and allowing designers and architects to construct materially oriented simulations (Deuss et al. 2015; Tamke et al. 2014; Zwierzycki et al. 2017).

Similar to FEM software, in Kangaroo, the membrane structures are modelled through cable net mesh-based geometries, informed by material properties of rest length and stiffness, assigned to each mesh segment. The discretised nature of mesh-based membrane representation, supported by the parametric capacities of Grasshopper, allows us to automate and steer the allocation of these properties across large membrane bodies. Once the approximate desired shape is form-found, a trusted FEM analysis that would output the stresses and deformations should be conducted. Until recently this was done in the mentioned above external engineering software for FEM analysis (Fig. 4).

Several plug-ins integrate structural analysis in the digital design environment. They can be classified into two distinct groups based on how the membrane is represented—(1) *discretised* and (2) *iso-geometric*, where the first uses *meshes*, while the second—*NURB*-continuum *surfaces*. Examples of the plug-ins that operate on mesh-based representations are Karamba (Preisinger and Heimrath 2014), SmartForm (www.smart.burohappold.com), FunnelWeb (Kimm 2018), Rhino Membrane (Philipp et al. 2015) and K2Engineering (Brandt 2016). The NURBs-based membrane design has found its implementation in the Kiwi3D plug-in (Philipp et al. 2016; Bauer et al. 2018). The choice of either representational method, and hence the tools, should be done based on the accuracy and capacity of each method to represent the material's varying properties. The *iso-geometric* method uses a smaller number of external control points in order to describe the geometry through B-spline formula, involving the degree, control points and knots (Piegl and Wayne 1997). However, considered more lightweight, it is not able to incorporate varied material properties into

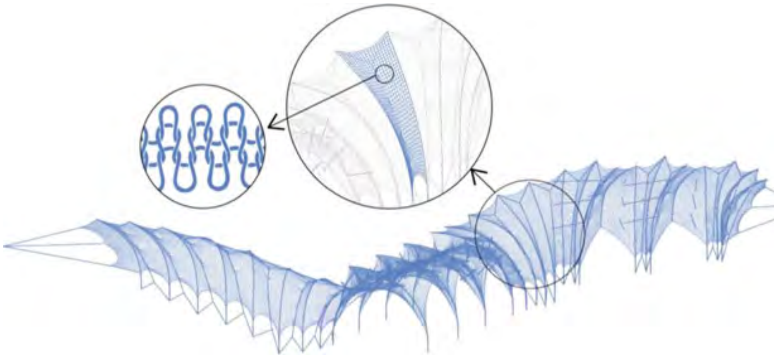


Fig. 4 Isoropia form-finding represented through quad-based mesh discretisations

the used NURBs surface. The *discrete* mesh-based representation uses a larger number of geometry subdivisions, allowing very fine changes in geometry properties to be constructed. This method is considered to be more applicable for modelling heterogeneous knitted membranes as it allows a detailed allocation of varied stretch properties, linked to mesh fine segments.

2.6 Properties Assignment Within Knit Simulations

Understanding property allocation mechanisms enables precise and accurate form-finding and simulation of differentiated membranes. A certain level of tolerance and imprecision is accepted within membrane simulations for representational and manufacturing purposes. Nevertheless, for some topological design solutions, a higher degree of geometric precision is required in order to avoid excessive membrane surface areas with reduced tension and the misalignment of compound elements due to surpassing of tolerances.

Before the emergence of plug-ins that allow for structural evaluation of membrane designs, mesh properties were assigned through an arbitrary cable stiffness value, which is comprised of *rest length* target values, calculated by Kangaroo Goal[1] as a percental reduction of the cable dimensions and its *strength* of achieving the target dimension. As a result, a differentiated mesh contraction is achieved during form-finding by varying these values using Kangaroo Solver (Mcknelly 2015; Baranovskaya et al. 2016; Karmon et al. 2018; Quinn et al. 2016; Hörteborn and Zboinska 2021). The results yield topologically similar geometries to physical outcomes as well as simulate the different degrees of mesh contraction for representing the different stiffnesses of the membrane. Form-finding simulations generated from these studies cannot be guaranteed to be geometrically accurate, since no quantitative comparison with physical models is made.

Alternatively, the use of K2Engineering cable goals allows to operate with the *E-modulus stiffness value* (Young Modulus[2]) in order to describe the material properties of the membrane, thereby departing from arbitrary stiffness value, used in the Kangaroo Cable goal. This allows for a more precise membrane material simulation, linked to the existing engineering standards of representing material properties through Young's modulus. However, the determination of the right Young's modulus value for the differentiated knitted membrane is a challenging task due to resolution misalignments and lack of studies. The

[1] *A component in the Kangaroo, K2Eng and Karamba plug-ins, that operates with the certain formula in order to describe the behaviour of the simulated object.*

[2] *The modulus of elasticity in tension or compression is a mechanical property that measures the tensile or compressive stiffness of a material when the force is applied lengthwise.*

differences occurring between sparsely discretised digital cablenet mesh geometry, which represents a much denser physical differentiated knitted membrane require the invention of *resolution translation concepts*. These are not present for heterogeneous knitted structural membranes in the available literature but are essential for building closer links between simulated and physically produced knitted membranes.

3 Extension of Design Models for Materially Differentiated Textile Membranes

The workflow presented here is based on the comprehensive design-to-production for knitted architectural membranes, developed over the past years by the authors (Deleuran et al. 2015; Ramsgaard Thomsen et al. 2019a, b; Sinke Baranovskaya et al 2020; Sinke et al. 2022a, b). This paper shows recent advancements especially the development of a *method for material differentiation informed by structural analysis* and a *method for heterogeneous membrane simulation calibration*, incorporating the data from structurally informed material differentiation and the values, derived from a physical experiment with homogeneous membranes of various densities. Both methods are closely interconnected as they inform each other, which is demonstrated in the example of design case study of Graded Knitted Ceiling panels.

3.1 Graded Knitted Ceiling—Design Case for Testing Digital Tools

Panels are three-dimensional, where the curvature is achieved by grading the programmed membrane pattern, based on the loading conditions of the membranes in the digital space (Figs. 5 and 6). The design intent drives the definition of the weight value in kg and their distribution across the membrane surface. Larger weight values produce deeper membrane geometry with a larger curvature, while the discontinuous edge clamping rearranges the tension distribution, where both directly reflect in the material grading patterns (Fig. 7). In order to achieve differentiatited stretch property two stitch types are combined—double jacquard stitch and unravelled version of it, where the stitch gets 3 times larger. We can control which stitches remain compact, and which get unravelled, achieving the controlled expansion of the fabric. Then panels are digitally produced with Serafil high tenacity polyester yarn on the industrial knitting machine STOLL 822 ki, using 12.8 N value for takedown and 9.8 N stitch length values. After that, panels are installed in space by clamping to the ceiling support structure (each frame 1.2 × 1.2 m), and loading with the weights in order to stretch the fabrics. In comparison to the digital environment, where the differentiated weights are used to trigger material differentiation, physical panels are loaded with the weights of same value. This is for activating

Fig. 5 Materially differentiated membranes, where the shape is informed by material differentiation, activated by the loading with weights and edge clamping conditions

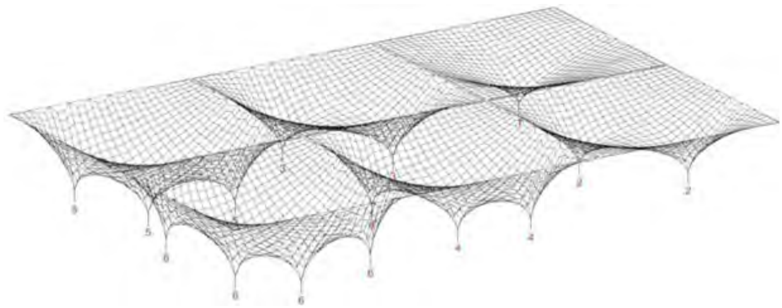


Fig. 6 Digital conceptual model of the textile ceiling panels with the increased surface depth transition. The arbitrary stiffness value used is 30 MPa in both U and V mesh directions

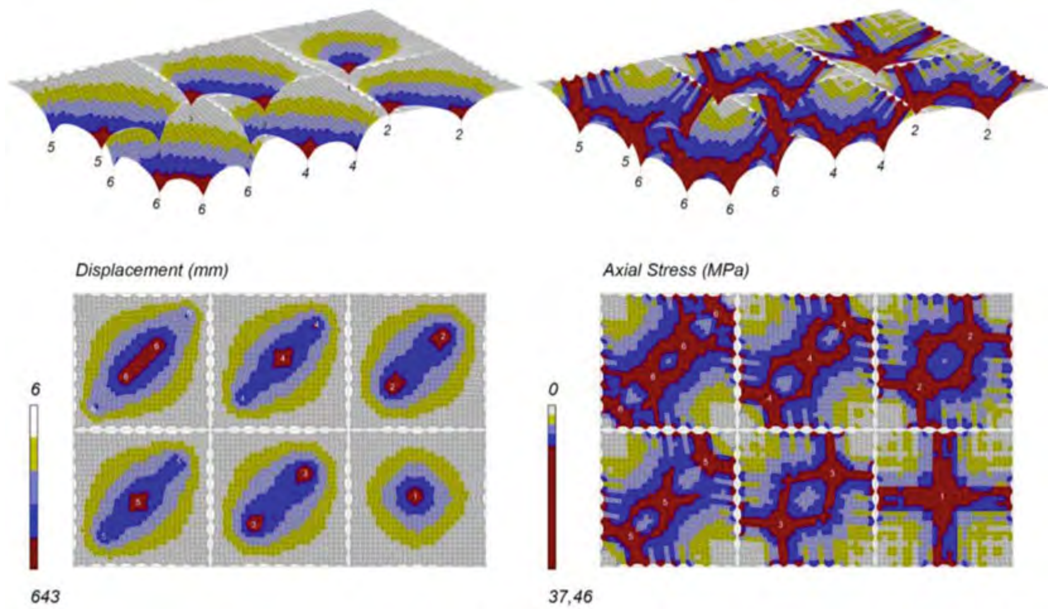


Fig. 7 Difference between displacement-based geometrical analysis (left) and tension-based structural analysis (right)

material differentiation, which is rather the result of membrane graded properties, rather than of differentiated loads.

3.2 Workflow Extension by Introducing Two-Stage Simulation

In order to determine the shape and grading within each membrane, we introduce a two-stage simulation, *A* and *B*. *Simulation A* is homogeneous in its set up and used to form-find a preliminary shape of a membrane in order to determine a plausible topology and conduct the structural analysis. The second—*Simulation B* – is materially informed differentiated simulation with distinct stiffness values per mesh area. It is built up on the results of structural analysis from Simulation A. The calibration of this model is done against the set of relevant knitted samples.

4 Finding 1. Structurally Informed Material Differentiation for Digital Manufacturing

4.1 Simulation A—a Homogeneous Form-Finding with K2Engineering Goal

As mentioned above, one of the findings described in this paper is an invention of a novel method for CNC-knitted membranes *material differentiation informed by structural analysis*. Its development is connected to the use K2Engineering goals already at the stage of preliminary form-finding during Simulation A. The membrane for Simulation A is constructed from a homogeneous mesh-based cable net with an *arbitrary* Young Modulus value, assigned evenly to each mesh cable segment. An arbitrary value is derived from standard handbook knowledge, as there is yet no information on membrane specification and its behaviour at this stage of the design process. Naturally, the designer operates with the parameters of membrane shape, clamping and prestress conditions, which in our case is the loading of membranes by weights, distributed across the surfaces and its attachment to the frame structure of the ceiling.

4.2 Structural Evaluation

After the preliminary form-finding (Simulation A) is converged, the *structural analysis* is conducted to extract the forces and the axial stress distribution across the resulting form-found mesh. It is a novel approach of membrane performance evaluation complementary to the earlier developed method of *geometrical analysis*, that calculates the surface displacement during the form-finding (Sinke et al. 2022a, b). The diagram in Fig. 7 compares these two analysis methods applied to the same geometry under the equal loading conditions.

In the current finding, the structural analysis is calculated with the aid of the BarOutput component of K2Engineering plug-in, where each mesh segment is associated with the axial stress value in MPa (Fig. 8A). Next, the axial stress values are interpolated into an average value per mesh face, allowing to cluster of the mesh *per mesh face*, rather than *per mesh cable* (Fig. 8B). This introduces the concept of treating the knitted membrane in simulation as a *shell* with distinct areal material properties, as opposed to a cable net made of single strands. This approach makes it possible to link the dense knitted physical surface to the sparsely subdivided mesh setup and introduces the concept of scalar translations between the low-resolution mesh and the high-resolution knitted fabric. As a result, meshes are clustered into zones, described by colour, where each colour is a result of a distribution of threshold tension data, present in the surface. Based on the resulting clustering arrangements, further material differentiation *for digital manufacturing* and for *heterogeneous simulation* can be performed on the mesh.

4.3 Knit Material Differentiation, Informed by Structural Evaluation

For further digital manufacturing of knitted membranes, the transition of differentiated material properties from the analysis is conducted through the dithering[3] graphic technique, due to the binary nature of knit. This permits the maintenance of the smooth variegation of material property for stretch while using only two stitch types for material differentiation—double jacquard (solid) and unravel double jacquard (loose). The dithering pattern is controlled through the percental density of double jacquard stitch type. This allows to correlate the tension-based clustering of the surface with the material density, where the areas of larger tension values receive the lowest material density, through the increased intensity of unravelling stitches,

[3] *– is an intentionally applied form of noise used to randomise quantization error, preventing large-scale patterns such as colour banding in images. A common use of dither is converting a grayscale image to black and white, such that the density of black dots in the new image approximates the average gray level in the original.*

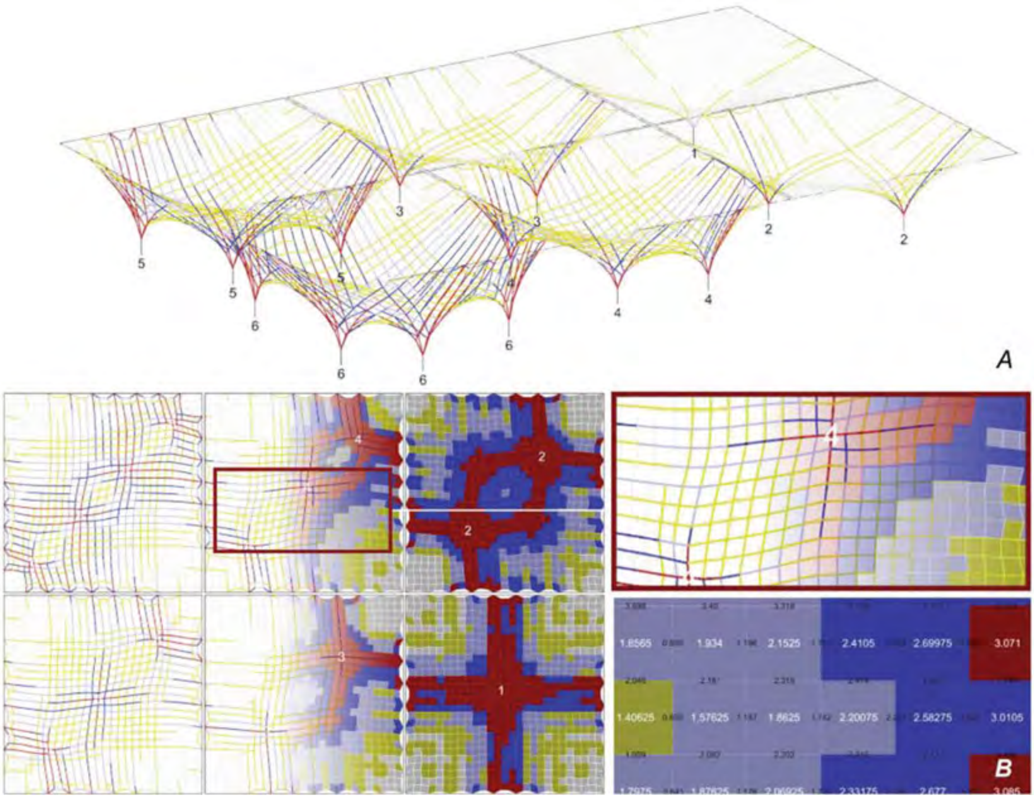


Fig. 8 Axial stress distribution in mesh cables and the translation of mesh cable tension value mapping per bar (mesh segment) to per mesh face

while the areas that experience less tension, remain dense, as they do not need to expand that much in order to achieve desired three-dimensionality.

This is counter-intuitive from the perspective of material performance for strength, as traditionally more dense textiles are perceived as more strong and expected to be in the areas of higher tensile forces. However, with the use of high-performance yarns, the integrity of the filament is guaranteed, which maintains the surface knitted strength despite stitch density. Here, the larger loops lock into their final locking position with the same strength properties as the smaller loops. Placement of larger loops in the areas of required larger deformation is very efficient in achieving material expansion and reaching required three-dimensionality with the fewer resources through the steering of material density. As the result, *cluster colour maps* are generated for each design, that are then translated to knitting machine-readable bitmaps (Fig. 9)

5 Finding 2. Structurally Informed Material Differentiation for Heterogeneous Simulation—Calibration Through Physical Prototyping with Homogeneous Membranes

With the membrane structural analysis, the cluster colour map is not only used for *material differentiation for digital manufacturing*, but also for *materially informed simulation*, incorporating these structurally derived surface gradings for more accurate digital representations of heterogeneous CNC-knitted membranes. Here each

Publication 6

SIMULATION-BASED ANALYSIS METHODS FOR DIFFERENTIATION STRATEGIES OF CNC-KNITTED MEMBRANES FOR ARCHITECTURAL APPLICATION

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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 customized 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 customized 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 and breathability 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).

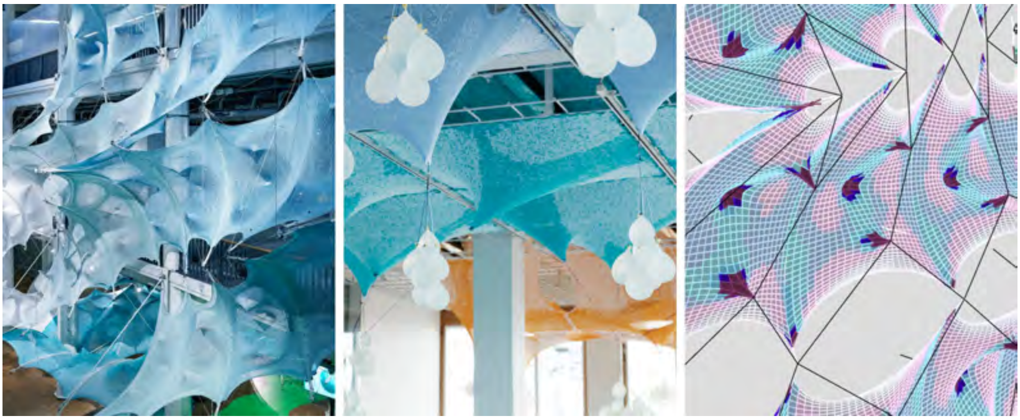

Figure 1: Three design cases, presented in the paper (left to right) - Zoirotia, Graded Ceiling and Zoirotia 2.0

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 analysed, 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.

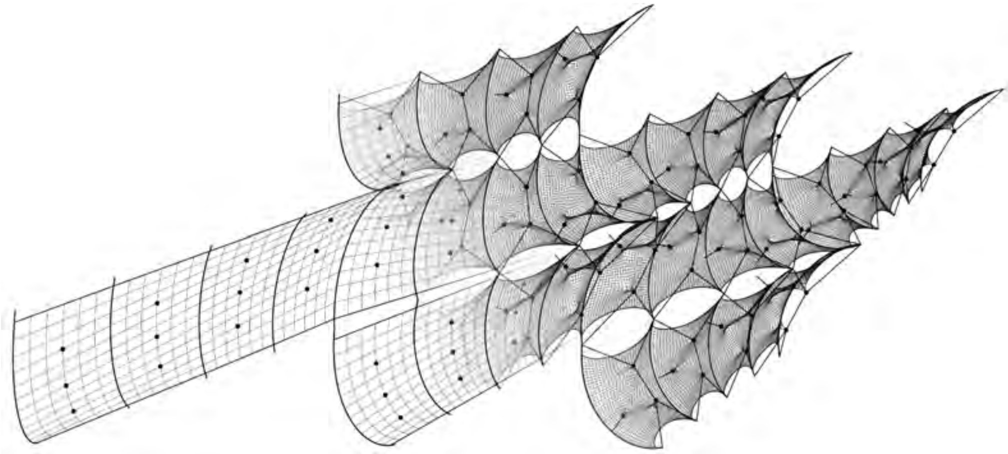

Figure 3: The form-finding set up (left side) and the corresponding equilibrium relation (right)

The form-finding setup and visualization take place within the Grasshopper (David Rutten, 2007) environment for Rhino modelling 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 a ground for material input. Unlike Kangaroo, which 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 membrane surface. This is done by the means of strategic distribution of larger and smaller stitch types across the surface for 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).

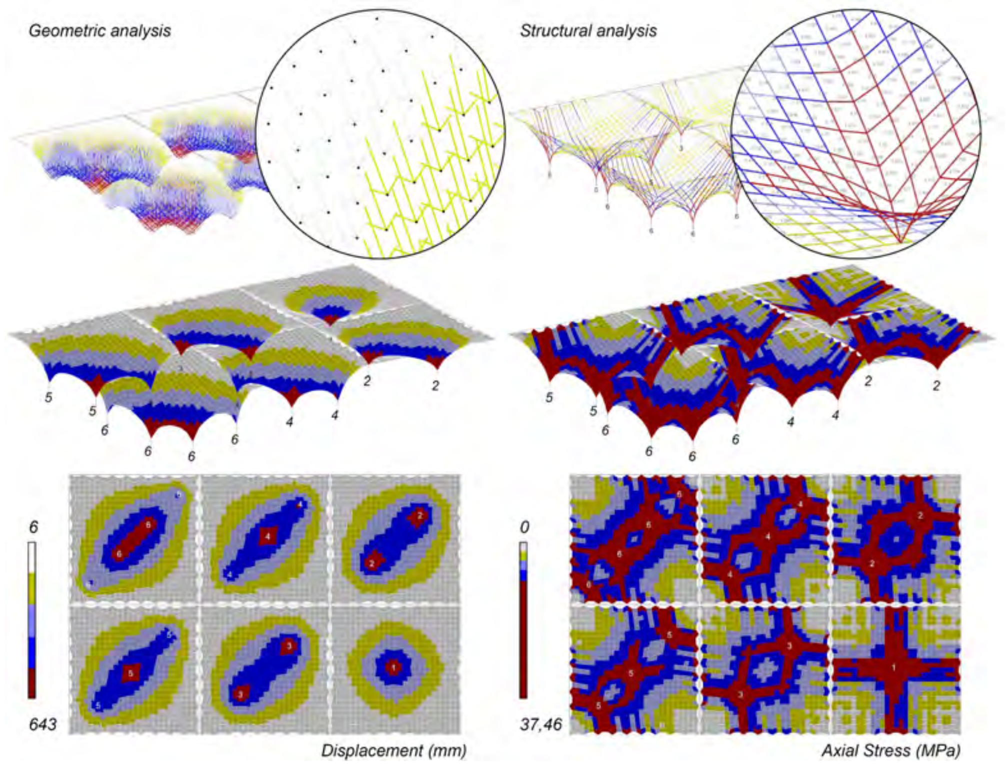

Figure 4: Diagram of geometric analysis (left) vs. structural analysis (right) approach for pattern generation

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/Cable 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 travelled 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 these two analysis mappings differ 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, are 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).

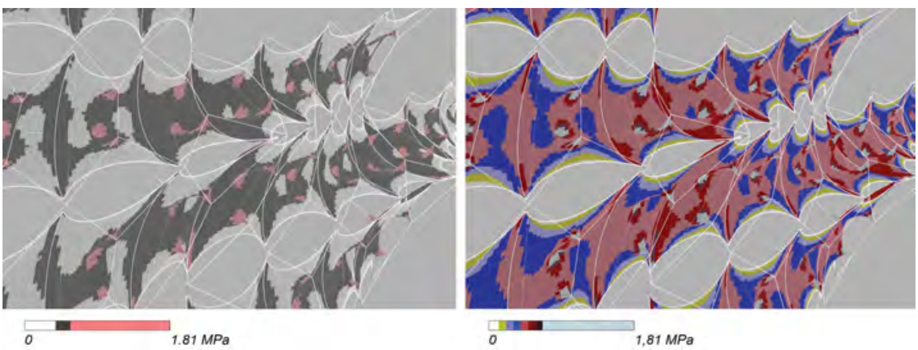

Figure 5: Color threshold diagram: 3 vs 8 colors range, shown using Zoirotia digital design case.

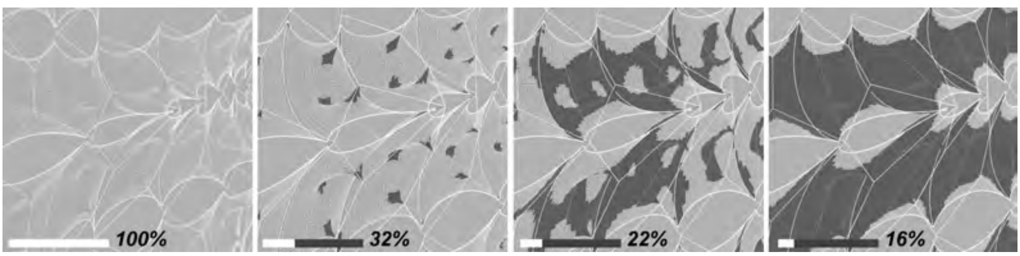

Figure 6: Gradients from 16 to 100% showing that threshold defines the part of the surface axial stress selection (here range from 0-1.56 (up to 1.81 MPa on some membranes)

The lower threshold percent involves the values at the beginning of data list, while the higher - 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, therefore the visualisation appears very homogeneous when taking these values. The biggest value change occurs at the range from 20-35% (in the given design case), therefore the pattern appears more geometry related and exciting, however this is largely dependent on the design and analysed geometry.

After that, the defined color clusters are used to determine 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 membrane 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 the color pixel-based bitmap file, that is later processed by the industrial knitting machine (Figure 7) (Sinke, Ramsgaard Thomsen, Albrechtsen, et al., 2022).

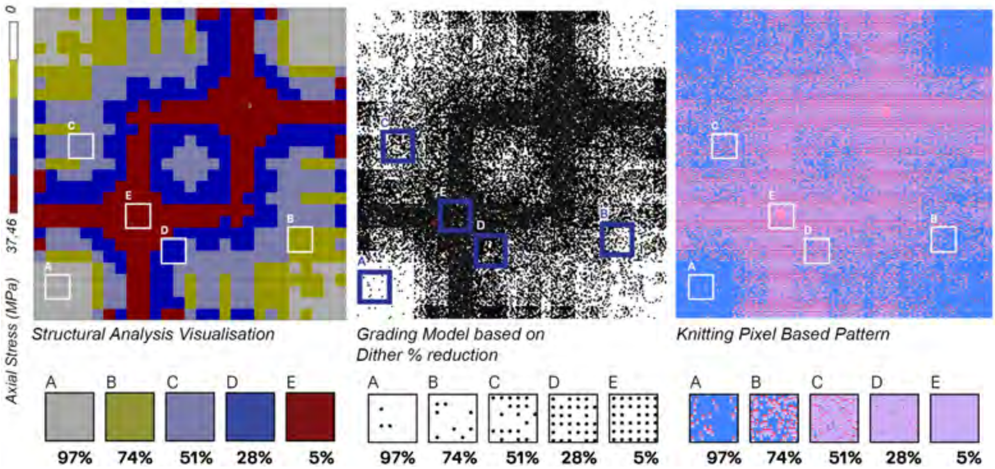

Figure 7: Translation of *structural* analysis data and surface cluster grouping into a knittable pixel-based pattern at the right resolution

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 for the mesh 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).

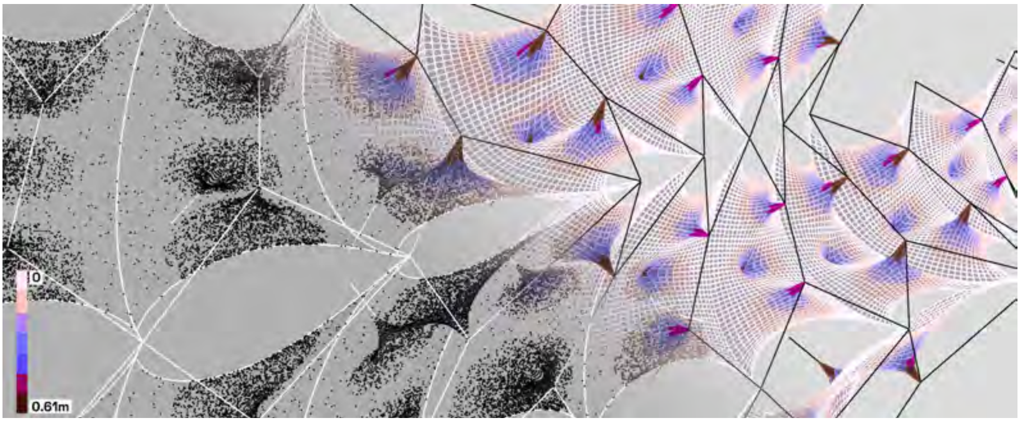

Figure 8: Clustering nature of the membrane surface (right half of image) together with informed material differentiation through dithering (left side of image), 2023.

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 explained by the mesh resolution used in the simulation and post-analysis in determining these.

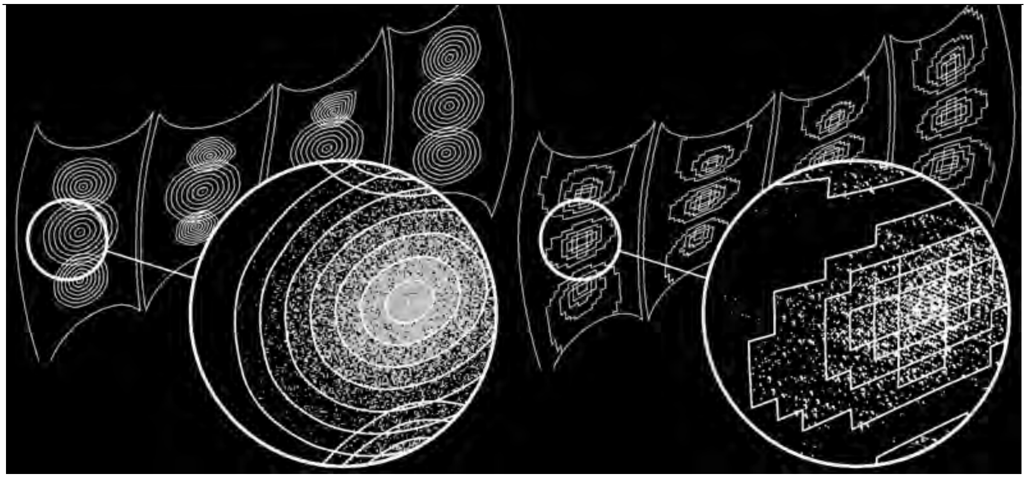

Figure 9. Material differentiation of knitting files of Zoirotia from 2021 (left) based on the planar offset vs. adjusted differentiation files from 2023 (right), based on the simulation-integrated mesh clustering, both using the geometrical analysis

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 accounts for 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, which results in textile wrinkling and underperformance (Figure 10). Insufficiently tensioned areas are preferred to be avoided within tensile membrane design as they reduce overall structural stability. For this reason and in order to maintain three-dimensional freedom of planarly produced CNC-knitted membranes, it is necessary to develop an alternative analysis approach that would lead to the generation of more suitable and well-performing knitting patterns, thereby preventing membranes from sagging when loaded in an angled direction.

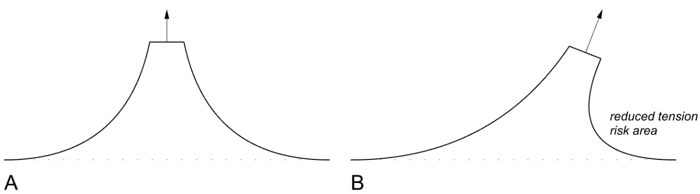

Figure 10: Perpendicular vs angled membrane loading

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).

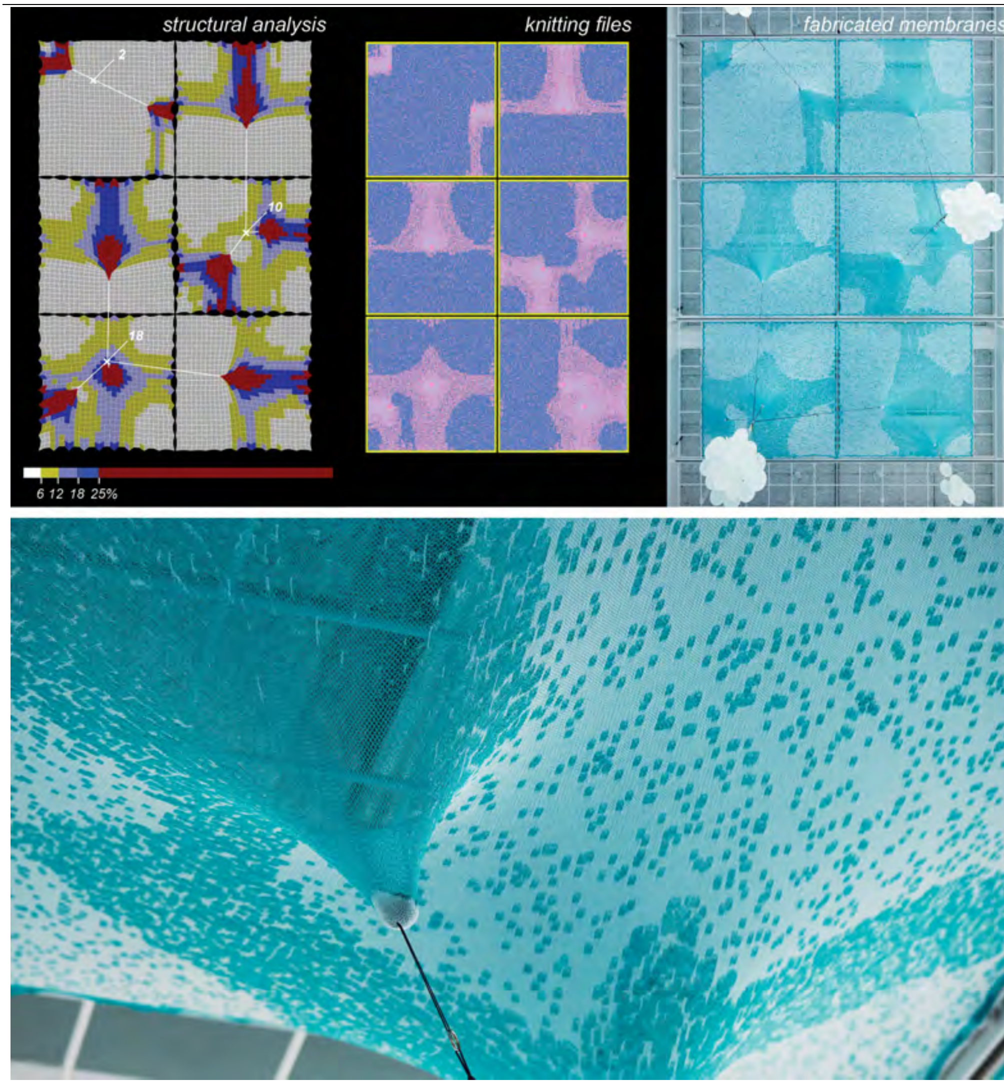

Figure 11: Structural analysis of graded panels, bitmap knitting files and the manufactured piece.

The chosen 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 the simulation and supported by structural analysis of surface tensile utilisation. Material programming allows the membrane expansion to be assigned 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, for the same canopy design the geometric analysis based knitting pattern was prepared. In order to proof the statement that geometric analysis is not a suitable strategy for this loading case, the membrane displacement (in a shape of concentric circles around loading points) under the load is overlapped with the tension analysis, highlighted 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.

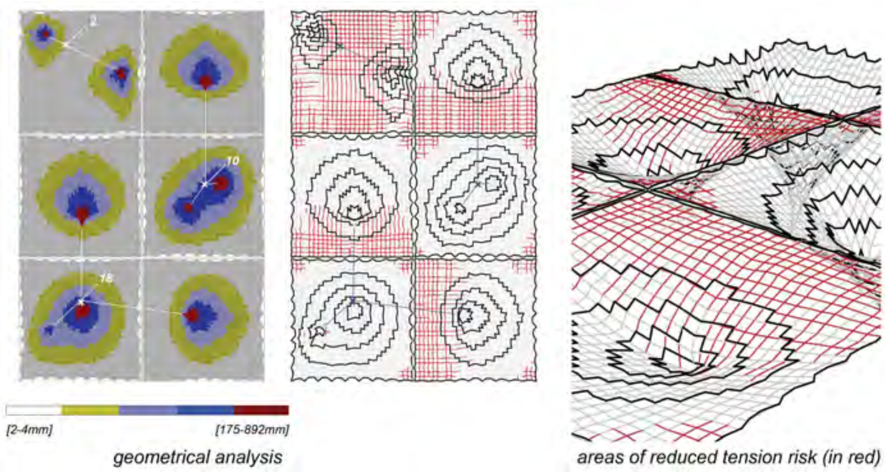

Figure 12: Diagram of material differentiation based on geometric analysis for evaluation purposes

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 earlier mentioned design case of Zoirotia. This exploration allows for speculation 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.

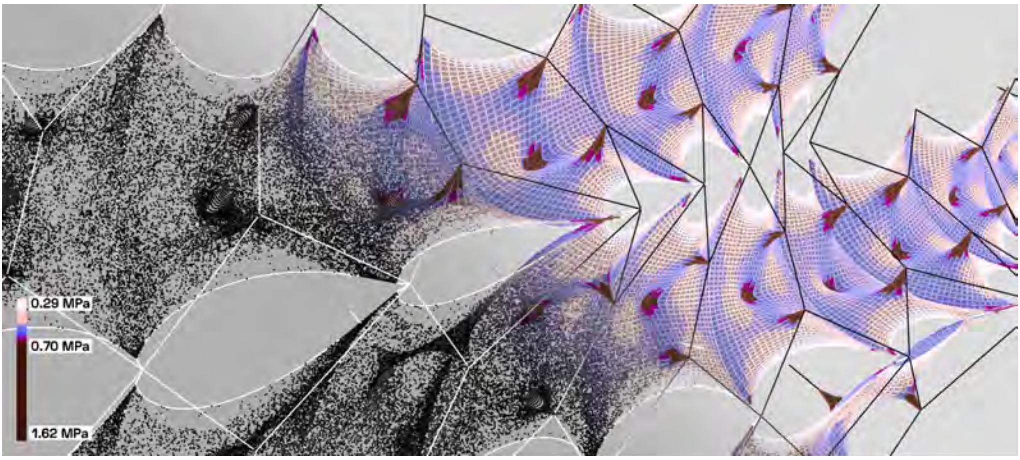

Figure 14: Zoirotia 2.0 digital exploration of structural analysis based material differentiation

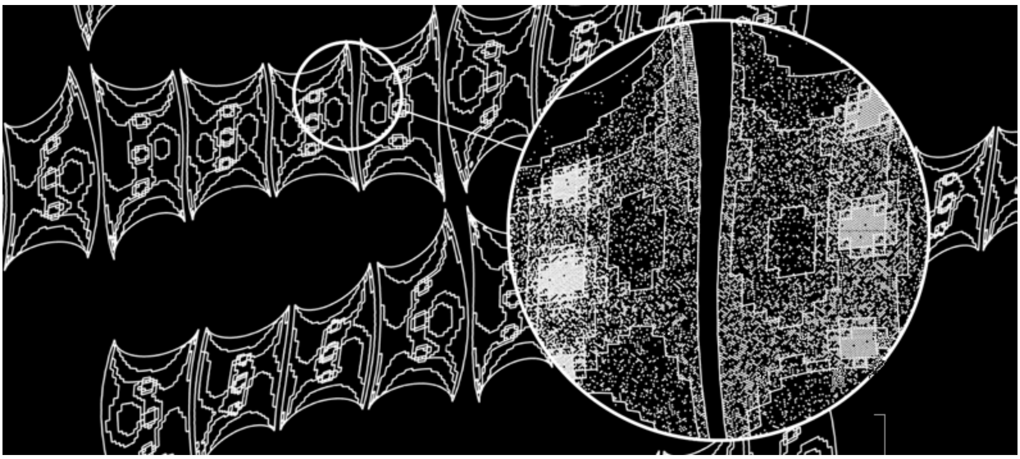

Figure 15: Diagram of material differentiation through the dithering of larger and smaller stitch types

5. Conclusion

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 guarantees 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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DIFFERENTIATED KNIT MATERIALITY

Publication 2

MACHINE LEARNING FOR FABRICATION OF GRADED KNITTED MEMBRANES

Machine Learning for Fabrication of Graded Knitted Membranes

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Abstract. This paper examines the use of machine learning in creating digitally integrated design-to-fabrication workflows. As computational design allows for new methods of material specification and fabrication, it enables direct functional grading of material at high detail thereby tuning the design performance in response to performance criteria. However, the generation of fabrication data is often cumbersome and relies on in-depth knowledge of the fabrication processes. Parametric models that set up for automatic detailing of incremental changes, unfortunately, do not accommodate the larger topological changes to the material set up. The paper presents the speculative case study *KnitVault*. Based on earlier research projects *Isoropia* and *Ombre*, the study examines the use of machine learning to train models for fabrication data generation in response to desired performance criteria. *KnitVault* demonstrates and validates methods for shortcutting parametric interfacing and explores how the trained model can be employed in design cases that exceed the topology of the training examples.

Keywords: Machine learning · Fabrication · Graded membranes · Knitting

1 Introduction

New interfaces between design and fabrication have fundamentally changed and extended the practice of architects, expanding our design agency from the designers of artefacts to the designers of material systems [17]. The direct design interface to digital fabrication at the material scale allows a new degree of material address and enables the steering of material behaviour in respect to performance criteria. In contrast to composites, functionally graded materials are singular multi-materials that vary their consistency gradually over their volume [8]. Due to their optimized material composition, they better respond to given conditions and a particular set of design and environmental constraints.

Although the integration of graded material properties into design is advantageous, these systems require a deep understanding of fabrication processes and depend on the detailed parametric and simulation models to steer the material composition. This in-depth knowledge of dedicated fabrication systems often requires specialist training and manufacturing setups can be unintuitive and repetitive. The current way to solve this

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is setting up parametrically defined interfaces that link the specification of geometry and material with fabrication steering data [5, 6, 9, 14]. These workflows employ a simulation-model-validation loop, where the performance of the graded materials is validated through simulation and physical testing of fabricated probes. However, the predefined fixed topology modelling logics are often linear and inflexible, thus can not readily be changed on the fly [4].

2 Machine Learning for Complex Graded Material Systems

The integration of machine learning into design systems enables new measures for feedback in the architectural design chain. These methods allow to rethink the organisation of the parametric model and break its inherent reductionism [17, 18]. Where machine learning is finding application in design generation, design optimisation and analysis [20], special interest lies with the application of machine learning for fabrication. Here, the training of models to detect and automate simpler parts of the steering process could lead to more intuitive specification processes. The process of design specification for fabrication lends itself well to machine learning. By being inherently data-heavy training data can be provided on an ever-expanding data set. In this way the quality of the model's outcome increases with each fabrication cycle, evolving its mapping, complexity and scope while remaining intuitive and design integrated. The second potential of employing machine learning for manufacturing is its adaptability. The promise here is a higher degree of versatility in the design process where trained models can predict fabrication data with a higher degree of the topological variance than parametric models. The following case study examines the training of a fabrication model, its validation through physical prototyping and its application on topologically different situations that would otherwise be impossible through traditional parametric interfaces.

3 Knit as a Model for Material Specification

KnitVault takes a point of departure in the research project *Isoropia* [16]. Developed for the 2018 Venice Biennale, it represents a CNC knitted membrane architecture based on a system of arches pulled into tension by a cable-net system. Being a site-specific installation, it required the bespoke variation of each membrane through functional material grading [12]. In order to increase the structural performance of the arches, the knit variation took place through the methodical evaluation of fibre length and its deduced extendability to increase the depth of tensioned cones. The design model incorporated a parametric interpretation of a series of stitch pattern boundaries and translation of these into encoded pixel images as a means of material automatic specification.

The difficulty in evaluating the performative effect of the patterns and the inflexibility of the parametric set up is the starting point for this study. The process of specifying for CNC knitting is highly cumbersome relying on an in-depth understanding of the fabrication parameters and their limitations. Design protocols remain non-intuitive and require special expertise for programming the fabrication files, complicated by many parameters such as yarn friction and tensioning, knit speed, roll down settings and the performance of the resulting fabric. Additionally, the material specification encoding is limited to typical garment templates, such as sweaters and trousers etc. The lack of integrated simulation tools means that the prediction of material outcome: the shape, size and performance of knitted materials are still mainly evaluated and tuned through physical prototyping [17]. The use of functionally graded knit structures increases design complexity which inevitably leads to extensive prototyping. Only recently related research in computer graphics has investigated more user-friendly design to manufacturing interfaces for users who have no or only limited knowledge in knitting [2, 11, 13]. As a consequence, state of art in design-to-manufacture workflows for knit production are not meeting the current architectural design and fabrication paradigms, where predictability and the simulation of a design's performance on all levels before making and construction are key [19]. The challenge of knit simulation lies in loops' intricate structure and their interaction at multiple scales. If quite precise yarn-to-yarn modelling methods exist in textile engineering, these are only applicable on a sample scale, due to computational capacity limits. Besides, methods for abstracting knit behaviour through digital models are not yet fully understood.

Machine Learning offers an alternative approach for specifying graded knitted membranes. Here, the learning of relations between fabricated surfaces and corresponding design data replacing the simulation of highly detailed knit surfaces, their specification accompanied by the challenging encoding of knit parameters. As knit is interfacing with the machine through the image-based file, machine learning image-based algorithms are applicable here to generate CNC-fabrication data. KnitVault builds on and develops methods first examined in the probe Ombre [15] where the machine learning approach was first tested. In the following sections, it will be described how the methodology first established in *Ombre* developed further to *KnitVault*.

4 Ombre - Model for Light Filtering Textile Specification

Ombre investigates the specification of a light filtering textile. Constructed from two yarn types; the first a reflective monofilament and the second absorbent elastomer, *Ombre* is knitted in a single knit *jacquard*[1]. Here the technique is used to create a complex non-binary pattern as the floats affect and change the translucency of the knitted textile. The shifting between two yarns creates complex non-linear correlations between light and shadow that are not readily intuited by the designer. To explore the correlation between the shadow and the material specification, Ombre uses image-based sensing through photographs under an artificial sun to record the shadow effects of the textiles. This data is then used to determine the textiles' light filtering performances and map these to the corresponding fabrication bitmap patterns (Fig. 1). In *Ombre*, GANs [7] are employed to train the model and build the link between the shadow effect, fabric density and the corresponding fabrication bitmaps. Machine learning allows here to construct relations between sets of data when these cannot be described in a linear straightforward manner. The study proved the viability of predicting fabrication data for complex graded materials

[1] knitting technique often used in garments and fashion, in which two or more types of yarns are knitted together and allows the intermittent foregrounding of one yarn while the other yarns "float" behind the knitted surface [21]. The technique allows the designer to create highly complex patterns, while "hiding" the unused yarns on the backside of the fabric.

and demonstrated the relevance of image-based machine learning methods to train direct design to fabrication models. However, where the study focussed on simple performance criteria of light filtering, the further question of transferring the method onto *another performance criteria* provoked the development of the project into *KnitVault*.

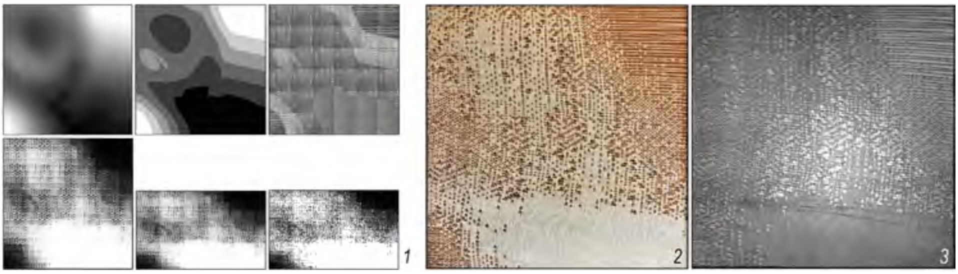

Fig. 1. *Ombre* 2019 - speculative probe demonstrating the link between the desired shadow and the fabrication files for knit production. 1 - design intent. 2 - resultant knitted fabric. 3 - shadow cast from the knitted fabric

5 KnitVault - Geometrical Performance Through Machine Learning

5.1 Experiment Description and Setup

In *KnitVault* the machine learning for fabrication approach is further extended to work on three-dimensional configurations. Rooted in *Isoropia* project, the aim is to study the functional grading of knitted textiles to control the deformation of the membrane under stress. The method is used to explore how the membrane can be better understood and how the trained model can be used on cases that exceed the topology of the training data.

The model is trained on a set of predesigned flat knitted textiles with varying patterns and fixed topology of a central node. All the textiles were knitted on an industrial knitting machine (STOLL 730T E7.2) with the same tension settings, in a single Dyneema® yarn[2], employing three knit stitch types (Fig. 2). This way the pattern geometry is the only changing parameter. Panels are then tensioned to a frame and loaded with 15 kg in the center, creating a 3d cone-like shape of different depths. The resulting shape is documented with a FARO 3d-laser scanner resulting in detailed point clouds to get the real-world geometrical performance. Pattern shapes were drawn manually, following the intention to create diversity in patterns. as vector files in turn transformed to bitmap files for fabrication (Fig. 3).

This shows that the *piquet* material is more stretchy (B expands by 13 cm) than *piquet lacoste* (A - by 12 cm). Stretch is also increased with *interlock* present in the stretched area (C - E), where E - the most stretchy of the investigated samples. The geometry of the patterns influences the stretch furthermore (C - I) (Fig. 4).

2 High-tenacity and ultra-high molecular weight polyethylene (UHMwPE).

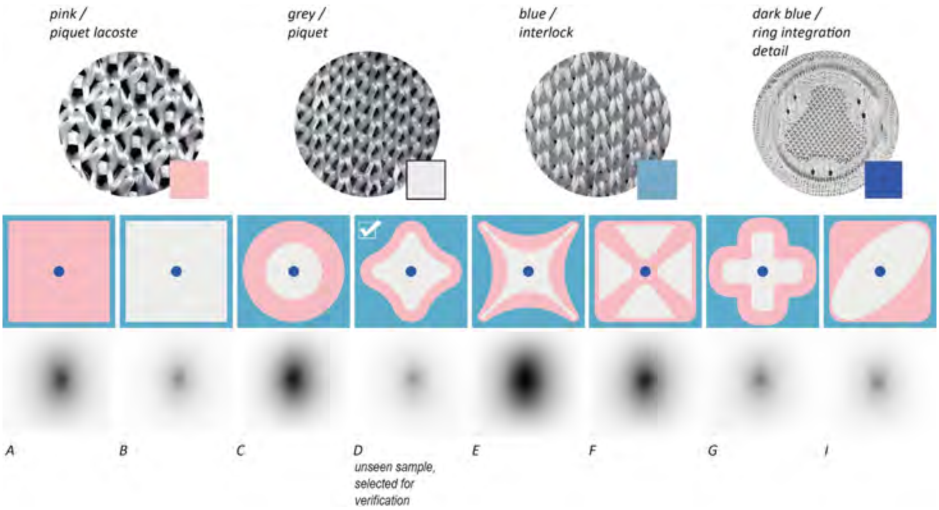

Fig. 2. Range of textile designs used in training with the close up of patterns compositions and their colour coding for the fabrication files

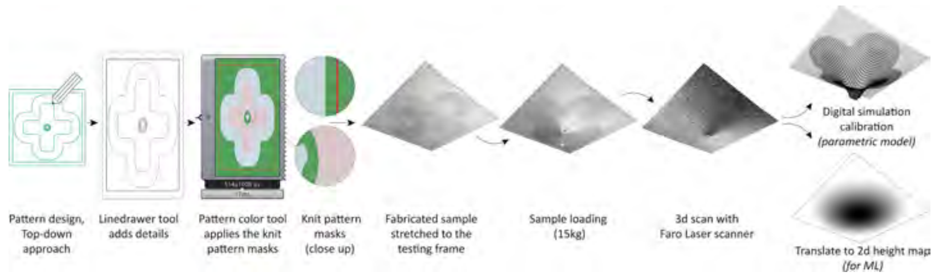

Fig. 3. The workflow of the sample design, fabrication and testing protocol (G as an example)

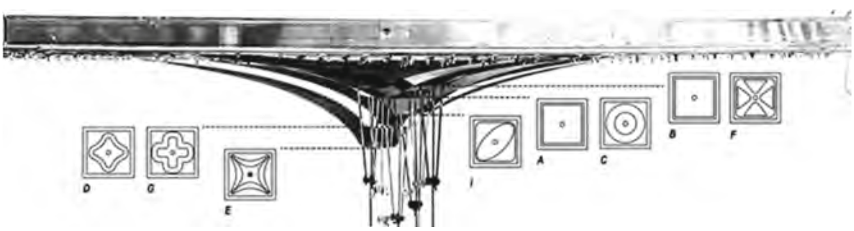

Fig. 4. Side view of 8 samples, performing the difference in depth of the expansion, under load

5.2 Description of Neural Network (NN) Workflow

The training of the neural network is based on the Pix2Pix architecture [10], implemented in Tensorflow [1]. Here the NN is learning a relationship between two sets of images: a training *input and an output*, where the 3D scans of the samples under stress are used for the input, and *pixel-based knit fabrication files* - for the output. Seven samples are used for training and one (D) - for validation. To interface the 3d data from point-clouds with the 2d image-based machine learning, clouds are translated into grayscale height maps (Fig. 2), where the darkness of the colour corresponds to the depth of the geometry (12–25 cm). For expanding the limiting teaching data, the image augmentation techniques [19] - flip, mirror, rotate, stretch and scale - are performed on the input and output files in parallel [3] (Fig. 5).

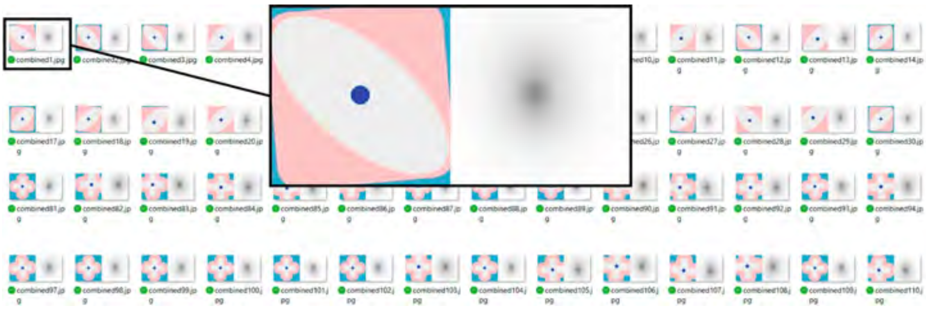

Fig. 5. Fragment of augmented input and output training pairs

The output images represent different pixel distributions - where each colour represents a particular knitting instruction for the machine. After training the NN for 150 epochs[3] on augmented fragments it is applied to the seven input full-size images and then verified on the "unseen" height map (Fig. 6).

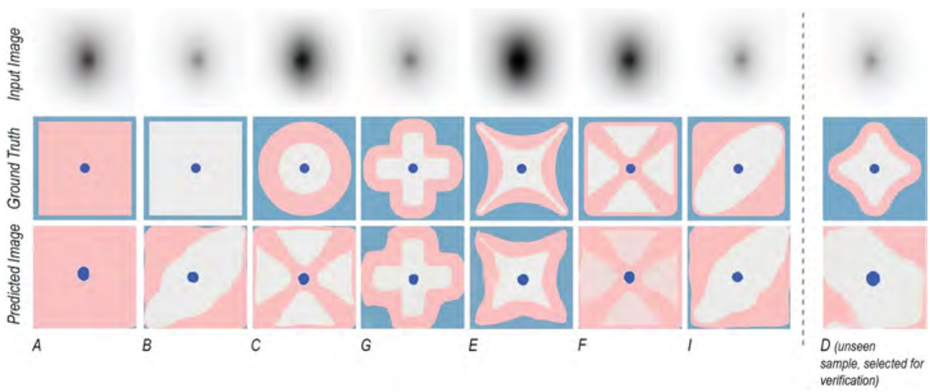

Fig. 6. Learned examples of the 7 seen samples and the 8th unseen knit sample

5.3 Results

The result of neural network application shows that it can correctly predict five of the samples (A, G, E, F, I) two of the predictions (B, C) are ambiguous (Fig. 6). This stems

[3] Cycles through the training data.

from a non-linear relationship between the pattern and the material stretching: alike samples have non-similar stretching behaviours and vice versa.

Although a 62% success rate is low compared to neural networks performances in other knowledge domains, it nonetheless seems reasonable, if assumed that ambiguity in the training data is the source of the error rather than the method itself.

The reassessment of the training data brings the understanding that one-dimensionality of the training data leads to logical errors where the high similarity of input files can be driven by very different output files, as visible through similar physical depths outcome for different knitting patterns (F/C "oval vs. cross"and I/B "oval vs. grey square" in Fig. 6).

5.4 Verification Through the Physical Prototyping

To verify the fidelity of the trained model the resulting pattern from the 8th "unseen" sample is physically knitted with previously established machine settings and tested on the loading rig (Fig. 7). Further, it will be referred to as ML sample.

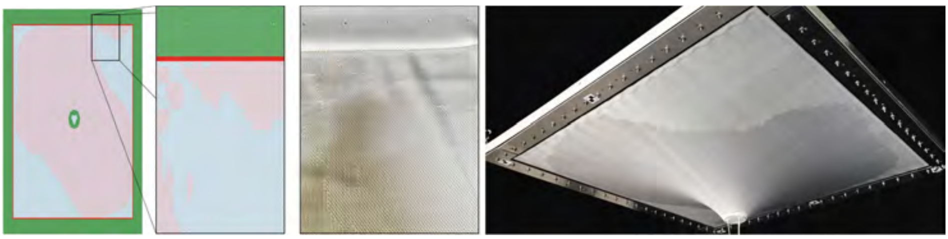

Fig. 7. ML generated fabrication file and the corresponding knitted textile

The loading of the 8th sample results in a depth of 25,1 cm (Fig. 8), which is relatively far from the predicted depth of 18.4 cm as in D. When looking at the per cent of stitch types between D and ML - they vary and we conclude that the ratio of stitches and their visual distribution in the surface affects the expandability of the textile under load. Also, the same conflation of inputs and outputs during training can be the reason for the depth difference.

Then, the visual examination was conducted to find patterns within the range of samples which are more similar in material composition and performance to the ML sample. I and E are the selected candidates for the discussion (Fig. 9). Although I sample, being visually similar to ML (asymmetric oval-like geometry) does not have an aligned depth in its physical sample (25 cm in ML vs. 16 cm in I). The closest in the depths of the physical sample is sample E, however, it remains challenging to explain the reasons, as it has different stitch ratio proportions and not-alike in its pattern geometry to ML. However, in general, the machine learning sample did achieve the predicted cone geometry, albeit with 6 cm tolerance.

We conclude that none of the identified parameters such as relations between the stitch ratios, pattern visual configuration (oval, cross, free shape etc.) alone is determining the stretch of the material. Yet it proves the complexity of the problem and confirms the

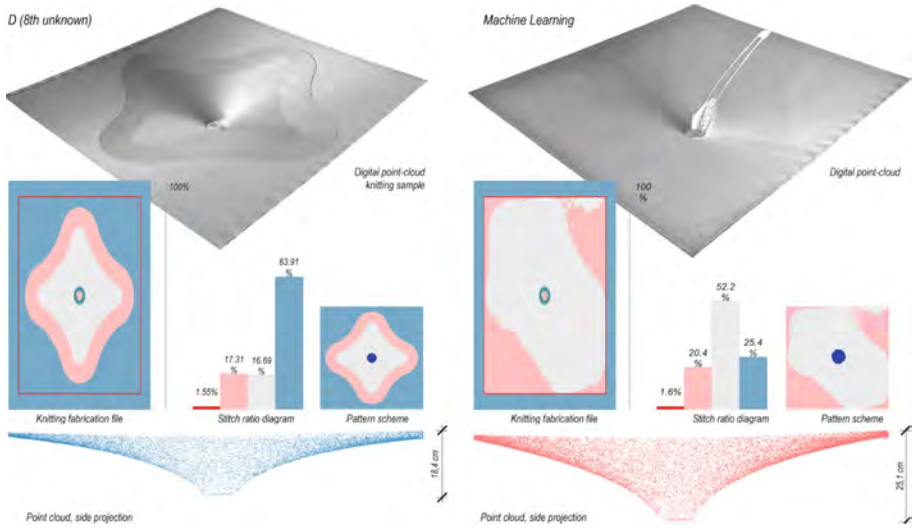

Fig. 8. The comparison between the ML and D sample knitting pattern samples

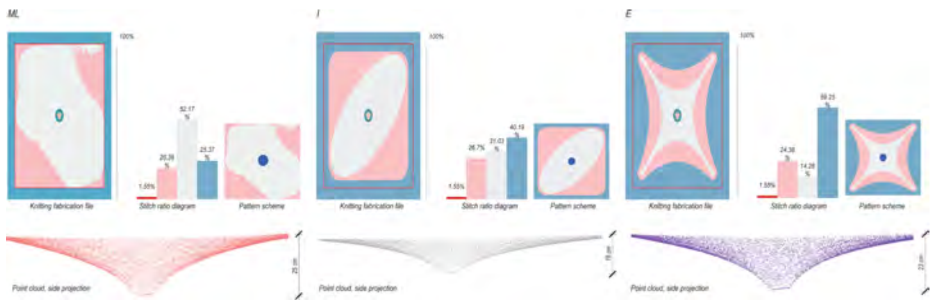

Fig. 9. Comparison between ML and the other two pre-defined designs (I and E)

expediency of exploring machine learning techniques for predicting fabrication files for challenging material behaviours.

5.5 Testing the Neural Network on the New Design Topology

The second part of the *KnitVault* experiment tests the adaptability of our trained neural network to predict outside of the learning scope. If previously the training data was based on the same single cone topology, the second test explores how double and triple cone configurations lead to novel fabrication files (Fig. 10).

Successfully, it shows the capacity of a neural network to translate from single to double and triple cones while keeping the logic of the colour encoding. This confirms the possibility to use NN to overcome the limitations of parametric workflows. While a parametric model needs to be restructured to deal with new inputs or new output typologies, a neural network is more flexible and can transfer from one problem domain to another without further specification. This approach is especially useful for modelling

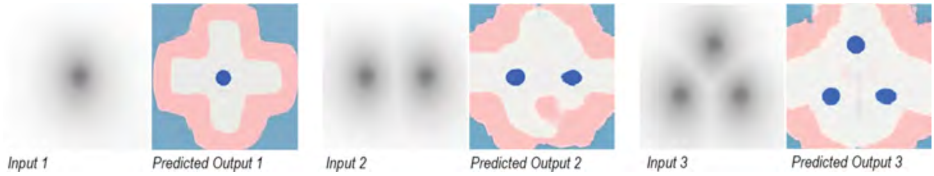

Fig. 10. 3Dot experiment to test the flexibility of the method

environments where input and output types are fixed but their degree varies over the time of design-to-production.

6 Conclusion

While the results of the first test of predicting the fabrication file from a desired stretching depth remains ambiguous, the success of the method's adaptability across different topologies is promising for future digital workflows. Generally, the project shows the possibility of bypassing domain-specific limitations of parametric models. Nevertheless, the used data set for the training was small and ambiguous and therefore the training results of the neural network are equally indistinct. Eventhough the heavy augmentation of a small data set is not advised in machine learning communities, it is symptomatic for the real-world problems in architectural applications, where big data sets are not always available. The question is how much data will be needed to train neural networks in architectural contexts to help to inform design decisions.

The second test of the adaptability of the method to different topologies, showed the possibility of transferring from one problem domain to another. Further probes have to be made to determine how far away from the training data a neural network can be used to predict the outputs.

The general approach of skipping the simulation-model-validation loop by training neural networks directly on the fabrication data can have useful implications for the other design-to-production workflows where a non-linear relation between design intent and fabrication data exists. For example, CNC milling usually includes cumbersome procedures of manual labour, when 3D models are translated to G-code. Nonetheless, there is a relationship between model and g-code which potentially can be learned by a neural network. Sharing fabrication data and design models for different fabrication machines (robots, CNC milling, 3d printing, knitting, etc.) can potentially help to overcome the limitations of small data sets and too much data augmentation for machine learning approaches in architectural digital fabrication.

Finally, the presented image-based approach can be extended to either parallel image-based approaches (optimizing for different problem domains simultaneously), voxel-based GANs or potentially even time-based voxel GANs in the future.

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RESEARCH TRACK B

DIFFERENTIATED KNIT MATERIALITY

4.2 RESEARCH TRACK B: FABRICATION MODEL: ADDRESSING THE DOMAIN SHIFTS FROM DESIGN-TO-FABRICATION

Research Track B, addresses **Research Question B**, formulated as *How the incompatibilities of design and fabrication environments can be handled with the computational models in order to ensure the accurate production of differentiated CNC-knitted membranes?*. This question is examined through the development of a custom digital **Fabrication Model**, which acts as a platform for integrating computational mechanisms that facilitate seamless data transition from digital intent to the materialized form of CNC-knitted membranes.

Addressing the research question and objectives requires a comprehensive understanding of *domain shifts* occurring between digital design and production environments. This section highlights and is structured around the **three key shifts** the Fabrication Model addresses —*spatial*, *resolution*, and *dimensional* — by integrating solutions at various stages of its development, using computational or physical processes to bridge the domain's incompatibilities from design to production.

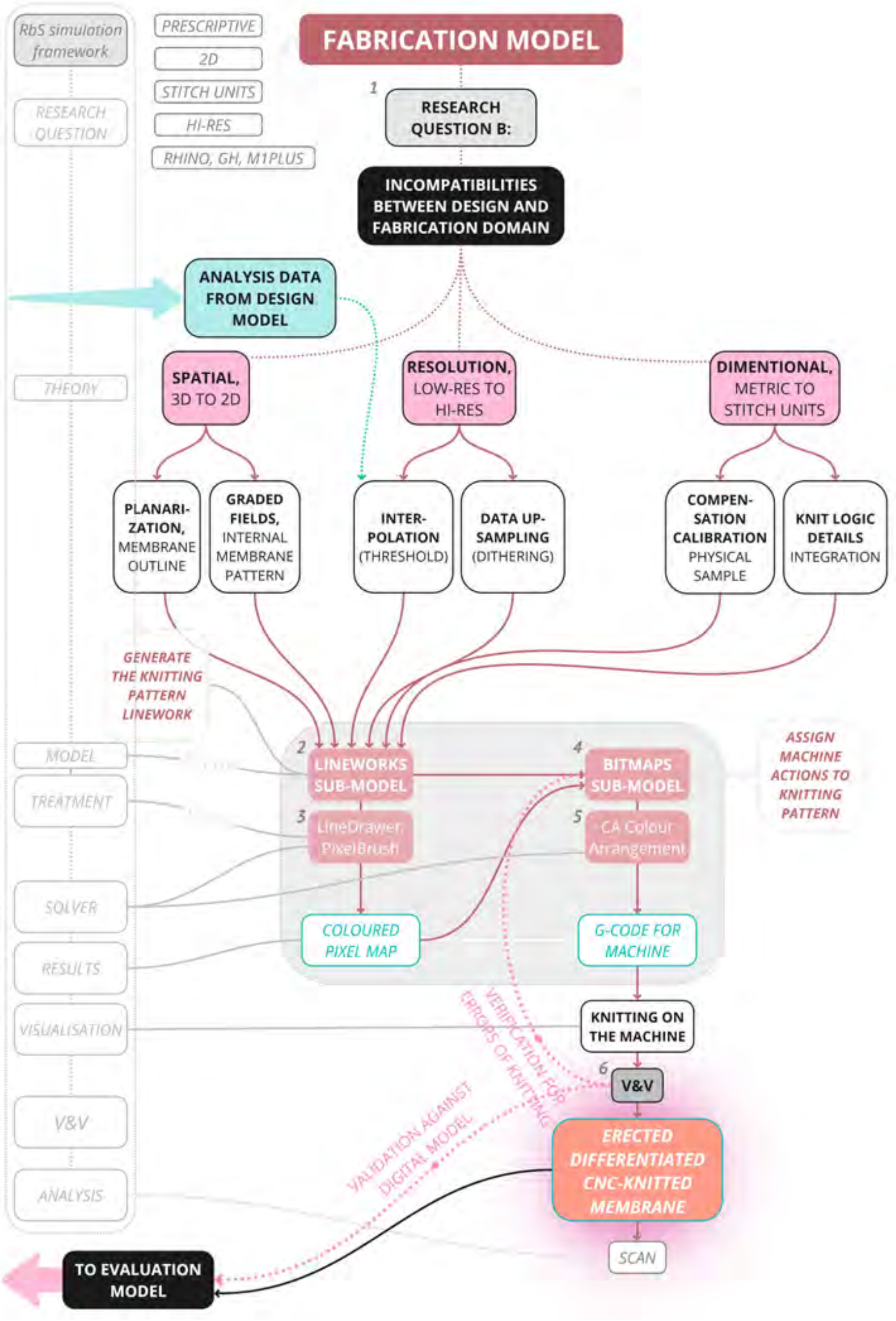
SPATIAL The *Spatial* Domain Shift *(3D to 2D)* involves translating the volumetric, *three-dimensional* mesh representation from the Design Model into the *two-dimensional*, planar data format required for knitting production. This translation process must preserve critical information about the membrane's shape, local material differentiation, and the placement of functional fabric details essential for installation.

RESOLUTION The *Resolution* Domain Shift *(Low-Res to Hi-Res)* involves adapting the *low-resolution* mesh—and the associated analysis data from the Design Model—into a *high-resolution* representation. This high-resolution format, which details every stitch, is essential for manufacturing the differentiated knits as coloured pixel images.

DIMENSIONAL The *Dimensional* Domain Shift *(metric to unit-stitch)* entails transforming between two distinct measurement standards present in the digital design and fabrication domains. This transition involves converting the *metric*-based standard used in the design space—characterizing the membrane's overall target dimensions and aligning with architectural design thinking—into the *unit*-stitch-based standard used for CNC-knit production, where the knitted membrane material system is defined in terms of stitch elements rather than metric values.

The Fabrication Model's primary purpose is to translate the form-found membrane designs from the Design Model into machine-compatible instructions, enabling the production of physical fabrics on an industrial knitting machine. Achieving this goal requires fulfilling two critical conditions: (1) ensuring that the instructions accurately reflect the intended design and functional requirements of the fabric, and (2) verifying that the instructions are executable by the machinery.

The Fabrication Model addresses these objectives through its two sub-models:



F 4.18: Fabrication model schematic workflow in relation to RbS framework. Diagram shows the complexity of the translation processes that model accommodate in order to overcome incompatibilities between Design domain and Fabrication domain

LineWorks and **BitMaps**. The *LineWorks* sub-model integrates custom-developed digital tools, *LineDrawer* and *Pixel Brush (S3, Treatment)*, offering solutions for managing *spatial*, *resolution*, and *dimensional* domain shifts. The second sub-model, *BitMaps*, receives the fully transformed design data in the form of a bitmap image and directly translates it into machine-readable instructions within the knitting programming software M1Plus, which is native to the STOLL knitting machines employed in this thesis.

The *LineWorks* sub-model operates within the parametric environment of Grasshopper, shared with the Design Model, and facilitates *planarisation* and *data transfer* to prepare knitting pixel-based files compatible with M1Plus, where the *BitMaps* sub-model, further refine the file using the custom *CA ColorArrangement* component, developed specifically for this PhD project.

To better navigate the Fabrication Model, please refer to the schematic diagram of models internal and external data flow in **F**4.18, as well as in illustrated diagram in **F**4.19, on a case of single point loaded square membrane panel.

The appendix at the end of this section includes two **key publications—4 and 3** (ordered according to the section narrative — that document the application of the Fabrication Model in the case study of the Zoirotia large-scale commission at CITA. In this project, the author of this PhD contributed to advancing the Fabrication Model into a seamless design-to-fabrication workflow, incorporating complex multi-dimensional knit material gradings.

The Zoirotia design case provided a valuable opportunity to test the boundaries of the design-to-production workflow and to refine both the Design and Fabrication digital models to meet the project's specific demands. These included integrating membrane-expressive three-dimensionality and achieving colour expression through high levels of detail and pattern sophistication. While the step-by-step instructions of the design-to-fabrication workflow are detailed in *Publication 4* by Sinke et al. 2022a, the *publication 3* by (Sinke et al. 2022b) addresses the challenges of handling multi-dimensional knit material grading at a large architectural scale. Publications are referred in text as **P**.

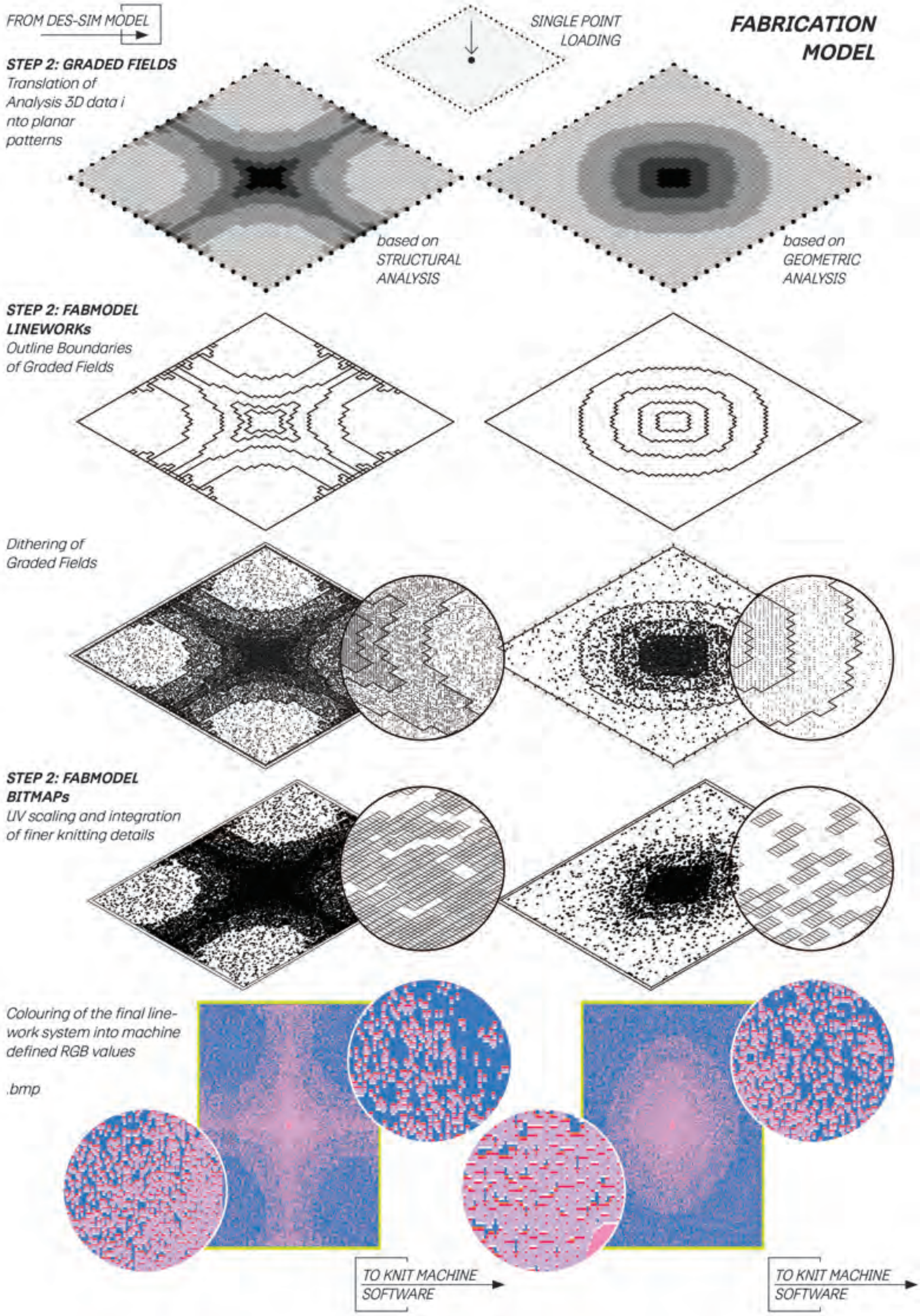
This section, however, focuses on highlighting the specific solutions the Fabrication Model offers to overcome domain shifts and manage data flow within the *RbS*-inspired framework for creating simulations.

4 Sinke, Yuliya, Mette Ramsgaard Thomsen, Drua Sif Simone Albrechtsen, and Martin Tamke (2022). **Design-to-Production Workflows for CNC-Knitted Membranes**. In *Hybrids & Haecceities: Proceedings of the 42nd Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, University of Pennsylvania, Weitzman School of Design. Philadelphia, Pennsylvania, USA, 2022. p.168-181.

3 Sinke, Yuliya, Mette Ramsgaard Thomsen, Martin Tamke, and Martynas Seskas (2022). **Strategies for Encoding Multi-Dimensional Grading of Architectural Knitted Membranes.** In *Towards Radical Regeneration*. Berlin, Germany: Springer, p.528-542.

4.2.1 SPATIAL DOMAIN SHIFT: 3D TO 2D

Within the Spatial Domain Shift, *Conformal Mapping Theory* supports the transformation of a 3D mesh into a 2D plane while preserving its local geometric relationships as much as possible. Mathematically, a conformal map is a function



F 4.19: Fabrication model: translation of analysis data into bitmap data that preserves angles locally but does not necessarily maintain lengths. This approach is essential for planarizing complex 3D meshes while minimizing distortion during the transition to a 2D production space.

The term *planarization* broadly refers to the process of transforming a three-dimensional surface into a two-dimensional plane while minimizing significant distortion, stretching, or compression of the surface geometry. The planarization of complex non-manifold meshes, as addressed in this thesis, cannot be achieved using conventional unrolling surface techniques. Instead, the planarization process in this research manages the flattening of complex form-found meshes by carefully prioritizing which mesh parameters to preserve and which to disregard during the transformation. The outer edges dimensional priority ensured the units alignment during assembly, while the material gradings, related to membrane curvature permit for certain tolerances.

The planarization considerations are closely related to the knit material differentiation strategy employed in this thesis. This material strategy utilizes a specialized *unravelling stitch* technique developed to create pronounced differences in fabric surface properties. By combining *closed dense* and *open loose* versions of a **double jacquard stitch**, filament length can be locally encapsulated and then released by *dropping* a stitch during production. This controlled unravelling results in an enlargement of the membrane's surface area when tensioned on-site. In this way, the graded-for-strain surface perfectly facilitates planar knitting production while ensuring the membrane's ability to adopt a three-dimensional shape through material stretching. A comprehensive description of this technique, including its application and implications for fabric behavior, is detailed in **P**3 Sinke et al. 2022b.

Taking into account this technique and its effects on the membrane, the spatial domain is addressed through: 1) the *planarization* of the outer membrane boundaries, complemented by 2) *internal patterning*, which leverages the controlled expansion capacity of *graded* knitted fabrics to achieve the desired 3D form. The extraction of the *outer membrane boundary* is achieved using the Planarization Solver, while the adaptation of analysis data from the 3D mesh into the *internal pattern boundaries* introduces surface patterns through the Graded Field Method.

PLANARIZATION - OUTER PATTERN BOUNDARY The Planarization Solver executes a 2D form-finding process on an artificially generated generic mesh that is topologically identical to the form-found 3D mesh, meaning it has the same number of subdivisions in UV. The Solver adjusts the angles in the 2D mesh based on the target angles of the outer edges from the form-found 3D mesh, effectively translating complex three-dimensional geometries into two-dimensional meshes.

The conformal mapping method preserves the angles between the form-found 3D mesh and its planarized equivalent, ensuring minimal distortion along the edges while neglecting the inner mesh's three-dimensionality. This inner complexity is addressed through the material's strain properties. The planarization process facilitates the extraction of the membrane's outer boundary, which can then be used for the further development of knitting files, establishing the framework for further cross-domain pattern translations that accommodate the knit material's strain capacity.

GRADED FIELDS - INTERNAL PATTERN BOUNDARIES The local material differentiation, accounting for material strain properties, is adapted using the *Graded Field Method*. This method employs a network of planar closed outlines to define the membrane's *internal differentiated features*, associated with stretch and color, and informed by analysis from the Design Model. The concept of Graded

Fields is further refined in this thesis, building on the author's prior experience in the Isoropia and Hybrid Tower projects. It is methodologically clarified in the State of the Art section on p.66 and detailed in **P**4 on p.172.

In this thesis, the *Graded Field Method*, initially developed to assign material surface properties through a series of outlines (fields), has been expanded to integrate analysis data. The Fabrication Model achieves this by automating the generation of outlines, which streamlines the creation of knitting patterns and establishes a direct link between the global membrane topology and its local properties.

During the design process, particularly in the manual approach to material differentiation (e.g., KnitVault, **P**1), the pattern is defined before the membrane undergoes form-finding. In this approach, *outlines* are drawn on the pre-simulation schematic Concept Model, which simplifies their translation into a two-dimensional fabrication domain. In contrast, computationally derived patterns, informed by *geometrical* and *structural* analysis (e.g., *Zoirotia* (**P**3-4) and *GraCe* (**P**5-6-7)), emerge later in the simulation process when the membrane has assumed its 3D form. The analysis data, consisting of displacement and axial stress numerical values, is mapped using conformal mapping, which establishes a consistent relationship between 3D and 2D meshes. This mapping ensures that their inner subdivisions align logically, facilitating precise data transfer for pattern distribution and the placement of functional details.

This thesis introduces a method for translating mapped numerical analysis data from the 2D mesh into areal zones defined by outlines. The range of stress or deviation values is divided into segments corresponding to surface subdivisions, creating thresholds that group mesh springs and define boundaries around them, thereby forming a surface pattern. Conformal mapping links these 3D groupings of springs to the 2D planarized mesh, enabling the seamless transfer of complex 3D analysis data from the Design Model into 2D surface patterns. This ensures that the structural and geometric characteristics of the membrane are accurately reflected in the final fabric output. The development of an automated tool for translating analysis data into surface patterns is critical for accommodating the diverse membrane topologies characteristic of customized architectural designs.

The spatial domain shift methodology has been continuously refined throughout this thesis, gaining increased automation and robustness. This culminated in the Zoirotia project, where 88 custom units were planarized and patterned with a high level of detail in an automated manner, documented in **P**4.

4.2.2 RESOLUTION DOMAIN SHIFT: LOW-RES TO HI-RES

INTERPOLATION AND DATA UPSAMPLING

Within the Resolution Domain Shift, *data interpolation* and *dithering* techniques guide the transformation of data from the low-resolution mesh in the Design Model into the high-resolution specifications required for CNC-knitted production.

Data interpolation in computer graphics refers to estimating values between *known data points* to create smooth transitions or fills. This technique is commonly used in rendering smooth curves, textures, or animations where intermediate values are *unknown*. *Data upsampling*, on the other hand, increases the resolution of an image or dataset by generating additional data points. This is particularly useful for scaling graphics without losing quality, such as making low-resolution images appear sharper.

Additionally, the *dithering* technique in computer graphics simulates gradient tones by scattering or adjusting pixel intensities. This effectively reduces visible artefacts and provides a smoother appearance, especially in low-color or low-resolution scenarios.

These computer graphics techniques are essential for maintaining visual fidelity and achieving smooth transitions across resolutions and color limitations. In this thesis, they are strategically adopted to address challenges related to resolution differences between the Design and Fabrication Models, complicated by large scale of architectural knit application and fine material specification requirement, complicated by the binary constraint of knitting technique.

This theoretical framework enables the adaptation and refinement of spatial analysis data from the Design Model, such as *stress distribution* and *geometric displacement*, for integration into two-dimensional low-resolution Graded Fields.

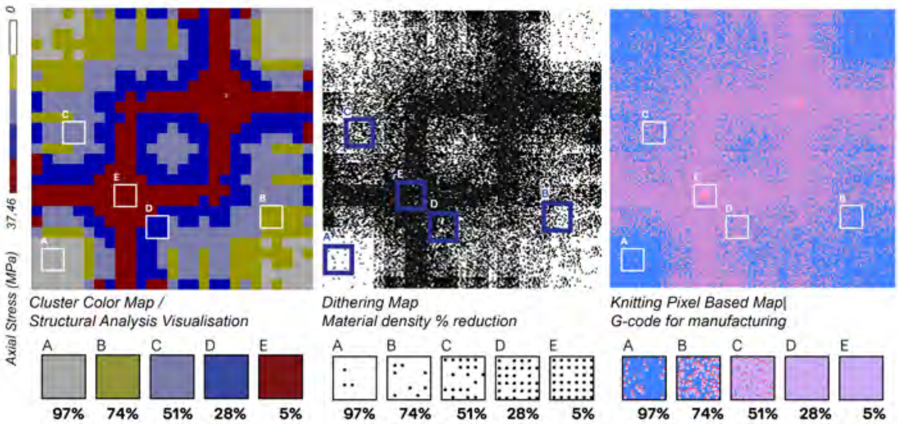
Data interpolation links analysis data describing the membrane's global behavior (e.g., stress accumulation or surface displacement) to material density. This is achieved through numerical mapping across the *threshold* subdivisions in the Graded Fields. For example, areas of the membrane with the highest stress or displacement are correlated with the lowest material density, assigned via percentage values. Conversely, the least stressed or displaced areas are assigned the highest material density, enabling those regions to remain stiff and contribute to the membrane's global structural behavior.

DITHERING

Material density, represented as a percentage value, is visualized using the *dithering* technique. This method creates gradient transitions between low-resolution Graded Fields by numerically controlling the population of points within each field. This approach captures subtle shifts in stress distribution or displacement across the membrane, even when using the lower-resolution mesh subdivisions inherent to the Design Model. *Dithering* thus translates global membrane properties into smooth material patterns using only two stitch types for structural surface differentiation.

In this thesis, the *dithering* technique also consolidates multiple differentiation features by utilizing a density-based numerical approach. This universal format specifies saturation levels for various material properties, which can be differentiated either structurally (e.g., loose-dense stitch combinations) or chromatically (e.g., multi-color combinations) (see Fig. 8 in **P**3). While the binary nature of dithering may initially seem limiting for design flexibility, its efficiency lies in achieving fine-grained control with minimal parameters. This results in smooth transitions that enhance both functionality and aesthetic expression. By strategically distributing points representing stitches, dithering enables seamless transitions between material properties despite the binary constraint of knitting.

To address the challenge of transferring color data across different resolution scales, an auxiliary *Colour Model* plays a critical role. This model facilitates the transition from globally defined color differentiations, spanning multiple membrane units at a large architectural scale, to an upsampled color density gradient for individual panels at finer resolutions. It uses a height-map approach, where proximity to attraction points representing primary colors determines the color density within each panel. This process is detailed in **P**3 (Figures 9–11) through the Zoirotia case study, which outlines strategies for multi-dimensional grading and demonstrates how to bridge the resolution gap between simulation and fabrication models at an architectural scale.



F 4.20: Data Interpolation, upsampling and dithering

The combined approaches of data interpolation and dithering offer a layered, adaptive solution that aligns low-resolution data from the Design Model with the high-resolution material configurations required by the Fabrication Model. This approach establishes a detailed, functional correspondence between simulation outputs and production requirements, maintaining continuity and fidelity across design and production resolutions **F**4.20, successfully bridging the gap between them.

4.2.3 DIMENSIONAL DOMAIN SHIFT: METRIC-TO-UNIT MEASURE SYSTEM

COMPENSATION CALIBRATION THROUGH MATERIAL SAMPLING

Within the *Dimensional* Domain Shift, the transition from metric to unit-based measurement standards is managed through geometric compensation by scaling knitting files, calibrated using small physical samples.

The compensation is necessary to accommodate the vertical shrinkage of knit during the production. The shrinkage occurs due to the square pixels used to program the knit result in rectangular stitches. As a result, dimensional compensation of the knitting files is required to ensure predictable dimensions in the resulting fabric. It is common practice in textile design to scale knitting patterns vertically to produce square physical fabric. This scaling factor acts as a bridge between the digital file's coordinates and the physical patch dimensions, ensuring that every digital measurement aligns proportionately with its real-world counterpart. The scaling factor must often be calibrated against physical textile samples, as the resulting knit dimensions depend on numerous factors, including machine settings, stitch selection, and pattern choice. By comparing the measurements of physically produced textile samples (e.g., in centimeters) with the pixel dimensions of the digital file, a UV scaling factor can be derived to compensate for the dimensional differences.

It is important to note that the UV scaling factor may not be precise on the first attempt. Designing a preliminary testing sample that accurately represents the behavior of large-scale graded fabric presents challenges, as differentiated knits behave differently at different scales. Small textile patches do not directly reflect the behavior of larger membrane surfaces, where forces and stretch properties interact dynamically. Additionally, manual measurement of samples can introduce tolerances and inaccuracies that further affect scaling precision. Despite these uncertainties, creating a preliminary sample—ideally at least 1 m x 1 m for architectural applications—is essential to obtain a more precise initial approximation of the compensation scaling factor, ensuring better accuracy in the dimensions of large-scale fabrics.

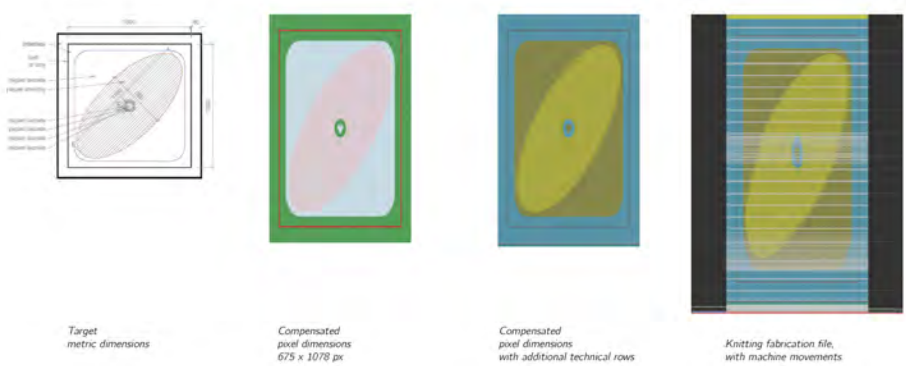
KNIT LOGIC DETAILS

Preparing knitting files involves more than simply scaling the design pattern for dimensional compensation. It also requires embedding essential knitting logic to ensure the pattern is machine-compatible. This includes addressing specific programming modes for certain knitting processes, such as startup procedures, bind-off techniques, and additional needle actions. These elements must be incorporated into the file alongside definitions for surface material properties. Successful file preparation demands a deep understanding of CNC knitting techniques and their execution on industrial knitting machines. This knowledge ensures proper integration of production functions and simplifies the machine programming process. The sequential nature of knit additive manufacturing dictates that the Fabrication Model must align with the production constraints inherent to CNC knitting, including machine mechanics, machining sequences, and file format requirements.

MACHINE MECHANICS The computerized flat-bed knitting machines used in this thesis include several key mechanical components essential for their operation. These components include two *needle beds*, housing needles actuated by driving *carriages* equipped with electronically programmable CAM systems. These systems control the needles to create knitting patterns by intertwining yarn filaments, which are supplied by yarn carriers. Rollers in the machine manage *yarn tension*, guide the fabric, and prevent stitch accumulation, ensuring a smooth and consistent knitting process. The specific industrial knitting machines used in this thesis are the STOLL CMS 822 HP ki and the STOLL CMS T730 knit&wear E7.2.

MACHINE INSTRUCTIONS All mechanical components are controlled linearly, with material assembly and structural logic defined sequentially, row by row. Programming the knitting machine involves scheduling the movements of the driving carriage and yarn carriers, selecting the CAM system, and coordinating needle operations. On modern knitting machines, this complex scheduling is simplified for programmers, who primarily define needle operations by assigning stitches to pixels in the input bitmap file.

FILE FORMAT - BITMAP The knitting machine programming software M1Plus uses a time-needle representation, where each stitch is depicted as a colored pixel. The pixel's color indicates the yarn carrier or needle action, while the x-axis defines the needle location within the bed, and the y-axis represents the knitting process's timeline. These pixel images are read from the bottom, reflecting the additive nature of knitting. This pixel-based format serves as an interface with the native programming tools and can be prepared externally, enabling better integration with the 3D shape data of the designed membrane.



F 4.21: Patch dimensional dynamic when translating from metric- to stitch-based units. The patch scales up vertically to compensate the non-square stitch dimension.

AUTOMATISATION OF COMPENSATION AND INTEGRATION OF KNIT LOGIC DETAILS

In garment textile industry, which often focuses on mass production, scaling factors and knitting logic file specifications are typically handled manually. This involves intricate placement of specific stitches to define knitting starts, edge conditions, and other complex stitch combinations. However, the architectural knitted membranes used in large-scale projects and in this thesis, require custom shapes and surface differentiations, making manual adjustments impractical and inefficient.

This thesis addresses scaling compensation and the integration of knit logic features through automation within the design-to-fabrication workflow. The automated *LineDrawer Tool* scales the imported outline-based linework from the Design Model, which contains information on membrane boundaries and inner graded field patterns. The tool further integrates functional membrane features (e.g., channels, holes) and knitting logic details such as startup procedures, edge shaping, stitch dropping, and other crucial processes for CNC knitting. Scaling compensation is performed before integrating knit logic details, as these often involve single-pixel features that cannot undergo scaling.

Automating knitting file preparation accelerates the iterative loop from design to production, enabling rapid adjustments and more efficient tuning of the scaling factor with each successive prototype. This iterative calibration process begins with smaller samples and progresses to larger physical prototypes, refining the scaling factor over time and ensuring a smooth progression from design to full-scale manufacturing.

Automation also reduces the need for manual adjustments by placing essential stitches in a rule-based manner, effectively linking the patch topology to its local features. This approach streamlines prototyping and helps maintain project timelines by enabling membrane design adjustments with the assurance that the knitting file will be ready within seconds.

The finely defined linework is then colored using the *PixelBrush Tool* to generate pixel-based **bitmaps**. During this thesis, the complexity of the *LineDrawer Tool* was continuously enhanced, culminating in the Zoirotia project, where 52 colors representing distinct knitting functions were embedded within each knitting file, as documented in **P**4.

4.2.4 KNITTING SOLVER: THE EMERGENCE OF THE PHYSICAL MODEL

A highly detailed bitmap, embedding all the knitting functions necessary for the membrane's fabrication, is imported into the M1Plus knitting programming software. Here, the BitMap sub-model, powered by a custom CA Colour Arrangement component, transforms the indexed color bitmap into precise machine-readable knitting instructions. **P**4 offers an in-depth account of the collaboration between the author of this thesis and textile designer Drua Sif Albrechtsen, a partnership that catalyzed the parallel evolution of the LineWorks and BitMap sub-models. This collaboration seamlessly integrated critical aspects of knitting production into the Fabrication Model, resulting in versatile, universal algorithms that enable an efficient design-to-production transition across diverse membrane topologies.

The successfully prepared bitmap file ensures the seamless operation of the M1Plus Solver, which translates assigned needle actions and settings into the binary mechanical movements of the knitting machine's intricate components. Within the M1Plus software, the Solver processes the bitmap's color assignments and performs a syntax check, identifying errors while simulating the forthcoming knitting process. This virtual *preview* provides essential insights, including detailed machine action statistics and an estimated production timeline. The resulting G-code is then dispatched to the knitting machine, where the Fabrication Model transforms from an abstract binary construct into a tangible textile membrane, marking the momentous *emergence of the Physical Model*. The *physical model* term is an umbrella, encompassing a wide spectrum, from experimental samples and investigative probes to fully realized prototypes and demonstrators.

Upon completion of the knitting process, the membrane is erected and prestressed through on-site tensioning, activating its inherent material properties and unlocking its structural potential. This act of realization offers an opportunity for visual observation and critical assessment, allowing the verification of the digital Fabrication Model and the validation of the Physical Model against the envisioned Design-Simulation Model, discussed further down.

4.2.5 VERIFICATION & VALIDATION OF THE FABRICATION MODEL

Like the Design Model, the Fabrication Model is also subject to rigorous verification and validation processes. These processes are critical for ensuring that the Fabrication Model not only meets the technical and functional requirements of knitting production but also faithfully translates the intended design into a tangible physical artefact.

VERIFICATION: ENSURING TECHNICALLY SOUND KNITTING OUTCOMES

The *verification* process of the Fabrication Model focuses on ensuring technically robust textile outcomes, free from defects such as holes, unintended dropped stitches, and other knitting errors. This PhD research explores the drop stitch as a key local material feature to achieve controlled fabric expansion. Conventionally, in the garment industry, drop stitches are treated as errors because they lead to fabric disintegration by creating holes. In this thesis, however, the Fabrication Model reinterprets drop stitches as a deliberate technique for fabric expansion through *controlled unravelling*.

A notable challenge emerged during the collaboration with external manufacturers on the Zoirotia project, highlighting differing interpretations of errors across disciplines. The production team, unfamiliar with or perhaps insufficiently introduced to the concept of drop stitches as a functional design feature, perceived these stitches as indicative of issues in the knitting file. They assumed the fabric's loose areas resulted from incorrect machine settings. This misunderstanding caused delays due to unnecessary troubleshooting but also provided valuable lessons in interdisciplinary communication. Addressing this disconnect required thorough discussions to clarify that the unravelling stitches were an integral part of the design's expansion strategy rather than a defect. Such discussions underscore the importance of clear communication in interdisciplinary collaborations to align and ensure mutual understanding of design intentions.

Despite these efforts, the technical verification of drop stitches can remain challenging, as distinguishing between intentional and accidental drop stitches requires nuanced troubleshooting and careful inspection, particularly when unintended drop stitches occur within intended patterns.

VALIDATION: ENSURING FIDELITY OF DESIGN AND FABRICATION MODELS

The *validation* of the Fabrication Model ensures that digital design intentions are accurately translated into machine-compatible knitting instructions, aligning with the outputs of the Design-Simulation Model. Validation is achieved through consistent communication between the Fabrication Model's two sub-models: LineWorks and BitMaps.

The LineWorks sub-model manages the dimensional scaling of the design to match the machine's stitch settings, while the BitMaps sub-model ensures that the translated instructions are executable by the knitting machinery. This close coordination ensures that all necessary production details—from dimensional scaling to structural specifications—are incorporated into the final knitting files. This linkage effectively bridges the gap between design intent and production requirements, ensuring that every step reflects the envisioned functionality and aligns closely with the simulation outputs. Together, the LineWorks and BitMaps sub-models enable the Fabrication Model to faithfully reproduce the Design Model, facilitating a smooth transition from digital design to tangible textile, as detailed in the comprehensive design-to-production workflow in **P**4.

DESIGN-TO-FABRICATION-TO-EVALUATION

This section highlights the Fabrication Model's critical role in addressing design and fabrication domain differences by converting three-dimensional 3d meshes, representing tensile membranes into two-dimensional machine-readable instructions. It ensures that the final product aligns with both the design intent and performance requirements. However, while the Fabrication Model captures design and functionality with detailed local material programming, it does not guarantee that the physical artefact, knitted with these instructions will fully replicate the behavior predicted in simulation. To validate and address this gap, a third model—the *Eval-*

uation Model—has been developed in this thesis. This model validates the Design Model against physical knitted prototypes, creating a feedback loop that facilitates necessary adjustments and refinements to the Design Model. This iterative process enhances alignment between the digital simulation and material reality, as described in the following section.

Publication 4

DESIGN-TO-PRODUCTION WORKFLOWS FOR CNC-KNITTED MEMBRANES

Design-to-production Workflows for CNC-knitted Membranes

Strategies for design-to-production workflows for 3-dimensional non-developable CNC-knitted membranes

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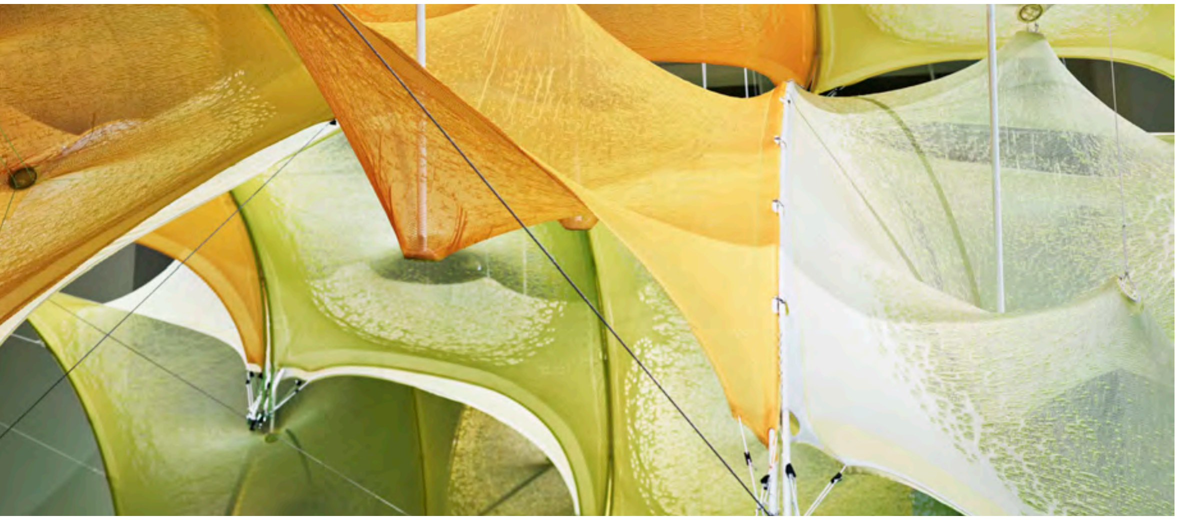


1 Close up of *Zoirotia* CNC-knitted membranes complex surfaces

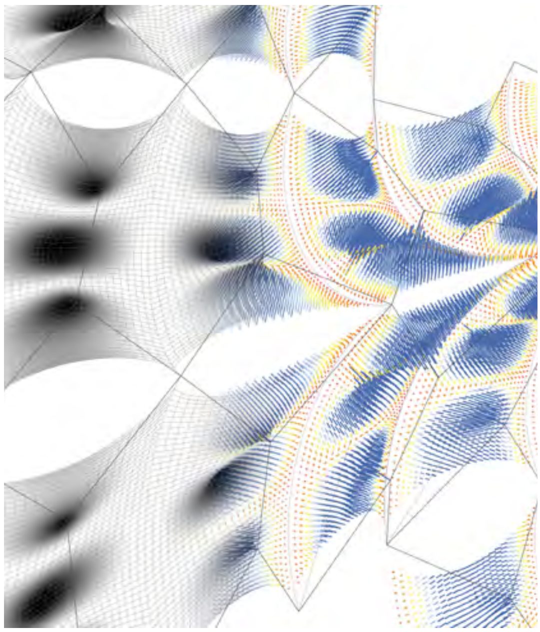
ABSTRACT

This paper discusses the design integration of knitted textiles into architectural workflows. The increasing interest in knit as a building material asks new questions of how knit can be designed, analyzed, specified, and fabricated at a large scale, with appropriate tolerances and verified performances. This paper presents a classification of two methods for fabricating 3-dimensional non-developable structural membranes with CNC-controlled industrial knitting machines: the graph method and the graded field method. It outlines the key differences in the two methods and discusses their individual benefits and limitations. It presents *Zoirotia* as a design case for the graded field method and describes a series of advances to this method as developed through the project.

INTRODUCTION

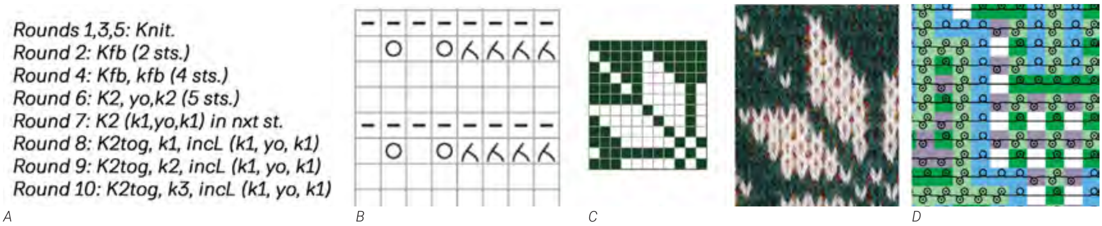
During the last decade research into knitted textiles for architectural application has gained increasing interest. Knitting technology presents a promising alternative to woven materials traditionally used in tensile textile design, as it allows for the construction of three-dimensional fabrics through the strategic placement and selection of stitches. Employed as alternative textiles substrates for structural membranes (Ramsgaard Thomsen et al. 2015; Ramsgaard Thomsen et al. 2019; Ahlquist 2015), formwork (Popescu 2019; Liu, Li, and Yuan 2020), and actuated structures (Scott 2013; Ramsgaard Thomsen and Karmon 2012; Ahlquist 2019), knit is understood as an innovative material system enabling complex geometry and bespoke fabrication while addressing the problem of waste in alternative textile systems such as a mass-produced weave (Ramsgaard Thomsen and Hicks 2008). By selecting high-performance yarns, such as high molecular weight polyethylene, aramid fibers, or high-performance polyester, the performance of the textile membranes can be designed in accordance with specific behavior demands.

This innovation relies on the creation of design-to-fabrication workflows that interface architectural design systems and CNC industrial knitting machines. CNC industrial knitting machines are developed for the garment industry and include specific workflows and software relying on the manual compiling of machine instructions. Knitting for architecture presents radically new demands to these workflows. Architectural knitted textiles depend on their three-dimensionality for performance, are large scale, have high demands to tolerance and customization, and need to incorporate material performance analysis that allow designers to control the geometry, strength and structure of the textile membrane. The acknowledgment that garment-based approach for knit design cannot be applied to an architectural scope has compelled the field to search for new approaches towards knit programming (Ramsgaard Thomsen et al. 2016; Popescu et al. 2017). In the field of architecture, two methods of design-to-fabrication automation are emerging. Both develop means of knitting three-dimensional non-developable geometries on flatbed knitting machines. Flatbed knitting machines are linear, therefore operating planarly during the production; however, addressing the control of the machine motion and knit structure will result in non-planar materials. The two methods, the graph method with a homogeneous knit structure and the graded field method with a discretized knit structure, respectively, use techniques of partial knitting or structural grading to create non-developable textile surfaces. This paper outlines the two methods, presenting their differences and individual limitations. It presents the *Zoirotia* design case and discusses the development of series of advances to the graded field method.

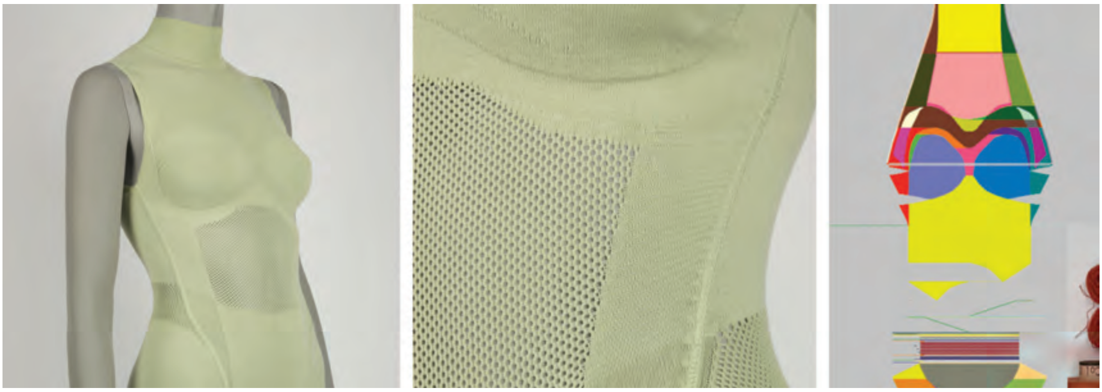


2 Frontal view of *Zoirotia*, 2022

3 Surface displacement visualization during the form-finding of *Zoirotia* membranes



4 Examples of knitting instructions: (A) String-based descriptions; (B) Symbol-based descriptions; (C) Colored grid based; (D) Color and symbol-based for CNC-production



5 Example of pre-set pattern from the STOLL pattern shop

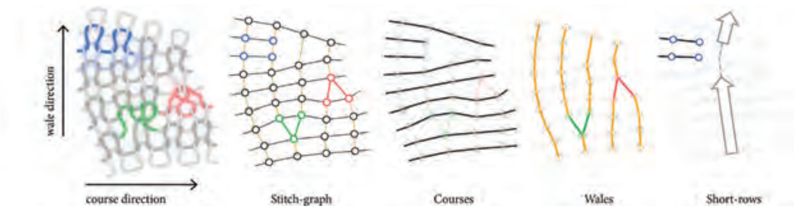
INSTRUCTIONS AND DESIGN-TO-PRODUCTION WORKFLOW FOR 3-DIMENSIONAL NON-DEVELOPABLE KNITTED MEMBRANES

The tradition of knit instructions relies on linear descriptions in which the material assembly and structural logic of the material is declared sequentially, annotating needle-yarn manipulation row-by-row and following the order of fabrication. In manual knitting, these instructions are expressed as text- or symbol-based depictions organized either line-by-line or in a grid form (Figure 4). For CNC knitting, this underlying logic is continued. Here, the fabric material is encoded through the series of sequential instructions for the machine, existing within a two-dimensional drawing environment of the knitting machine software (M1Plus for STOLL or KnitPaint for SHIMASEIKI). These are represented in a form of time-needle schedules (Kaspar 2022; McCann et al. 2016), made of colored grid-organized symbols (Figure 4D). In these, the *x*-axis represents the needle space, while the *y*-axis represents the time. Through the color and symbols, these schedules allow for programming the engagement of the machine knitting carriage with the needles and the yarn carriers to form the stitches.

The preparation of knitting instructions requires a strong level of competence in understanding the relations between the pattern encryptions and their physical stitches equivalent to predict the fabric outcome and the volumetric behavior. The creation of new custom patterns is accompanied by extensive prototyping to evaluate the design, structure, and performance of the textile as well as its aesthetics, and if necessary, manually fine-tuning of the pattern configuration to the best outcome (Figure 5).

In contrast to industries where knitting is used for mass-production (garment, shoe or automotive), the architecture field has a greater demand for highly customized non-repetitive modules. This necessitates automated interfaces that can input file variations without labor-intensive manual compilation. Architectural membranes, furthermore, are inherently three-dimensional, using complex geometry to support structural performance. Structural membrane design implies volumetric design modeling through form-finding and simulation, to arrive at well-performing geometries that support pretensioning for structural stability. These result in highly three-dimensional surfaces, which need to be translated into a two-dimensional representation in order to be manufactured on flatbed knitting machines.

The time-needle schedule informs the two-dimensional machine instruction programming and can be replaced with a bitmap image, loaded to the native machine software. This pixel-based raster bitmap file plays the role of the linking interface to native machine programming tools



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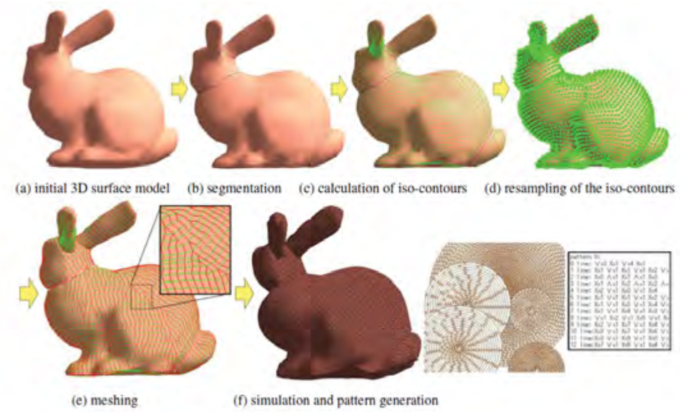


7

6 Partial knitting technique illustration; garment design workflows for on-demand machine knitting

7 Knitting a 3D model: graph method workflow

and can be prepared outside of the native knitting software with stronger links to the 3D shape data. The interfacing of the three-dimensional membrane geometry and its manufacturing two-dimensional bitmap file is understood through various ways of evaluating the membrane design three-dimensionally and its specification into an arranged pixel-based bitmap. The choice of methods used for volumetric shape evaluation is strongly linked to a knitting technique that is selected for the fabrication of membranes and affects the size of a design space.

TWO METHODS FOR SHAPE SPECIFICATION OF THREE-DIMENSIONAL KNITTING

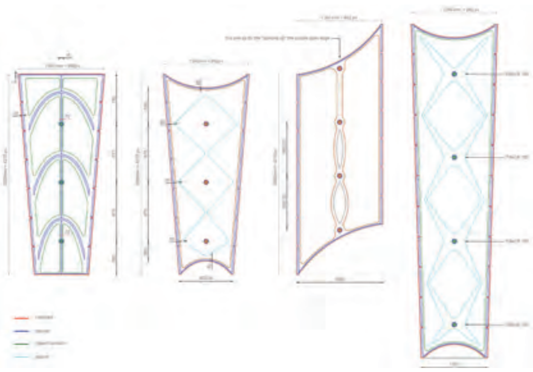
To aid the fabrication of knitted complex non-developable surfaces, two methods for shape specification and manufacturing instruction representation are described further. These are graph and graded field methods. The following classification is defined by the paper authors and informed by existing workflow descriptions within the community of computer scientists and architects working with architectural knitting. The two methods achieve three-dimensionality through either accumulating selected stitches (partial knitting technique) or through the grading of the stitch structure (structural knit grading technique).

Graph Method

The graph knitting method employs a partial knitting technique to produce a three-dimensional fabric. By building on techniques coming from the field of computer graphics (Igarashi, Igarashi, and Suzuki 2008; McCann et al. 2016; Narayanan et al. 2018; Kaspar, Makatura, and Matusik 2019; Wu, Swan, and Yuksel 2019; Nader et al. 2021), the method allows the introduction of short rows, locally taking in and taking out stitches, resulting in the accumulation of material and hyperbolic bulging out of the plane, thereby forming a 3D surface (Figure 6). Focusing mainly on complex non-developable geometries to be made with the short-row technique, the fundamental discoveries of these laid a ground for further extension of the method to a larger scale of architectural elements and structures (Liu, Li, and Yuan 2020; Popescu et al. 2017; 2020). Although mentioned authors have some minor differences in their research aims and results, it is possible to define unified steps for describing the graph method, that lay fundamentally behind the method in our research.

To describe the three-dimensional surface in this manner, the graph method develops a series of steps to analyze and describe the surface along its courses (Figure 6).

The first step analyzes the textile form to define the start and end of the production cycle and determine the direction of knitting. Then the model is segmented and sliced into isocurves, which introduce the knitting rows (Figure 7). Each isocurve is sampled (divided) and populated with evenly distributed points, equal to the number of stitches per row. These points then are interconnected vertically to define pairing stitches. Unpaired



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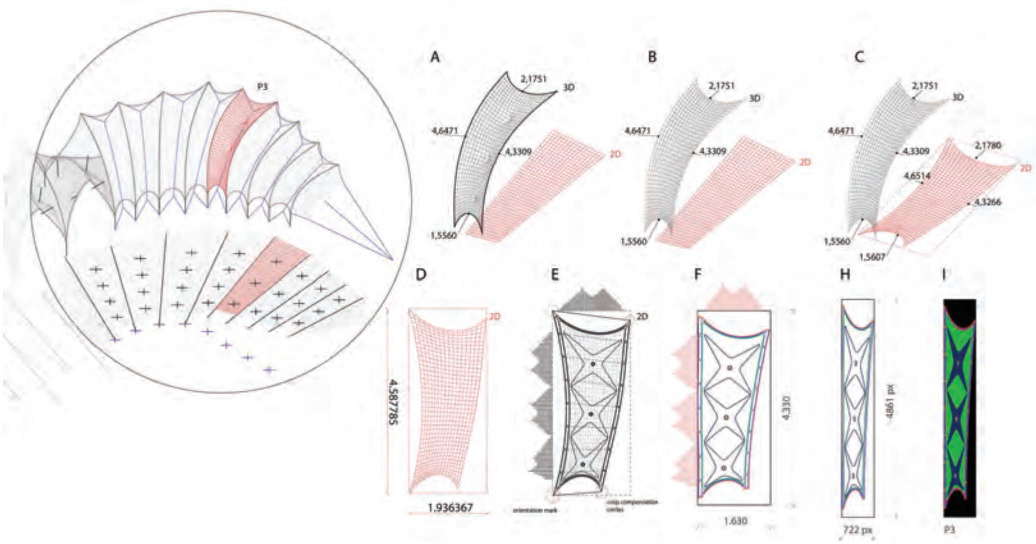

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stitches would mark the boundary of the short row. Constructed links between the points form a surface network, that informs the build-up of the graph diagram, representing the relations between rows and columns. As a result, a grid-bound planarly arranged map of square pixels is constructed (bitmap) to be used for further machine instructions.

The graph method results in a three-dimensional textile with a homogeneous structure. As the stitch structure remains the same across the surface, the textile is undifferentiated in its initial structure. Further additions of yarn changes or structural changes can expand this expression.

Graded Field Method

The second method, developed at CITA uses the strategic grading of the textile surface by interchanging the stitch patterns. In knit the interchange between how the stitches are connected, the correlation between the front and the back bed (flatbed knitting), and the yarn tension create different locking points for the individual stitches. The locking point is the state in which the knit stitches are fully in tension. The grading of locking points is supported by the knitting machine's automated take-down systems that allow the differentiated tensioning of the textile under production. Unlike the graph method, in which the same stitch is used across the textile, the graded field method constructs each row out of varied stitches creating a heterogeneous pattern. These differ in their geometrical configuration, and therefore, in their structural performance, which results in the formation of the three-dimensional surface. Stitches with bigger and smaller locking point lengths are placed in relation to structural performance and surface displacement to enable the textile expansion under the load (Figure 9).

11

8 Varied graded field geometric shapes are iterated during the prototyping phase

9 Stitches with bigger and smaller locking point lengths, represented by green and dark blue colors, are used to achieve membrane surface expansion

10 Graded field method workflow (2008) in *Isoropia* project by CITA

11 Close up to the structurally graded membrane of *Zoirotia*, with the visible difference in the knitted structure composition

The graded field method defines the planarized boundary of the three-dimensional membrane shape. The areas of three-dimensional extension are then defined around their tension point. Through the prototyping, different field shapes were examined, and the most controlled and expanded shapes were chosen (Figure 8).

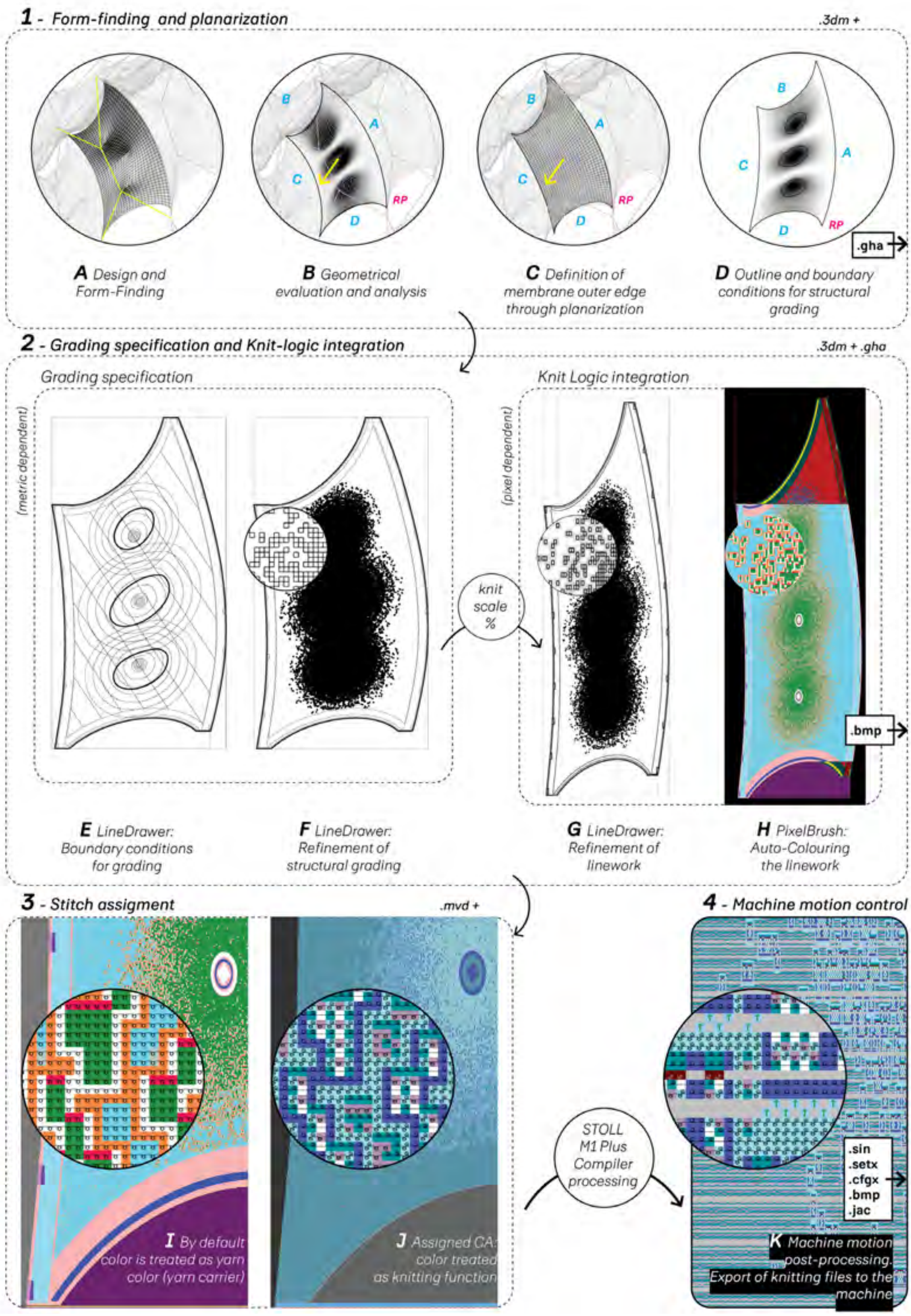
This allows us to define the graded field in which we place stitch types with bigger locking point lengths. In the first iterations of the method, the fields and their resulting membrane extension were defined through processes of prototyping and analyzed using the parametric calculation of the yarn usage per row. The method uses the automated generation of pixel maps as a common interface to the CNC knitting machine. Through the architectural design environment, the graded fields are defined as colored zones with specific RGB values and a BMP file with a predefined resolution is exported (Ramsgaard Thomsen et al. 2019). This BMP file is used to interface the knitting machine software through the assignment of specific stitch specifications and machine motion control (Figure 10).

EXTENDING THE GRADED FIELD-BASED METHOD: *ZOIROTIA* AS DESIGN CASE

The following presents the further development of the graded field method. Here, we depart from predefined field shapes to a structurally informed gradient field where the resulting three-dimensional extension is directly informed by a geometric analysis of the membrane performance. The method is developed through the design case *Zoirotia*, a large-scale installation developed for the ZKM Center for Art and Media in Karlsruhe, Germany. The method extends the graded field method by enabling a stronger performance integration and a more refined surface differentiation by introducing dithering strategies that allow to locally tune the transition of the membrane expansion properties. This is achieved through the development of an automated workflow allowing for the integration of complex structural grading informed by geometrical analysis with a high degree of detail for the interface file specification.

Zoirotia consists of 88 unique tensile CNC-knitted structural membranes, that are three-dimensional and pretensioned, which creates a non-developable membrane geometry. To achieve their geometry and structural performance, the membranes are graded using two stitch types with different locking point lengths. In *Zoirotia* we use a highly differentiated stitch structure (double jacquard and unravel double jacquard) that allows us to locally expand the membranes by up to 200% (Figure 11).

The method builds on the automated generation of pixel maps as an interface to the CNC knitting machine and extends this by further detailing its file generation capacity to enable highly detailed specifications that allow the dithered grading



12 Extended workflow diagram for graded field method (2022) for structurally differentiated knitted membranes

13 Close up of the surface differentiation with the double jacquard and unravel double jacquard stitches

of the membranes. It includes a stronger integration of knit logic that analyzes the structural integrity of the membrane and automates the adaptation to fabrication needs.

The method extends beyond the pixel map generation to create a bespoke parametric tool (Color Arrangement, heretofore referred to as CA) that assigns stitch functions to the files. This step allows to treat the color in the imported bitmaps as knit functions, rather than yarn carriers, as usually done by default in the STOLL software for knitted garments with double jacquard.

KNIT SPECIFICATION PHASES IN EXTENDED GRADED FIELD METHOD

The workflow process described below demonstrates an extension of the graded field method used to design and fabricate the surface graded membrane. For that, two custom parametric modules (LineDrawer + PixelBrush and CA STOLL module) are developed in collaboration between the design team and the machine operator. These tools allow for the automation of material specification and machine motion control. The workflow includes four specification phases moving from design to production through: 1) form-finding and planarization; 2) grading specification and knit logic integration; 3) stitch assignment; and 4) machine motion control specification (Figure 12).

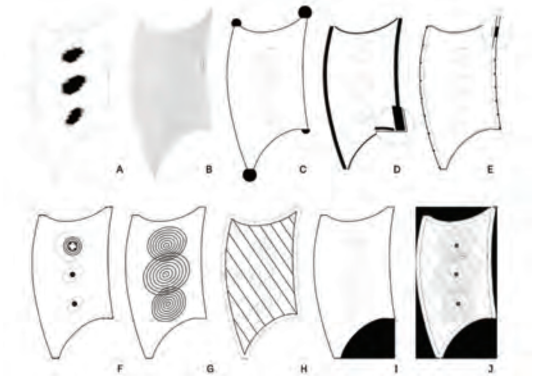
Specification Phase 1: Form-finding and Planarization

The first phase sees the definition of the textile outline and its three-dimensional extension. The translation from 3D design to 2D field graphics linework takes place through the strategic planarization of the volumetric shape (Figure 12C). Here, the untensioned surface is evaluated against its final structural pretensioning, allowing us to calculate the displacement, and therefore, the needed surface expansion (Figure 12B). Here, a hierarchy of membrane measurements is established, defining the outer boundary of the membrane, and the outline shape of the graded field is planarized onto a 2D plane (Figure 12D). To inform this, we implement a monochrome displacement gradient map used to define the areas with a larger expansion value (unravel double jacquard stitch) (Figure 13).

Specification Phase 2: Grading Specification and Knit Logic Integration

Once the outer boundary of the membrane and outline shape of the graded field are generated (Figure 12D), a series of refinements of the membrane outlines are implemented (Figure 14A-J) and the programming of the graded field can begin.

To translate the monochrome gradient map into a dithering strategy structurally grading the membrane, we define a series of circular threshold boundaries that control the number of sequential unravel stitches in each row in turn defining the three-dimensionality of the membrane (Figure 12E). At first, this is treated as a binary grading in which the grading strategy is declared. After this, in a second process, we generate a series of boundary stitches defining the drop stitch and the transitional boundaries around the dithered



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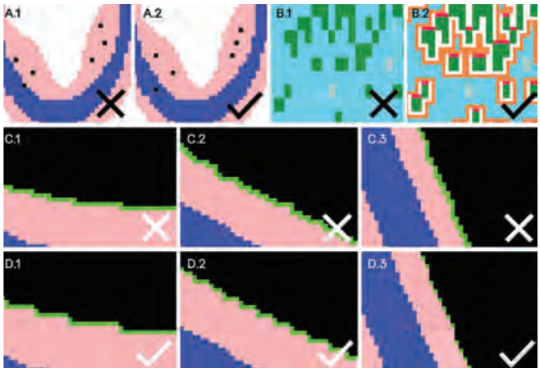

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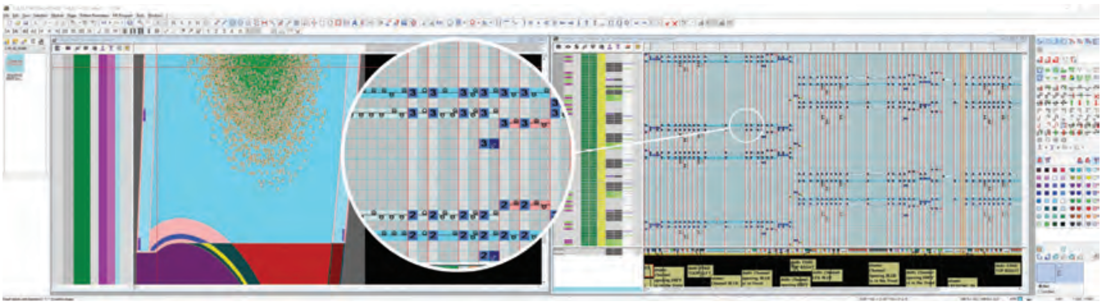

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fields (Figure 12G). These are crucial for the unravel double jacquard texture integrity during the production (Figure 15, B.1-B.2).

The membranes are knitted to shape by decreasing or increasing the number of stitches at the edge of the membrane. It follows fabrication-driven rules for stitch stepping angles. To enable this we generate the placement of cast-on and cast-off functions at each edge of the membrane, where the stepping configuration is informed by the curvature of the edge outline in respect to the knitting direction (Figure 15, C-D).

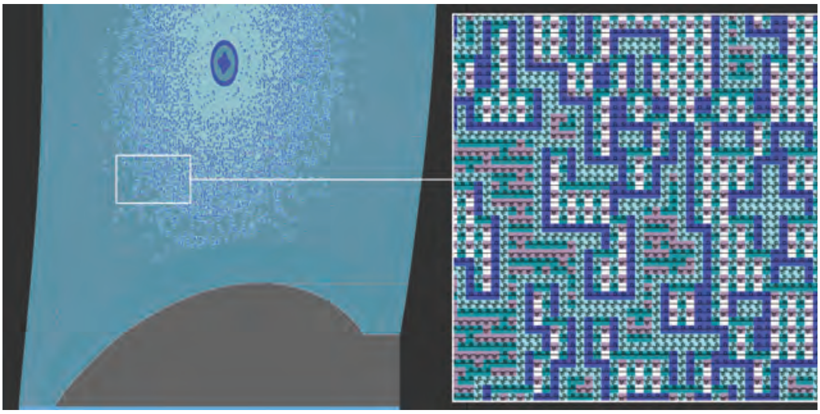
Once all the refined field linework is generated, it is assigned an RGB color value and exported as an index-colored bitmap file. The detailed knit interface programming results in automatically generated highly-differentiated bitmap files, each characterized by total 52 indexed colors, corresponding to the number of assigned knitting functions (Figure 19).

Specification Phase 3: Stitch Assignment

The automatically generated bitmaps are imported into the STOLL native knitting machine software M1Plus), where the pixel map colors are associated to machine instructions. The use of a custom-developed parametric component in CA allows for the automated function assignment. The CA component contains small units of pattern codes that are programmed to be applied to specific color areas within the canvas (Figure 16). The colors, therefore, no longer correspond to the yarn carrier but to a knit function and act as an information package that can be unfolded by the program. Here, all information related to a needle actuation is programmed and machine-specific values can be edited within the global CA to match the chosen machine type (Figure 17). In *Zoirotia*, a universal CA module is created containing all possible knitting functions within all 88 bespoke membranes of the structure.

Specification Phase 4: Machine Motion Control

During the last phase of the workflow, the additional carriage and needle bed-related functions (effecting transfers and racking) are integrated into the pattern through a native post-processing compiler within STOLL M1 Plus software. It unfolds the stitch modules into compound elements (simpler needle motions) and expands the knitting rows based on the carriage drive direction (grey lines) (Figure 18). The completion of this phase relies fully on the structural integrity of the material grading and the knit logic of the support stitches around the dithered fields, where the pixel-dependent knitting features are refined so to make the program physically knittable.



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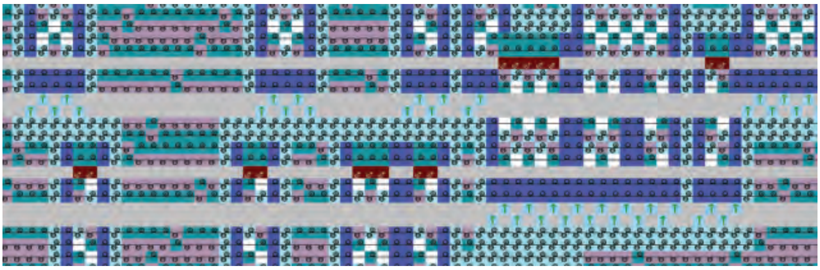

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14 Grading knit specification defining the fields for distinct knitting features and structures: refinement of the outer boundary (C), introduction of detailing (D and E, F), subdivision of zones for structural grading (G), the definition of color grading (H), integration of waste yarn to support the knitting machine's automated take-down systems (I); (J) shows joined linework

15 Illustration showing the level of detail for structural grading of the membrane with a graded field approach

16 Color Arrangement (CA) interface within STOLL M1 Plus

17 Stitch assignment phase; close up of the color-symbol based assignments

18 Machine motion generation during the last phase specification by adding transfers and racking functions

RESULTS

This paper presents two methods for the fabrication of three-dimensional non-developable knitted membranes. Below these methods are evaluated through a set of criteria to that outline their benefits and limitations.

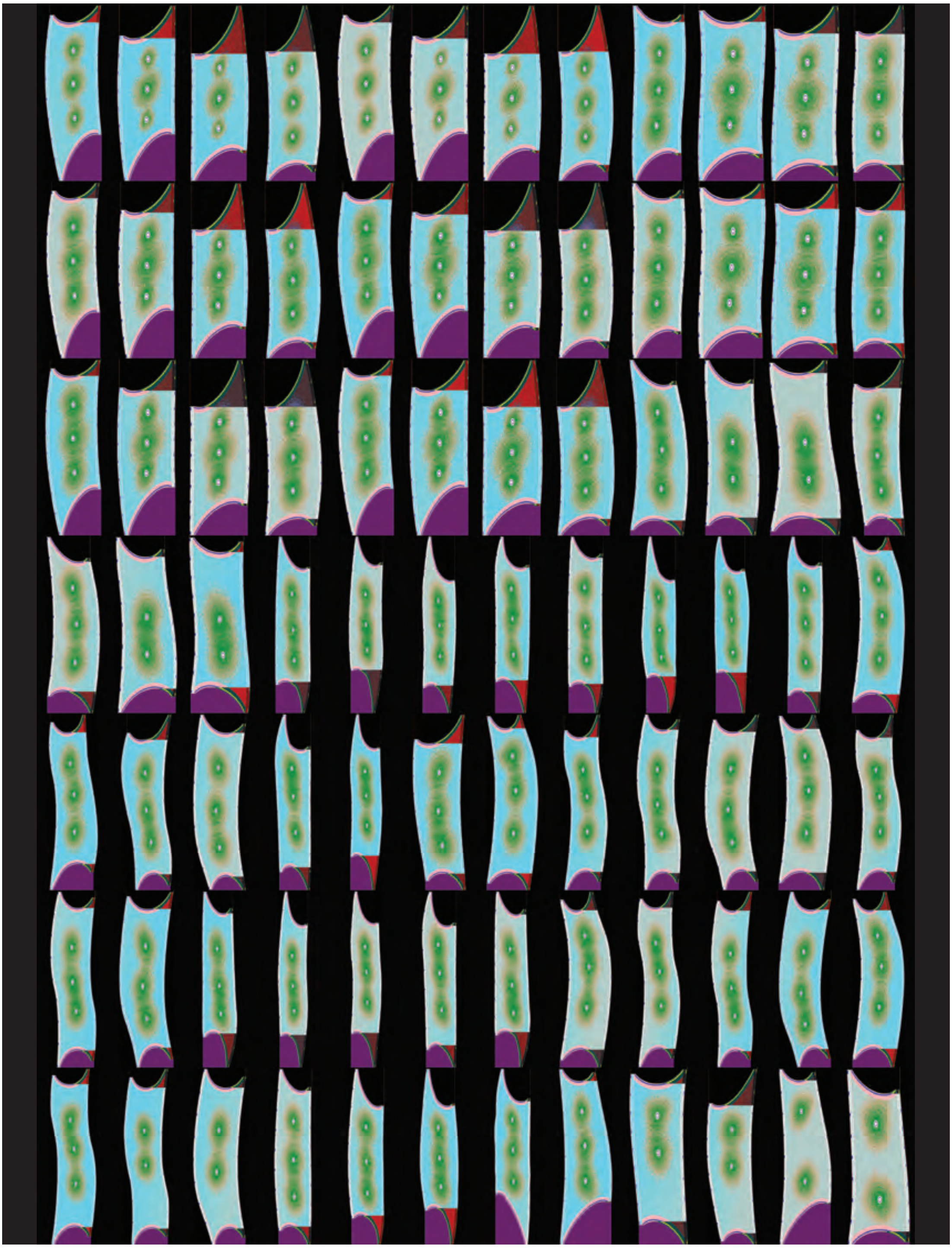
The main differentiation lies within the nature of their stitch structure: homogeneous in the graph method, and heterogeneous in the graded field method. This nature of surface composition has multiple implications in achieved topology, surface density, aesthetics, and material use.

Both methods allow for producing of double-curved shapes through the composition of stitches, either identical or varied. Here, the curvature degree of achieved surfaces varies based on the used knitting technique. Graph method, that uses partial knitting technique, allows for continuous surface addition and bending, which offers the opportunity for the production of helix, spiral, and hyperbolic surfaces. The graded field method works with the given width of the machine knitting row and operates within the space of stitch length modification. Here, the width between the needle beds and gauge of the machine defines the stitch expansion limits, which reflects in the smaller amplitude of the surface articulation.

The use of identical stitches in the graph method results in a homogeneous surface density, while in the graded field method, where variegated stitches are used, the surface shows variegated transparencies. The combination of double jacquard with unravel double jacquard stitch types in *Zoirotia* results in a very low-density surface in the places of surface expansion. However, it is possible to achieve firmer surfaces by combining of similar density stitch textures, while still maintaining a degree of surface expansion, like in the *Isoropia* project by CITA. The choice of varied stitch types defines the expansion property of the fabric and should be done carefully in response to the design and performance criteria.

The accuracy of both approaches is highly dependent on the loop dimensioning and requires preliminary prototyping to define these. However, the behavior prediction of structurally graded surfaces (graded field method) is challenging as should be prototyped at 1:1 scale rather than through an extracted smaller surface sample, which is acceptable for homogeneous surfaces. Therefore, the use of this method strongly relies on simulation tools in order to predict material behavior as 1:1 prototyping is not always feasible at the 1:1 architectural scale.

The graph method uses an initial design geometry without taking into consideration the internal material stresses and



19 Layout of 88 unique bitmap files, generated for the fabrication of the *Zoirotia* structure

20 Interior space of *Zoirotia* made of highly bespoke knitted membranes

physical processes but as a geometric shape that is subdivided for fabrication. In difference, the graded field method integrates the surface tensioning, and therefore, its performance under load to define the material expansion.

For achieving three-dimensional shapes both methods essentially use a different amount of yarn material. The graph method uses more stitches to achieve three-dimensionality, which results in a denser and more materially intense surface. The graded field method uses modified stitches of different lengths. This allows the minimization of material use.

CONCLUSION AND FUTURE DEVELOPMENT

The presented methods are understood as complementary as each has its benefits and limitations. However, the combination of the methods could bypass the limitations of each, while joining their advantages for further expansion of the surface three-dimensionality, density, and performance control. Here, the application scenarios of knitted fabrics in architecture could be extended and new functional surface expressions could be imagined.

For example, the dense homogeneous knitted membranes as manufactured with the graph method and used for formwork could potentially benefit from adding functionally graded areas of lower density offering the opportunity for a tighter engagement between the formwork material and casting liquid material. The examples of architectural application with the graded field method, which are often tensile roofs and canopies, are often criticized for their low precipitation retention capacity, as fabrics let the rain through. To improve the surface weatherproofing ability, a surface water repellent casting layer could be introduced; however, it often requires a homogeneous, relatively dense surface that could be achieved by employing the graph method.

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Publication 3

STRATEGIES FOR ENCODING MULTI-DIMENSIONAL GRADING OF ARCHITECTURAL KNITTED MEMBRANES

Strategies for Encoding Multi-dimensional Grading of Architectural Knitted Membranes

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Abstract. This paper introduces the knit as a special case of functionally graded materials. The ability to specify knitted material both structurally and materially allows for multi-dimensional grading of the knit. This ability to functionally grade knit is defining for knitted material's relevance to architecture and construction, as it allows for combining performance multiple criteria in one material by smoothly transitioning between the properties in a single manufacturing act. However, the scaling of knit to architectural scale brings computational challenges for automating material specifications. This paper investigates the methods for solving these computational challenges when operating with multi-dimensional material gradings that increase the scale and resolution of knitted textiles and therefore increase the complexity of their encoding.

The method for multi-dimensional material grading of CNC-knitted membranes is developed through the project of Zoirotia, a large-scale textile installation (Fig. 1). Zoirotia is made of 88 unique membranes, where each is uniquely graded at the levels of both material structure and yarn composition. This results in surfaces of varied expansion properties and color transitions across the entire structure, achieved by changing yarn morphology and material. The project is understood as a testing ground for solving the challenge of large volume material graded specification through simplified numerical data and the process of binarisation. A dithering technique is used to translate rich design-driven gradients for material specification into binary gradients for CNC fabrication. This paper presents the gradient numerical map as a solution for handling the material specification spanning across the multi-element structures.

Keywords: Multi-dimensional grading · CNC-knitting · Computation · Digital fabrication · Functionally graded materials · FGMS

1 Introduction

1.1 Background

In architecture, lightweight composite materials contribute to resource and energy saving by combining different properties towards improved performance and reduced weight of the structure. Here, several homogeneous matters are fused together to achieve a

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multi-functional composite material. However, these types of fused composites create an undesired accumulation of internal material stress at the point of material sudden shift (Fig. 2) (Shinohara 2013).

Fig. 1. Multi-dimensional grading of architectural knitted membranes in Zoirotia, 2021.

Functionally graded materials (FGMs) can be understood as a novel class of composite materials characterized by the gradual variation in composition and structure throughout a surface or volume (Ichiro and Yoshinari 1997). Here, the smooth transition between the properties reduces the thermal and residual stress concentrations found in traditional composites. Furthermore, FGMs optimize material deployment, reducing unnecessary material deposition, while concentrating it in the places of structural utilization.

The usefulness of FGM composites was recognized by Bever and Duvez already in 1972. However, this has had a limited impact on the industry due to a lack of suitable production methods. Early fabrication methods were based on the manual sequential casting of matrix-based materials (Pajonk et al. 2022), which was slow and imprecise. The emergence of additive manufacturing, supported by computational interfaces, has led to new fabrication processes of digitally controlled material deposition enabling the production of FGMs of higher grading complexity (Richards and Amos 2014; Grigoriadis 2015).

In this paper we introduce knit as a special class of FGMs. Knit, being constructed by an accumulation of stitches to form a textile, is an additive manufacturing technique. The advancements in CNC knitting technologies has enabled the fabrication of textiles of higher material complexity with a fine level of material differentiation (Ramsgaard Thomsen et al. 2016). Here, the shift of stitch structure and material composition allows

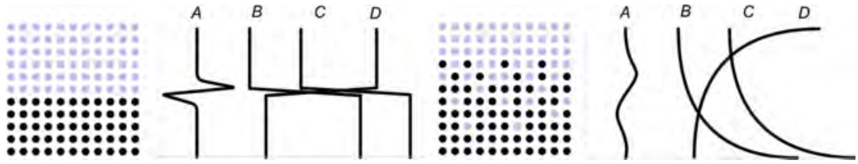

Fig. 2. Comparison between composite (left) and functionally graded materials (right) composition, metal+ceramics: A - thermal stress, B - thermal expansion, C - thermal conductivity, D - heat resistivity. Original image by Shinohara (2013), reworked by Sinke 2022.

the definition of knit as a technique allowing for a multi-dimensional material grading, which extends the definition of FGMs.

This paper presents the conceptualization of a new class of multi-dimensional FGMs for architectural application. By using the installation Zoirotia as a material case, we examine knit as a functionally-graded additive manufacturing technique, that allows for the making of differentiated architectural membranes. By controlling the design and specification of the material composition and structure at the micro-scale of the stitch we can steer the membrane performance at the macro-scale, smoothly incorporating varied surface properties without the need for cutting and sewing as done with woven textile materials for architectural membranes.

1.2 Problem Definition and Goals

Where knit allows for micro-scale control of the textile this also compounds the problem of specification. Textile traditions are frequently based on patterns that repeat across the surface allowing for relatively compact specification data. When appropriating knit for architectural scale and engaging in performance-driven functional grading, the specification data is radically extended. To enable the design and production of complex and highly differentiated knitted structures we, therefore, have to develop means of translating design intent into compact encodings, described with a small number of parameters that can be steered towards high-performance multi-layered designs.

Multi-dimensional grading is often handled independently for each parameter of change, as they are informed differently. This naturally introduces parallel layers of multi-grading representations and presents the challenge of overlapping these into a single binary mono-dimensional file for fabrication. These tasks are not trivial, as reflect the ongoing challenges of computer science regarding modelling complex systems and managing big data (Stanley and Miikkulaninen 2002; Doursat et al. 2012).

The work presented in this paper, prototypes and tests efficient methods for multi-dimensional material grading of multiple criteria into a single fabrication file. The presented method describes a workflow for interfacing and combining the specification of two independent grading criteria and its further adaptation for fabrication. The method furthermore develops ways of defining local grading strategies from global design intent, while keeping the high resolution for fabrication specifications. We introduce the application of these approaches through the material case of Zoirotia, a large tensile membrane structure commissioned by the ZKM museum (Zentrum fuer Kunst und Medien), Karlsruhe, 2021–22.

2 State of Art

2.1 Functionally Graded Structures

Functionally graded materials (FGMs) belong to a relatively new class of materials characterized by gradient variation of micro-structure and mechanical properties. They consist of two or more constituent phases with a continuously variable composition creating properties that change spatially within the structure, in order to design components optimized for specific applications (Maalawi 2018). They solve a number of engineering problems, eliminating the stress singularities occurring at the sudden shift of materials, like in traditional composites. The emergence of digitally informed additive manufacturing has enabled more detailed material specifications of FGMs, allowing for smoother transitions between material graded properties.

FGMs are studied and applied within fields where it is crucial to provide great material performance. In the medical industry, additively manufactured FGMs are applied for producing biological tissues and organ transplants, successfully replicating the original heterogeneous nature of these (Watari et al. 2004). In aerospace, the thickness of the metal parts for airplanes can be functionally graded to achieve the best mechanical performance and improve aerodynamics (Saleh et al. 2020). In mechanical engineering geometrical optimization is used to materially grade mechanical joinery in order to reduce material deposition while keeping the performance intact (Maalawi and Badr 2009).

2.2 FGMs in Architecture and Construction

The principles of lightness, high performance, and shape optimization, have high relevance to architectural construction. FGMs for architectural application have been investigated by combining several materials (Grigoriadis 2015; Herrmann and Sobek 2017; Duque Estrada et al. 2020) and grading the density of the structural composition (Nicholas and Tamke 2012; Soldevila et al. 2015; Tish et al. 2018; Lesna and Nicholas 2020). These demonstrate smooth material property transitions based on required structural performance or design indent as well as the feasibility of adopting FGM strategies in architecture and construction.

Following the classification for FGMs (Loh et al. 2018) the examples mentioned above can be classified as either *mono-material* FGMs or *multi-material* FGMs. In mono-material FGM a single matter is used to form a graded material. The grading is achieved through gradual structural modification, smoothly transitioning between the properties by changing the density of the material. In multi-material FGM several different materials are combined in a single additive process to create objects with varied properties. Both strategies for mono- and multi-material grading are mono-dimensional as they operate with *one* parameter of change, either change of material density or the change of material types. This is primarily because of the fabrication limitation of additive manufacturing of 3d printing as this technology doesn´t permit a multi-criteria change during the fabrication (Oxman 2010).

2.3 Knit as Multi-dimensional FGM

Knit is inherently both multi-material and multi-structural, which enables the fabrication of multi-dimensional knitted FGMs. In knit, fine material structures can be achieved, as the yarn is manipulated between the needle beds. Several yarns can be intertwined simultaneously, combining different material properties in one surface. As such, knit allows for *multi-dimensional* material gradation, both at the level of the structure (stitch type) and matter composition (yarn type), thereby combining in itself concepts of mono- and multi-material FGMs.

The recent interest in knit as an architectural material instrumentalises this ability to design the textiles specifically for performance and initiated the investigations of knit application as an alternative for structural membranes and formwork. The principles of *structurally graded surface* have been examined through the mono-material grading, where a single yarn, entwined into various stitch types, is used (Ahlquist 2015; Deleuran et al. 2015; Ramsgaard Thomsen et al. 2016, 2019a, b; Tan and Lee 2018). These surfaces result in homogeneous matter composition but vary structurally across their surface, which results in differentiated density and expansion properties across the membrane. The principles of *materially graded surface* have been examined in multi-material grading strategies, where multiple yarns of varied matter origin (e.g. elastic cotton+stiff polyester etc.) are combined, using the same stitch type (Ramsgaard Thomsen et al. 2016; Ramsgaard Thomsen 2019a, b; Anishchenko 2021). These textiles often result in a structurally homogeneous surface with a heterogeneous material composition, which can be reflected in color or texture variation.

A few research outputs explore multi-dimensional aspects of knit specification (Hörteborn and Zboinska 2021; Liu et al. 2020; Tan 2021) by incorporating multi-colored structurally differentiated surfaces. However, the potential for finer material gradings and transitions between the properties is not fully explored as distinct property transitions are observed in these precedents.

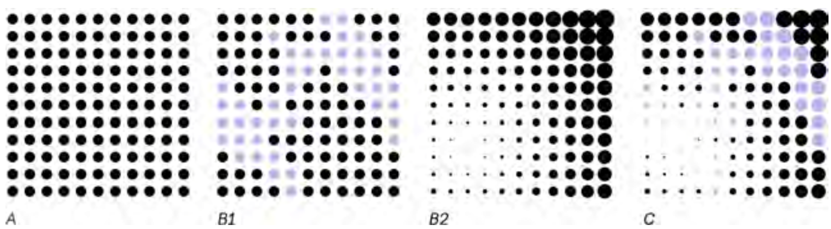

Fig. 3. A - non-graded material, B - mono-dimensional grading (B1 - same stitch varied color. B2 - same colour, varied stitch). C - multi-dimensional grading combining (varied stitch and color). Important to note that within this classification the dimension is implied in a meaning of a parameter, rather than as a direction of grading as used by Hascoet et al. (2011).

3 Multi-dimensional Knitted Membranes of Zoirotia

3.1 Core Parameters of Zoirotia Material Grading

This paper presents Zoirotia, a large-scale tensile installation, that uses multi-dimensional grading, extending the modes of material differentiation towards smooth transitions between the properties. The installation is made of 88 individual unique membranes, where each is graded in a bespoke manner for two purposes (Fig. 4):

- Structural grading for three-dimensionality and structural performance. It influences the expansion of the material and is achieved by combining two stitch types of varied locking point lengths: open loose double jacquard and dense double jacquard stitches.
- Material grading of different yarn colors for visual expression (via double jacquard technique) creates transitions in hue, across a large body of the installation and contributes to the chromatic perception of the design.

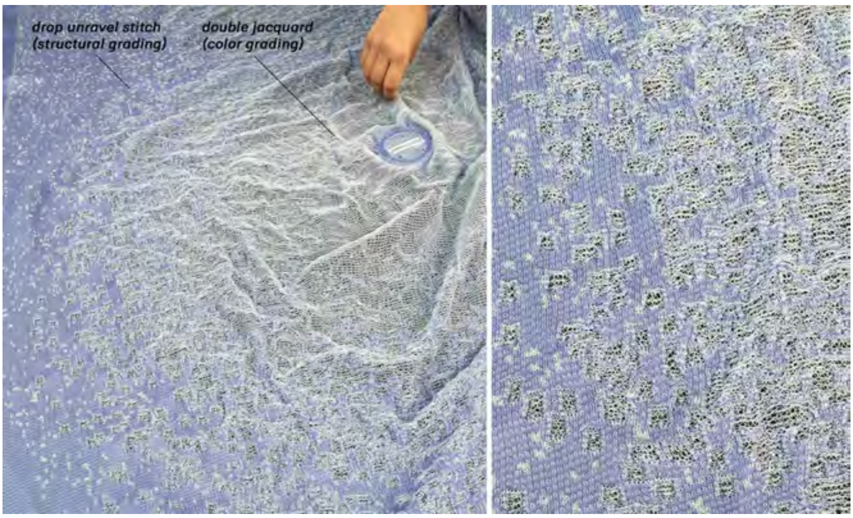

Fig. 4. Prototyping membrane shows multi-dimensional grading through the double jacquard technique (color and structure)

Here, the morphology of stitches and yarn color are the two core parameters of surface differentiation, simultaneously existing within each membrane. However, these parameters of material grading are informed and operate differently, which requires different modes for their representation, reflected in two individual parallel models: one for structural grading and another for color grading. Both models serve the purpose of material grading design and generate material specification data reflected in a form of color gradients, which is then modified for fabrication purposes (Fig. 5).

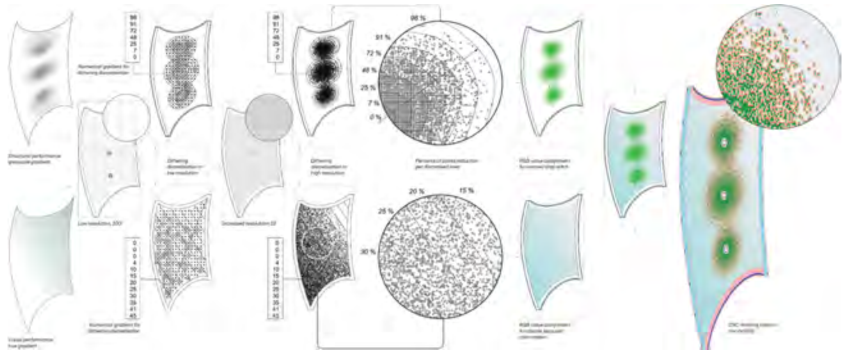

Fig. 5. Membrane surface programming through dither gradient patterns

3.2 Informing the Grading Models

The fundamental differences between these models lay in the modes how they are informed. The structural grading model is informed by geometrical analysis, where the form-found surface is evaluated for identification of areas of larger displacement (or stretch). The structural textile units are form-found using a spring-based simulation, where the mesh is simulated as homogeneous mesh in order to represent the behavior of the non-differentiated surface. This allows to identify the areas of larger expansion and where the specification with a larger stitch type would be required in order to achieve desired textile expansion into a three-dimensional shape when under tension. The calculation of mesh displacement is done between the final equilibrium mesh and the stage of form-finding, before prestressing the surface with the cabinets. The displacement distance values are remapped onto a planarized monochrome grayscale gradient that

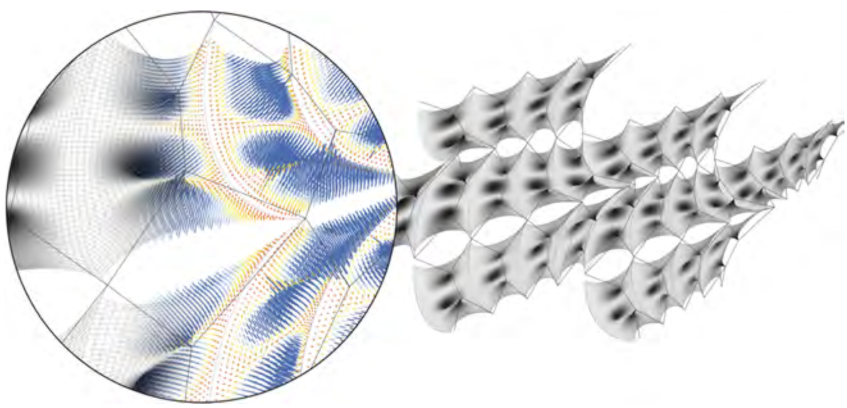

Fig. 6. Form-finding of the facade of the structure showing the displacement degree of the meshes represented through the monochrome gradient of the meshes

informs the stitch type concentration density over another (Fig. 6). Later, these gradients are modified in order to be read by the knitting machine for fabrication, which is described further in more detail.

The material grading model is informed by the design intent of combining multiple colors within the body of the installation. The ambition to achieve a vivid color expression is strongly connected to the knitting technique of double jacquard, which is used to introduce the color to the patch. Given the structural grading complexity already present in the membrane the color transition per patch was limited to two colors. This implies the nature of color distribution across the structure through the linear gradient, which allows to keep the dual-color shift per membrane (Fig. 7).

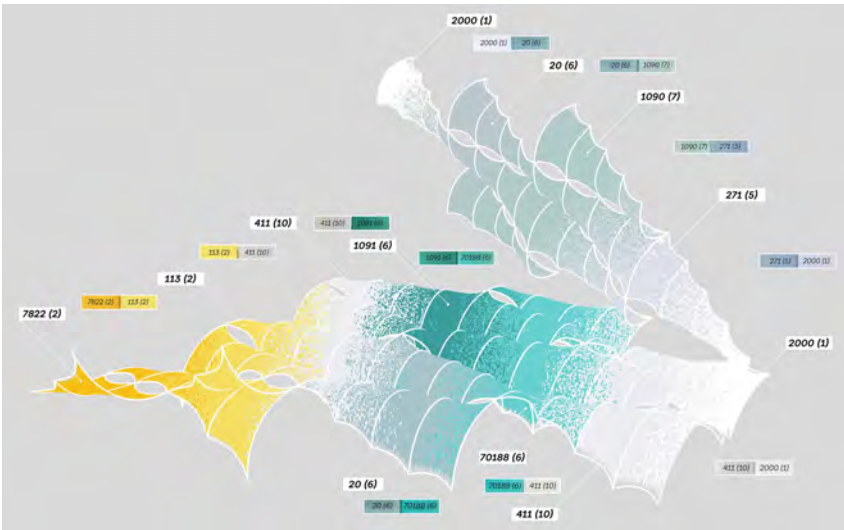

Fig. 7. Axonometric diagram with remapped colors and yarn color code labels

3.3 Challenges of Knit Multi-dimensional Grading

The differences between design and fabrication environments possess a challenge of data translation. The gradient in the digital design environment, representing the material gradation, is constructed through an almost indefinite range of colors when transitioning from color A to B, while the CNC knitting is a binary technique, operating with a definite number of stitch types and yarn carriers (hence the colors). This implies a necessity of translation of a continual material gradation, represented through these rich color gradients into binary material gradients achieved through a *dithering* technique. In computer graphics, dithering is an image processing operation used to create the illusion of color depth in images with a limited color palette (Fig. 8). The colors that are not available in the palette are approximated by a diffusion of colored pixels within the available color range (Furht 2008). In Zoirotia only two stitch types and only two color yarns per patch are used to achieve the local structural differentiation accompanied by the global hue material transition across the entire structure, total expressing gradients between 12 colors.

The dithering of colors through the density gradation, rather than through the additional intermediate colors, allows for maintaining the effect of a smooth transition through the optical effect of blending while using a low number of instrumental colors.

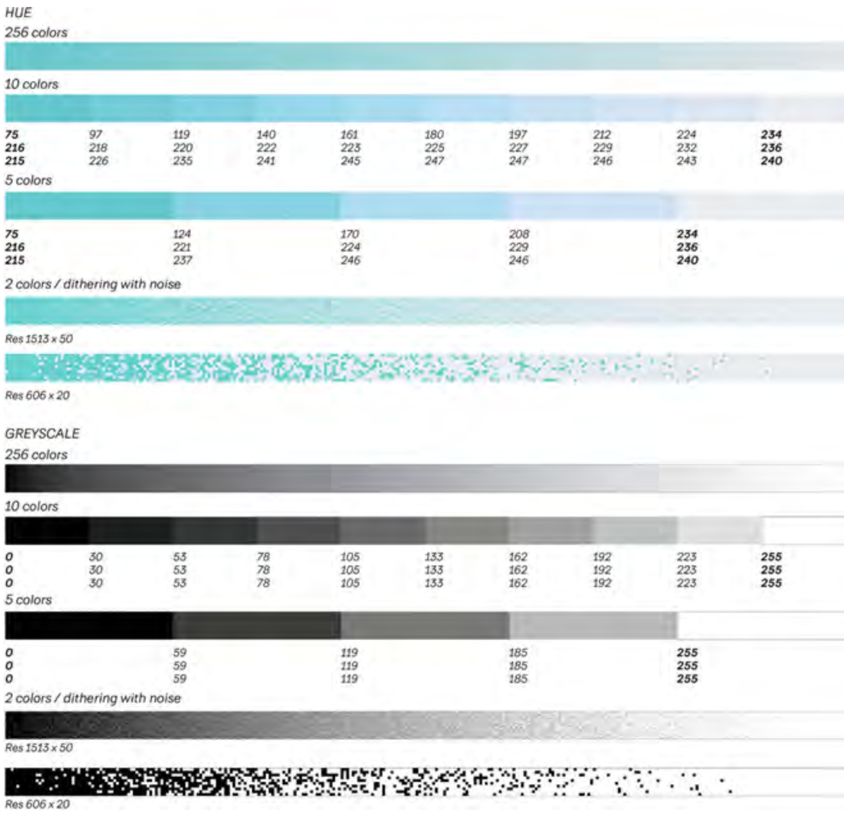

Fig. 8. Gradient representation through the varied amount of colors/resolution, for color and structural change.

In Zoirotia, the material gradings are coded within the grid-based system of points, representing the knit stitches. The dithering gradual transition is achieved through the reduction of points density, which is informed by the numerical value, representing the number of removed points per the subdivision area, introduced at the range of the gradient. For the structural grading, these are the circular areas around the pulled cones, while for the material grading these are diagonal parallel subdivisions, informed by the vector of color transition. The random function for the selection of removed points is applied, which results in the noise-like appearance of the gradient and is believed to provide a smooth blending between subdivided areas of gradient densities (Fig. 5).

The varied scales of multi-dimensional material grading pose the challenge of their resolution, compatibility and combination of these independent gradings. Zoirotia is made of 88 individual membrane units and is structurally graded within each single membrane, which allows for a high resolution of specification as computationally affordable. In contrast, the color grading of Zoirotia spans across the entire structure and is designed globally, as the overall gradient is constructed from multiple gradients of individual membrane patches. Here, the use of high resolution for material grading of color is computationally expensive when used across such a large model.

In order to ensure computational feasibility and accuracy in transferring the property density data from the global design down to the patch scale when shifting between the scales, a method of numerical gradient map is used (Fig. 11). For that, an auxiliary gradient map model is constructed, where the numerical value is used to describe surface parameters of dither density. This way we elevate in scale and do not grade directly on the stitch level, but rather through subdivision areas of the entire structure (Fig. 10). Here, the center of each subdivision area generates a vertical line, that differs in its height based on the proximity to the areas of the most color intensity, assigned manually by attractor points (Fig. 9). The height values of these lines (domain 0–100) correspond to the intensity (%) of the dither per subdivision area. The percent value describes the amount of present/removed points per subdivision area. This results in a noise dithering pattern, that smoothly transitions between subdivision areas. As a result, the independent numerical gradient values are extracted from this map into an individual list of gradient numbers, that are used to grade membranes locally at high resolution, combining structural and hue differentiation within one membrane.

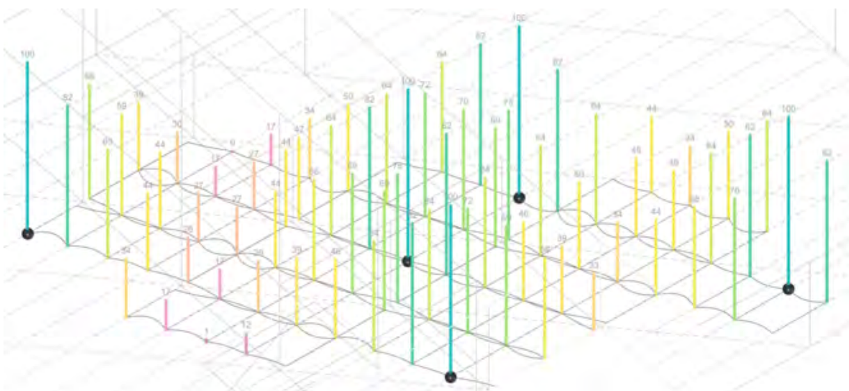

Fig. 9. Auxiliary model for generating color height-map gradient landscape

Fig. 10. Auxiliary model for generating height-map gradient landscape

Fig. 11. Numerical gradient map model of the facade part of the structure.

4 Conclusion

The method described in this paper makes a step towards the integration of multi-dimensional performances of architectural knitted membranes. Here the membrane material local grading is correlated with the structural performance of membranes informed by simulation, as well as global design intends of color distribution, which introduces the knit as a multi-dimensional functionally graded material. Through the use of advanced CNC-knitting manufacturing and computational interfaces, knitted material is graded finely at the level of stitch, transitioning membrane structural and material properties in a gradient manner (Fig. 12).

The computational challenges associated with this process are discussed and methods for solving these are presented. Through the process of binarisation by using the dithering technique only two structural stitch types and only two yarn colors per patch are combined to achieve a very continuous merge of properties on structural and material levels at the scale of the single patch as well as across the entire structure. Here, a random-based density reduction dither pattern is generated, through the reduction of pixel density derived through the function of the curve. However, alternative dither patterns could be potentially tested as they might contribute with the novel surface expressions as well as better performing properties of the material. The translation of rich gradients is done by binarisation over pixel reduction through curve function and concentric zones subdivisions. However, in further work, a direct link between the monochrome-rich gradient to the dither reduction percentages should be explored as believed to be more integral.

Additionally, a numerical gradient method is used to link scalar differences when converting from the lower resolution in design environments - to high-resolution for fabrication.

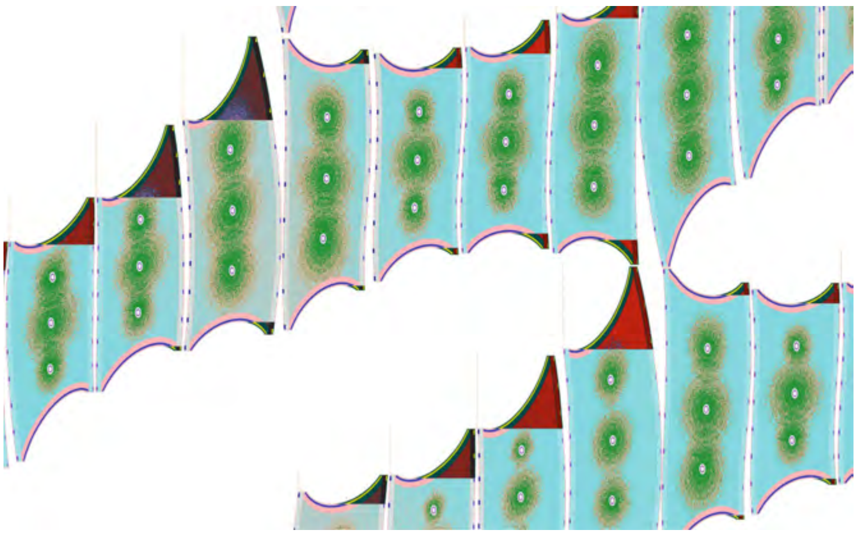

Fig. 12. CNC-knitting bitmaps demonstrating the multi-dimensional gradients for structural and color transitions

The overall color gradient appearance was successful, although some imperfections in the technique and the method were observed. The nature of the double jacquard technique creates inverted colors at the backside of the membrane (Fig. 13). This reversed gradient becomes more visible when the high contrast yarn colors are used. In addition, the translucency of the fabric drastically affects the perception of the color gradient in multi-directional lighting conditions. Here the actual perception of hue transition in the physical structure differs from the smooth diagram from the digital environment of not transparent meshes used in the design phase (Fig. 7). An intarsia approach (in which yarns are fully replaced across the textile) for color gradient might have been a more successful knitting technique, as it has the same color appearance from both sides of the textile.

On the overall note, the degree of grading increases with the number of overlayed properties of material differentiation. While a higher degree of grading adds additional richness to the fabric it simultaneously increases material intricacy and hence the complexity of functional grading material models. Therefore, the investigation into these models and their improvement is considered a worthwhile direction for further research investigations.

Fig. 13. Photo of the finished structure (view from the facade part)

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RESEARCH TRACK C

DIFFERENTIATED KNIT MATERIALITY

4.3 RESEARCH TRACK C: EVALUATION MODEL: ADDRESSING THE CALIBRATION OF SIMULATION

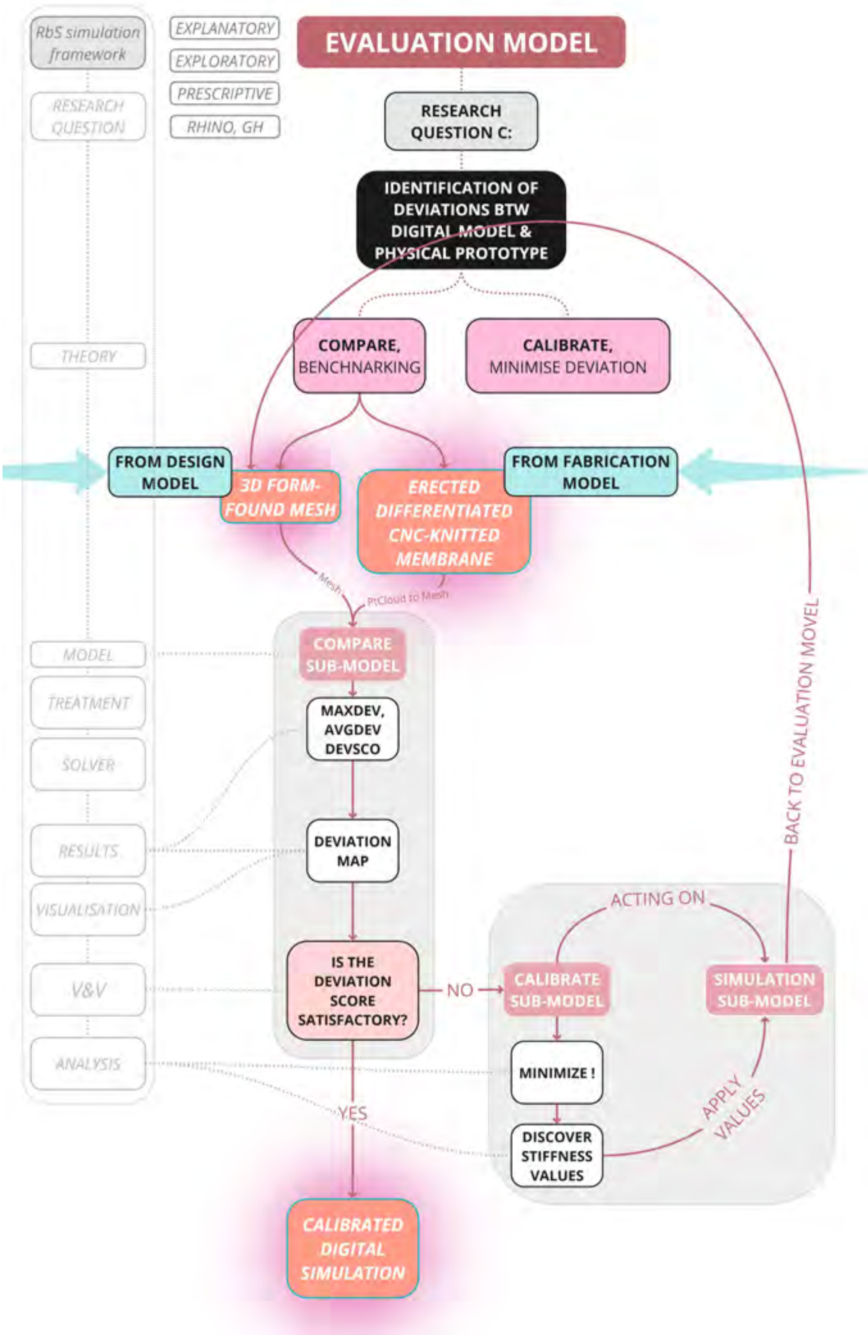
Research Track C addresses Research Question C, formulated as *How the computational tools can identify and address the deviations between the intended digital design and the manufactured differentiated CNC-knitted membranes?*. This question is explored through the development of a custom digital **Evaluation Model**, which serves as a validation framework to assess and align digitally designed tensile membranes with their physically produced artefacts. The model specifically focuses on evaluating the *accuracy* of the simulation—the output of the Design Model—against the CNC-knitted membranes produced by the Fabrication Model. When *deviations* are identified as too large, the Evaluation Model facilitates improvement of the simulation via calibration.

Deviations between the models arise due to the challenge of linking the stiffness values of the digital mesh with the real properties of the knitted membranes. The performance and material strain behavior of the membranes depend on numerous interdependent decisions made throughout the design-to-production workflow. This complexity stems from the intermediate steps required to translate a digital spring mesh into a physical fabric, each introducing potential inaccuracies. This thesis proposes a solution by connecting the *spring-based* stiffness values in the Design Model to the *material density* in the Fabrication Model. This is technically achieved through the *graded fields* and *dithering* methods developed to link these models. While these techniques ensure a functional digital chain, their accuracy and fidelity to real-world material systems still require rigorous validation.

The Evaluation Model is designed to address this challenge through two key processes: **benchmarking**, which involves comparing digital and physical outputs to assess their alignment, and **calibration** which refines the simulation model by adjusting its variable parameters to enhance the accuracy. These objectives are implemented through two sub-models: *Compare* and *Calibrate*, which structure the narrative of this section..

The *Compare* sub-model systematically aligns the outputs of the Design-Simulation Model — represented by form-found digital simulations—with the physical knitted membranes produced by the Fabrication Model. This alignment enables a detailed analysis of deviations, identifying specific areas where the digital and physical outputs diverge. When significant discrepancies are detected, the *Calibrate* sub-model initiates a feedback loop to adjust the simulation model. This iterative process minimizes the deviations, ensuring closer alignment between digital simulations and physical counterparts. Through ongoing evaluation and calibration, supported by a Genetic Optimization Algorithm, the Evaluation Model determines optimal values for uncertain material stiffness parameters. By introducing this robust evaluation component, the Evaluation Model enhances the integrity of the design-to-fabrication workflow, even in the face of uncertainties in material behavior. The schematic structure and the logic of the Evaluation Model can be followed in **F**4.22.

The appendix at the end of this section includes three key publications—1, 5.2, and 7—that document the development and progression of the evaluation workflow through case studies of KnitVault and GraCe panels. These publications detail



F 4.22: Evaluation model schematic diagram in relation to RbS framework. Diagram shows the feedback loop occurring between its Compare and Calibrate sub-models, that act on Simulation sub-model of Design Model methods for comparing digital and physical models and explore the application of genetic optimization algorithms to identify potential stiffness values within digital simulations, using data from recorded physical prototypes. *Publication 1* by Sinke Baranovskaya et al. 2020 establishes the foundation of the evaluation workflow by exploring comparison methods between digital meshes and point cloud recordings of physical prototypes. This study employs manually designed knit patterns in the *KnitVault* case study. *Publication 5.2* by Sinke et al. 2023a introduces a hybrid calibration mode, linking stiffness values to distinct material densities by incorporating auxiliary 1:1 scale physical prototypes, while the last *publication 7* by Sinke et al. 2024 addresses the challenge of unrestricted search spaces in genetic evolutionary algorithms, introducing specific constraints to guide the optimization engine toward better-fitting stiffness values. Publications are futher referred in text as **P**.

1. Sinke Baranovskaya Yuliya, Martin Tamke Martin, Mette Ramsgaard Thomsen. (2020). **Simulation and Calibration of Graded Knitted Membranes**. In *Distributed Proximities / Volume I: Technical Papers. Proceedings of the 40th Annual Conference of the Association of Computer Aided Design in Architecture (ACADIA).* Online and Global. 24-30 October 2020. Edited by B. Slocum, V. Ago, S. Doyle, A. Marcus, M. Yablonina, and M. Del Campo, p.198-207.

5.2 Sinke, Yuliya, Martin Tamke, and Mette Ramsgaard Thomsen (2023). **Integrated Design Models for Materially Differentiated Knitted Textile Membranes as the Means to Sustainable Material Culture within Membrane Architecture (part II)** In *Sustainable Futures, Leave No One Behind: Proceedings of UIA 2023 Copenhagen World Congress of Architects*. Copenhagen, Denmark: Springer, 2023. p.366-375 (from the section 5).

7. Sinke, Yuliya, Martin Tamke, and Mette Ramsgaard Thomsen (2024). **Simulation Calibration of differentiated knitted membranes with evolutionary optimisation tools** In *Advances in Computational Science and Engineering*, Vol. 2, No. 1: Springer, 2023. p 19-36.

4.3.1 COMPARE & CALIBRATE SUB-MODELS

The Evaluation Model was established early in this PhD research and has evolved in parallel with the other two models (Design-Simulation and Fabrication Models), gaining complexity and precision over time. While the *Compare* sub-model focuses on establishing links between the outputs of the Design and Fabrication Models and thereby benchmarking them, the *Calibrate* sub-model aims to minimize discrepancies by tuning the stiffness values of the Design-Simulation Model, thereby achieving calibration. The benchmarking and visualization methodologies of the *Compare* sub-model have remained relatively straightforward and largely unchanged from the initial setup presented in **P**1 (p. 201). In contrast, the *Calibrate* sub-model has undergone continuous refinement, informed by iterative experimentation and feedback from the other two models. The following text briefly introduces these two sub-models, with detailed descriptions provided in the associated publications.

COMPARE SUB-MODEL: BENCHMARKING METHOD

POINT-CLOUD TO MESH

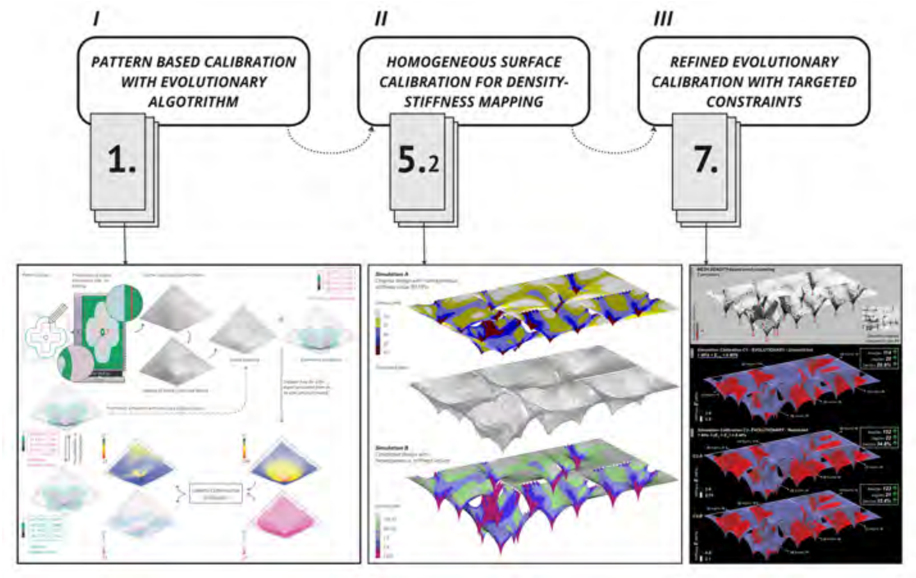
Benchmarking is a widely used method in simulation for linking digital models with real-world entities (Winsberg 2010). To align the digital and physical models, both must be represented in a *comparable* format. For this comparison, the physical membrane's shape is captured using a FARO laser scanner, which generates a point cloud. This point cloud is then transformed into a mesh, creating a comparable digital representation of the physical model that can be integrated into the digital Evaluation Model. To improve alignment, the mesh derived from the point cloud is constructed using the initial mesh from the Design-Simulation Model, with the support of the Volvox plug-in (Evers Leander and Zwierzycki 2016). This approach adheres to conformal mapping principles, enabling a topological comparison between the meshes.

DEVIATION ANALYSIS AND TOLERANCES

The deviations between the digital and physical meshes are assessed using three key metrics: maximum deviation (*MaxDev*, in mm), average deviation (*AvgDev*, in mm), and the deviation score (*DevSco*). *MaxDev* measures the largest distance between the most divergent areas of the mesh and the physical prototype. This metric highlights extreme localized deviations, which are critical for identifying areas where the simulation fails to capture significant features of the physical membrane. *AvgDev* provides the average deviation across the entire digital mesh surface. By summarizing the deviations into a single representative value, AvgDev offers an overall assessment of alignment quality, helping to evaluate the general accuracy of the simulation. Finally, DevSco quantifies the percentage of the mesh surface area that exceeds a specified allowable tolerance when compared to the physical prototype. This metric is particularly useful for evaluating the extent and distribution of significant deviations, ensuring that deviations fall within acceptable thresholds for practical applications. Together, these three metrics offer a balanced approach to assessing deviations, addressing both extreme discrepancies and broader trends, and supporting an iterative process of refinement in the design-to-fabrication workflow. In this thesis, the *allowable tolerance* is set at 25 mm, a threshold considered intuitively appropriate given the flexible nature of knitted fabrics and the architectural scale of the designs and prototypes. These deviation metrics, conditioned by the tolerance threshold, are visually represented on *colour deviation map*, a visualization tool consistently applied across the three publications to illustrate the degree of alignment between the digital Design-Simulation Model and its physical counterparts.

CALIBRATE SUB-MODEL: METHOD AND MESH STRUCTURE

Within the *Calibrate* sub-model, two key aspects are addressed: the **calibration method** used to minimize the deviations between the simulation and the prototype through determining the appropriate material property values, and the **mesh structure** onto which these optimized stiffness values are applied to.



F 4.23: Calibration method evolution through publications

CALIBRATION METHOD

The evolution of the calibration methodology is documented across three key publications included in this section. Each iteration builds upon previous experiments, incorporating refinements in calibration focus, setup, and methodological constraints. The development of the calibration method can be categorized into three progressive steps, described through experiments below and illustrated by **F**4.23. The first, *Pattern-Based Calibration with the Evolutionary Algorithm*, where the initial efforts focused on calibrating knitting patterns to match physical prototypes using an evolutionary algorithm. The second, through *Homogeneous Surface Calibration for Density-Stiffness Mapping*, where it introduces mapping relationships between material density and stiffness values across homogeneous surfaces. The last one, *Refined Evolutionary Calibration with the Targeted Constraints*, The final step refined the calibration process by introducing specific constraints to the evolutionary algorithm, narrowing the search space and improving the accuracy of stiffness value determination.In general, the calibration method by using the evolutionary optimisation algorithm can be described as "force into", as it uses the iterative form-finding with discovered by evolutionary algorithm material properties to *force* the simulation mesh into the geometrical boundaries of physical prototype.

PATTERN-BASED CALIBRATION WITH THE EVOLUTIONARY ALGORITHM The *Pattern-Based Calibration with the Evolutionary Algorithm* represents the first experiment in calibration investigation, using the KnitVault case study as described in **P**1. This experiment employed the "force-into" method, which involves tuning each digital mesh design to match the shape of its corresponding physical prototype. Utilizing the Genetic Evolutionary Algorithm engine in the Galapagos plug-in for Grasshopper (Rutten 2019), the calibration iteratively searched for suitable stiffness values, minimizing the fitness value (the deviation between digital and physical meshes) until a satisfactory threshold was reached. The minimum deviation was set at 5 mm, with the Evolutionary Solver achieving its best performance at 11 mm.

While this approach yielded relatively precise results, with deviations ranging between 11–36 mm, challenges arose due to *ambiguities* in the derived stiffness values. These stiffness values varied significantly for the same material density across different pattern designs. This discrepancy was attributed to two main factors: (1) the *limited ability* of the chosen knitting stitches (piquet lacoste and piquet) to produce pronounced surface strain differences, and (2) the *overly broad search space* used by the evolutionary algorithm, which lacked predefined constraints.

Despite these challenges, the experiment produced *valuable insights*. A relationship between membrane *depth* and derived *stiffness* values was observed, where shallower membranes exhibited higher stiffness values, while more stretched membranes displayed lower values. The experiment highlighted the influence of *pattern topology* on material behavior. It emphasized the importance of using knitting stitches with *more pronounced property differences*. The need for incorporating *calibration constraints* to produce meaningful results became apparent. These findings informed the methodology for subsequent experiments, leading to refinements in both calibration focus and setup.

HOMOGENEOUS SURFACE CALIBRATION FOR DENSITY-STIFFNESS MAPPING The second experiment, documented in **P**5.2 (p. 367, sec 5.1), employed the GraCe design case study to establish a structured method for defining stiffness values based on material density. This approach utilized unravel double jacquard (DJ) stitches, which demonstrated more pronounced strain differences in the material compared to the stitches used in the first experiment.

Three homogeneous physical knitted surfaces, representing *maximum*, *medium*, and *minimum* material densities, were produced. These corresponded to dithering percentages of 100%, 50%, and 0%, respectively, representing the density of loose DJ stitches within the surface. The physical prototypes were used to derive stiffness values by calibrating their corresponding digital meshes to fit the point clouds of the prototypes. The resulting stiffness-density relationship was plotted as a curve graph (Pub7, Fig. 13, p. 370), providing a basis for interpolating intermediate stiffness values. These interpolated values were then applied to the differentiated GraCe ceiling panels (Pub7, Fig. 15, p. 371).

Reapplying these interpolated stiffness values to the GraCe panels resulted in a calibrated simulation with significantly reduced deviations compared to the uncalibrated simulation, which had applied arbitrary, uniform stiffness values across all differentiated areas. However, an intriguing observation emerged: while the uncalibrated homogeneous mesh more closely resembled the physical outcomes topologically, the calibrated heterogeneous mesh exhibited sharp spikes due to the assigned stiffness values (Fig. 17 in Pub1, p. 372).

Despite these topological discrepancies, the experiment established a systematic relationship between knitted material patterns and their performance. It defined the extreme capacities of the unravel DJ stitch system and provided a reproducible stiffness-density mapping for interpolating intermediate values. This methodology narrowed the search parameters for calibration, improving both precision and efficiency.

REFINED EVOLUTIONARY CALIBRATION WITH TARGETED CONSTRAINTS The third experiment, detailed in **P**7 (p. 29, sec 4.2), revisited the force-into evolutionary algorithm approach from the first experiment while incorporating refined constraints informed by the second experiment. These constraints restricted the search range to values derived from prior physical sampling and manual post-tuning, ensuring numerical consistency between differentiated area densities and their corresponding stiffness values. This ensured gradual transitions in material stiffness that aligned with the graded CNC-knit pattern.

This targeted approach enabled fine-tuning of material stiffness values, significantly reducing deviations between the digital simulation and physical prototypes. Comparisons between calibrated and uncalibrated setups revealed the advantages of controlled calibration, including a more consistent correlation between stiffness and density. Additionally, the narrowed search range improved algorithm performance, reducing search time and enhancing calibration accuracy.

The experiment also explored two mesh clustering approaches for calibration: **field-based structure** (from Graded Fields) with the subdivisions based on the structural analysis thresholds, and **binary-based** structure, Generated via the dithering technique within the Fabrication Model and used for manufacturing files. Testing these mesh structures provided valuable insights into how varying levels of *mesh granularity* impact stiffness values, calibration accuracy, and computational efficiency. Both structures are presented in **P**7 (Fig. 2, p. 25: B - Graded Field-based; C - Binary), and their differences are discussed in the following paragraph.

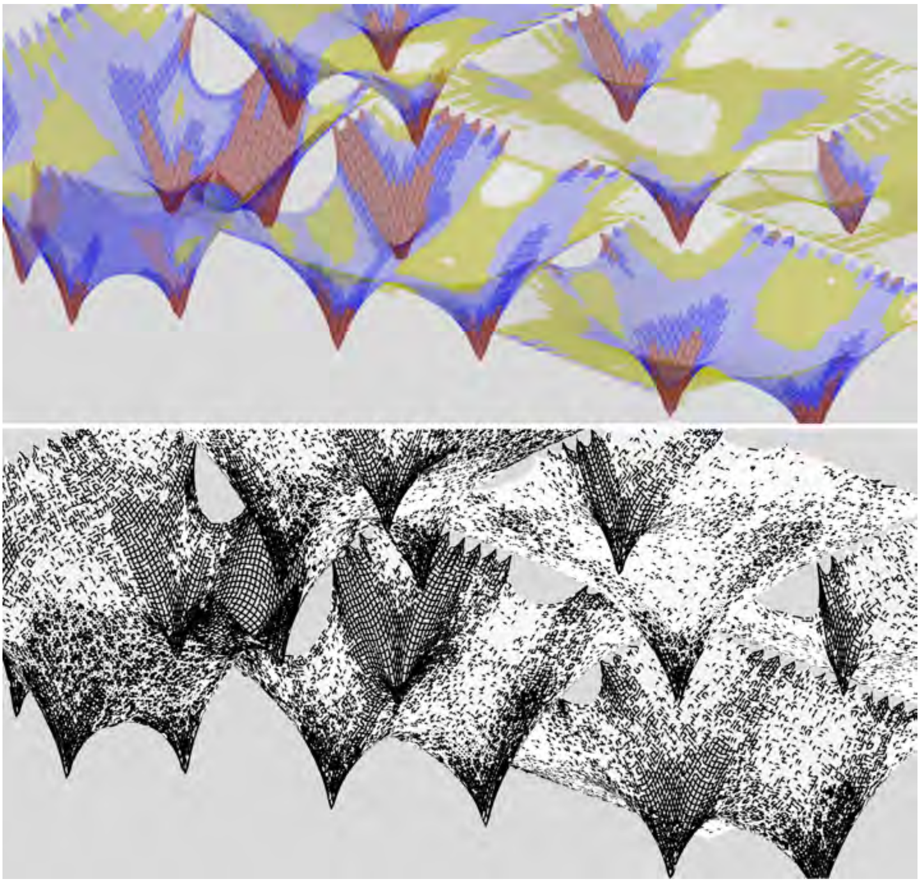
STRUCTURE OF THE CALIBRATED MESH

Refining mesh clustering for simulation calibration is crucial to achieving alignment between digital and physical entities, enabling more precise comparisons and accurate calibration. The analysis conducted earlier by the Simulation Model is instrumental not only in translating global membrane performance into localized material patterns but also in specifying a digital mesh with heterogeneous properties that better reflects the grading of manufactured knits. This refinement is addressed through two approaches: *field-based* and *binary-based*.

FIELD-BASED Field-based mesh clustering uses threshold-based subdivisions derived from the Graded Field Method in the Fabrication Model to create knitting patterns. This approach was first introduced in **P**5.1 (p. 364) as an extension of the evaluation workflow through the concept of *two-stage simulation*. In this setup*Simulation A*, within the Design Model, utilizes a mesh with homogeneously assigned properties to form-find the preliminary shape, while *Simulation B*, within the Evaluation Model, applies a heterogeneously specified mesh, with springs clustered into groups informed by analysis inputs.

BINARY-BASED Binary-based mesh clustering adopts a more granular approach, leveraging the dithering technique output from the Fabrication Model. It separates mesh springs into two groups, representing the binary nature of knitting techniques—loose and tight stitch types. This method, introduced in **P**7 (p.24, sec 3.2) as a mesh-density-based approach, is later termed *binary* in this thesis to better reflect its dual clustering structure and its precise representation of the graded material properties of physical knitted prototypes.

The choice of mesh clustering technique significantly impacts calibration *accuracy*, computational efficiency, and *visual outcomes*. The field-based approach subdivides the mesh into five differentiated areas (with finer subdivisions possible through the Fabrication Model), each calibrated to unique stiffness values. In con-



F 4.24: Structure of the calibrated mesh. Top - field-based, clustering based on structural analysis threashold domains. Bottom - binary-based clustering based on dithering technique.

trast, the binary clustering uses only two distinct groups of springs, reducing the computational load required for evolutionary algorithms to optimize stiffness values for two gene pools. The field-based mesh results in a nearly homogeneous appearance, with subtle differences in stiffness values that are less visually distinct. In contrast, the binary mesh setup reflects the graded physical knits more vividly, with its binary clustering immediately apparent in renderings. Both approaches demonstrated similar calibration accuracy. The field-based setup (Sim B4 in **P**7) achieved a 30.2% deviation score and an average deviation of 21 mm, while the binary setup (Sim C2B) achieved a 32.1% deviation score with the same average deviation. The comparative results are summarized in **P**7 (Figure 6, p. 33).

CONCLUSION OF EVALUATION MODEL

This section demonstrates a progressive refinement of simulation calibration methods for differentiated knitted membranes, bridging digital design simulations with physical prototypes through iterative validation of geometrical deviations.

The initial experiment, using pattern-based approach laid the foundation for understanding calibration challenges, highlighting inconsistencies in stiffness values across differentiated designs. Despite its limitations, this method validated the potential of genetic evolutionary algorithms to automate stiffness value optimization while providing critical insights into the relationship between pattern topology and material behavior. The second experiment introduced a structured calibration method, establishing a systematic correlation between material density and stiffness values. By using homogeneous physical samples to create a density-stiffness mapping, this approach significantly enhanced calibration precision and provided a reproducible framework for controlled results.

Building on these insights, the final experiment employed a refined algorithmic approach with targeted constraints. By exploring variations in mesh clustering, it effectively captured the graded properties of CNC-knitted membranes, reducing deviations between digital and physical models. The comparison of field-based and binary-mesh clustering revealed the trade-offs between computational efficiency, calibration accuracy, and visual outcomes, offering valuable strategies for future refinement.

Overall, this study highlights the value of a hybrid methodology that integrates empirical data, controlled conditions, and algorithmic optimization. The combination of these approaches ensures a comprehensive calibration framework that addresses both the inherent variability of knitted materials and the computational complexities of simulation models. By systematically bridging the gap between digital simulations and physical artefacts, the iterative calibration framework developed here provides a robust and repeatable process for refining simulation accuracy.

This methodology not only improves alignment between digital and physical outcomes but also enhances the understanding of how differentiated material properties influence the structural behavior of CNC-knitted membranes. It addresses key practical challenges, such as achieving consistency in material performance and accommodating the layered decisions inherent in the design-to-production workflow. At the same time, it tackles epistemological questions about the limits of simulation accuracy when dealing with anisotropic and graded materials. The framework also underscores the importance of interdisciplinary collaboration, combining computational design, textile fabrication, and physical prototyping to achieve high-fidelity results. As such, it represents a significant contribution to advancing the simulation and fabrication of architectural textiles, offering a scalable approach that could be adapted for future innovations in digitally designed and materially complex systems.

The following Conclusion chapter explores opportunities for further refinement of these approaches, aiming to enhance efficiency, scalability, and robustness in calibration methods for architectural textiles.

Publication 1

SIMULATION AND CALIBRATION OF GRADED KNITTED MEMBRANES

Simulation and Calibration of Graded Knitted Membranes

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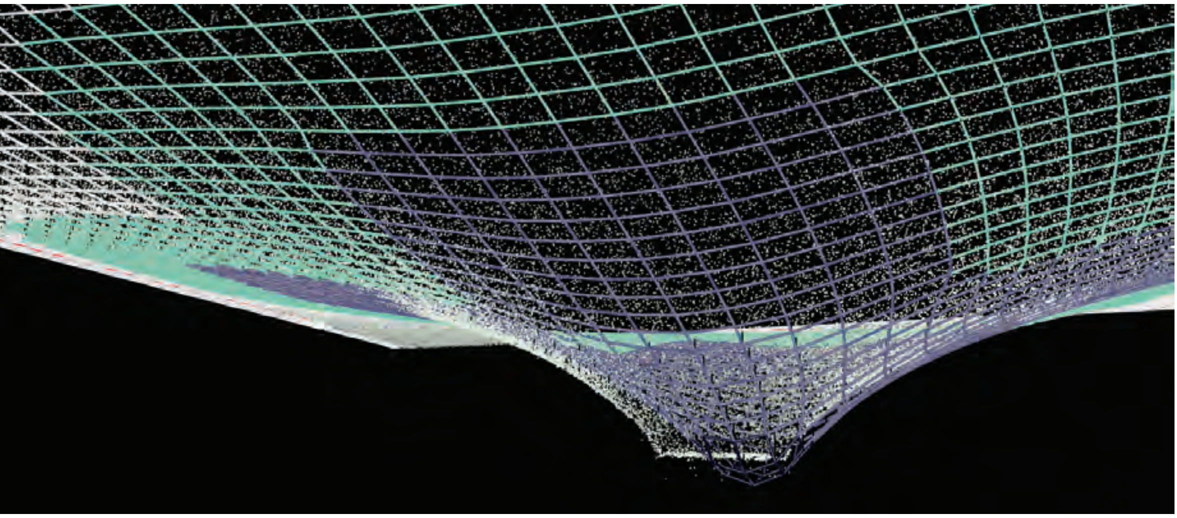

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1 Fragment from the simulation digital environment, where the point cloud data is overlapped with the mesh-based geometry of a knitted membrane.

ABSTRACT

The grading of knit changes its geometrical performance and steers membrane expansion. However, knit possesses challenges of material predictability and digital simulation, due to its multiscalar complexity and anisotropic properties. Taking as a challenge the lack of digital solutions incorporating CNC-knit performance into the design model, this paper presents a novel approach for the design-integrated simulation of graded knit, informed by an empirical dataset analysis in combination with genetic optimization algorithms.

Here the simulation design tool reflects the differences of industrially knitted textile panel behavior through digital mesh grading. Diversified fabric stiffness is achieved by intertwining the yarn into variegated stitch types that steer the textile expansion under load. These are represented digitally as zoned quad meshes with each segment assigned a stiffness value.

Mesh stiffness values are optimized by minimizing the distance between the point clouds and the digital mesh, which are documented through deviation colored maps.

This work concludes that design properties—pattern topology, stitch ratio, pattern density—play an important role in textile panel performance under load. Stiffness values derived from the optimization are higher for shallower designs and lower for the deeper cones.

INTRODUCTION

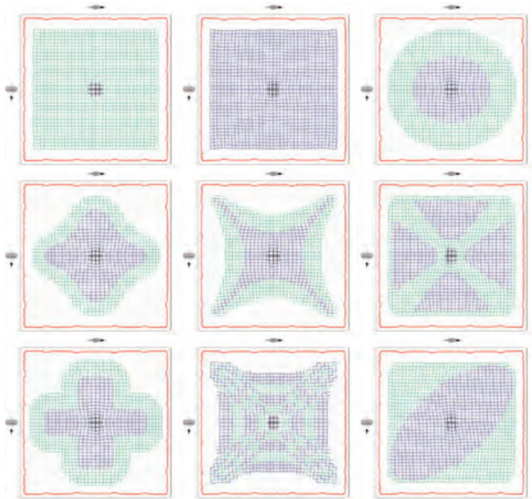
In recent years numerous projects (Gupta et al. 2020; Popescu et al. 2020; Ramsgaard Thomsen et al. 2015, 2019) have displayed the potential of CNC knits as a next-generation material for textile architecture in its integrated detailing, material differentiation, and sustainable production. Knit grading changes the geometrical performance of the textile, allowing it to steer the membrane expansion in the predefined areas under load. However, knits possess challenges of material understanding, predictability, and digital simulation, due to their multi-scalar complexity and anisotropic properties.

Currently, there are no digital solutions that would integrate the simulation of CNC-knit performance into a design model to specify fabrication data. Instead, the workflow is solved through a laborious sample-based prototyping, which inhibits scaling up and accessibility of knit application in architecture.

This paper presents a novel approach for the design-integrated simulation of CNC knits, informed by an empirical dataset analysis with the help of genetic optimization algorithms.

Existing simulation methods from fashion and computer graphics focus on human body templates, without taking into account the material stretch; rather, they represent fabric being draped over the mannequin (Kaldor, James, and Marschner 2008; ShimaSeiki 2007; STOLL 2007; Yuksel et al. 2012). Often these models are not connected to the fabrication machinery logic, although the behavior of the fabric is very realistic.

The application of knit in architecture aims to use fabrics under tension, where the geometrical performance and precision are highly crucial (Tamke et al. 2016). However, precise textile engineering methods of modeling through colliding stitches become computationally infeasible when scaling up (Kyosev and Renkens 2010). Architectural domain tools for woven membrane form-finding, although scalable, miss graded properties integration across the surface. Thus, the digital models for knitted membranes should reflect the differentiated surface properties of knit as these affect the geometry and material performance. Therefore, it is necessary to find ways to integrate graded properties of knit into design models (Ramsgaard Thomsen et al. 2016) in order to gain material understanding, inform its composition for fabrication, and promote the use of knit in architecture.



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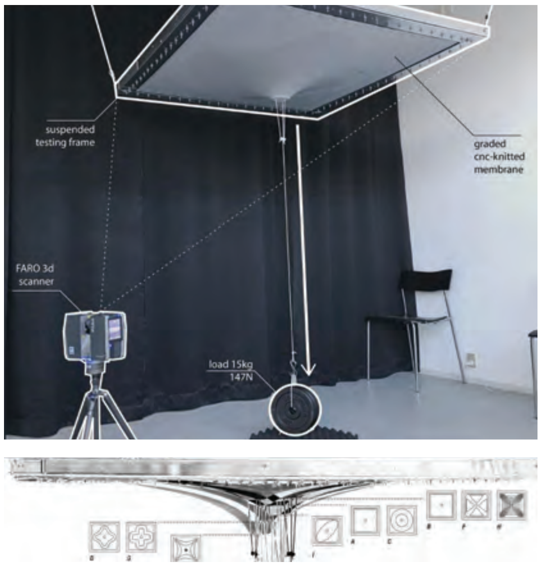

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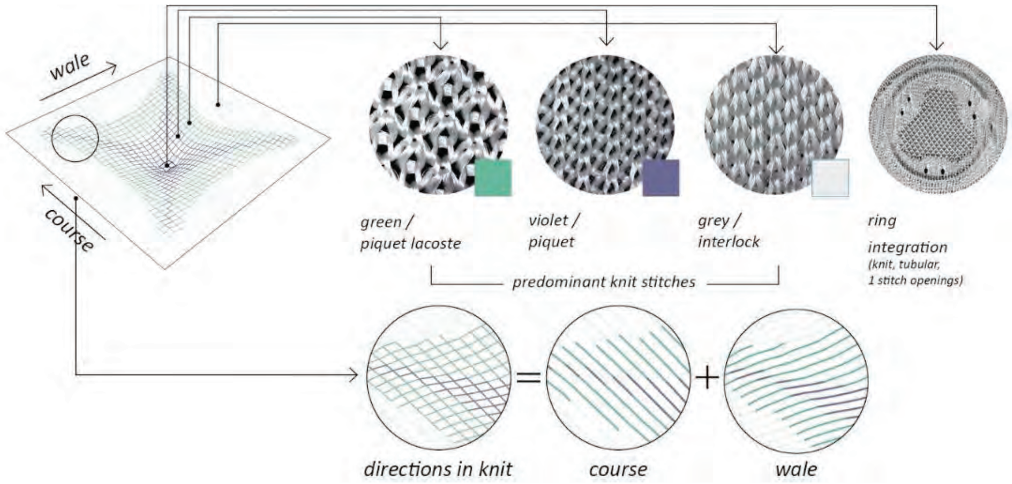
2 Nine selected designs for the experiment.

3 Testing setup: graded CNC-knitted membrane tensioned to a suspended frame, loaded with 15 kg and scanned with FARO laser scanner.



4 Digital setup for graded knitted membranes: mesh bars are sorted by color and divided into groups by the direction of wales and courses. 4

METHOD FOR SIMULATION AND TESTING OF GRADED KNITTED TEXTILES

Digital and Physical Correlation

In this paper, we present the development of a simulation method for graded knitted membranes through the KnitVault experiment that is designed to validate the method by testing the correlation between the digital and the physical aspects of the exercise.

The digital tool aims to follow the differences of physical textile panel behavior by incorporating variegated knit properties through the digital mesh grading. Despite the same yarn being used for the entire membrane surface fabrication, intertwining it into the different stitches results in a diversified fabric stiffness. As a direct yarn-to-yarn stitch modeling is computationally heavy, the abstraction of the knitted surface into a quad-based mesh is a compromise (Fig. 4).

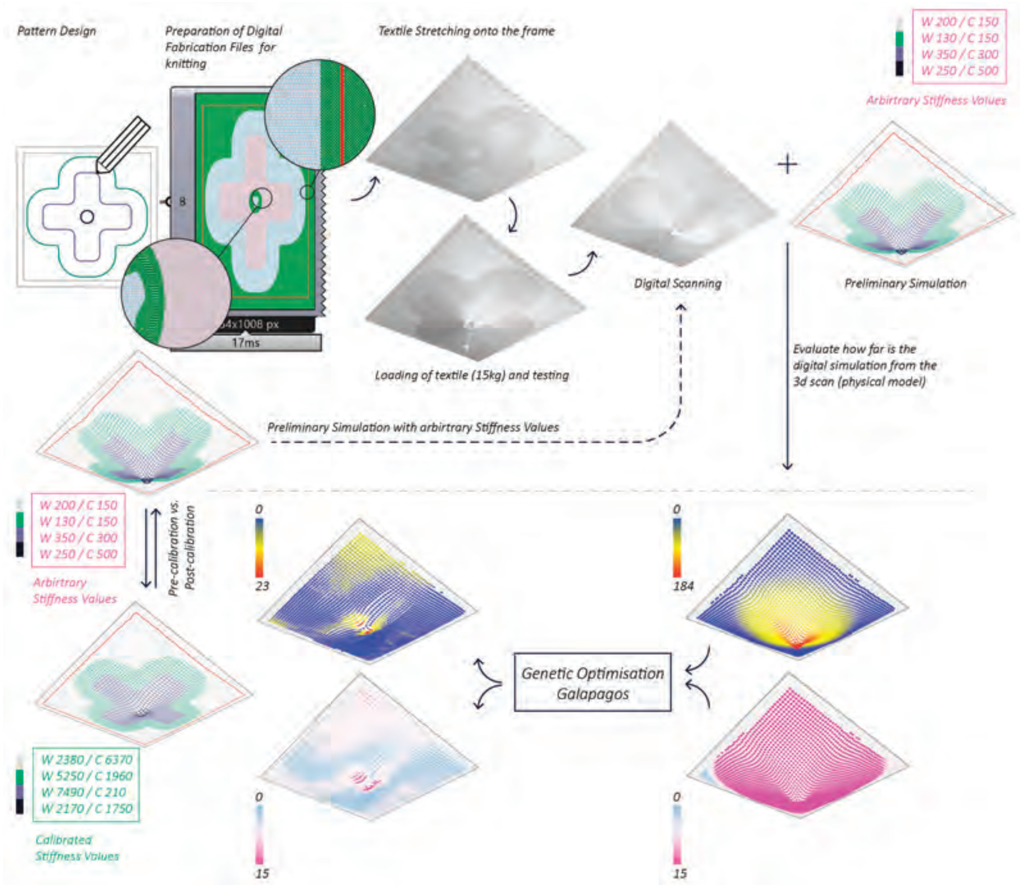
The physical side of the experiment is supported by the industrially knitted textile panels with varied topology patterns (Fig. 1), where three predominant stitch types (piquet, piquet lacoste, and interlock) are used to steer the surface degree of expandability under load (Fig. 4). Nine pattern configurations (Fig. 2), selected for the experiment, were designed manually to create different stitch-ratio proportions and pattern-drawing geometries. Although looking back to these decisions, the designs could be more irregular in order to challenge the experiment setup.

As the textiles are knitted on the industrial CNC-knitting machine using digitally generated bitmaps and equivalent machine settings throughout the production, the pattern difference is the only varied parameter between the panels. Once fabricated and attached to the frame, the dissimilarity in planar pretension is noticeable across the designs, which indicates the effect of patterns on the textile behavior.

Next, the panels are loaded with a 15 kg weight from the center, which results in different stretch depths, related to the pattern differences (Fig. 3). Each geometry is scanned with a FARO laser scanner in order to transfer the data into the digital environment. The processed point clouds of the loaded panels are compared to the corresponding simulations (K2 Engineering plug-in for Kangaroo [Brandt 2016]) for further digital tool calibration.

The directionality of the quad-mesh (UV arrangement) associates with the wale-course nature of knitted structures, where heterogeneous properties are defined through the mesh segments' stiffness assignment across the surface, defined by the pattern boundaries and the direction. The direction of knit is important to take into account, as it contributes to an anisotropic behavior of the fabric. Therefore, separate stiffness values are assigned to the course and wale directions of the mesh.

While the stiffness of the yarn is normally a known value, provided by the producer, *the stiffness of the knitted fabric made of this yarn remains unknown,* as various stitches can be used to form the textile. For that reason, it poses an interesting challenge to understand these relations in order to build a reliable, yet computationally viable, simulation tool of graded knitted fabrics.



5 Diagram of the workflow for graded knitted membrane design, digital setup, simulation, testing, and digital tool calibration. 5

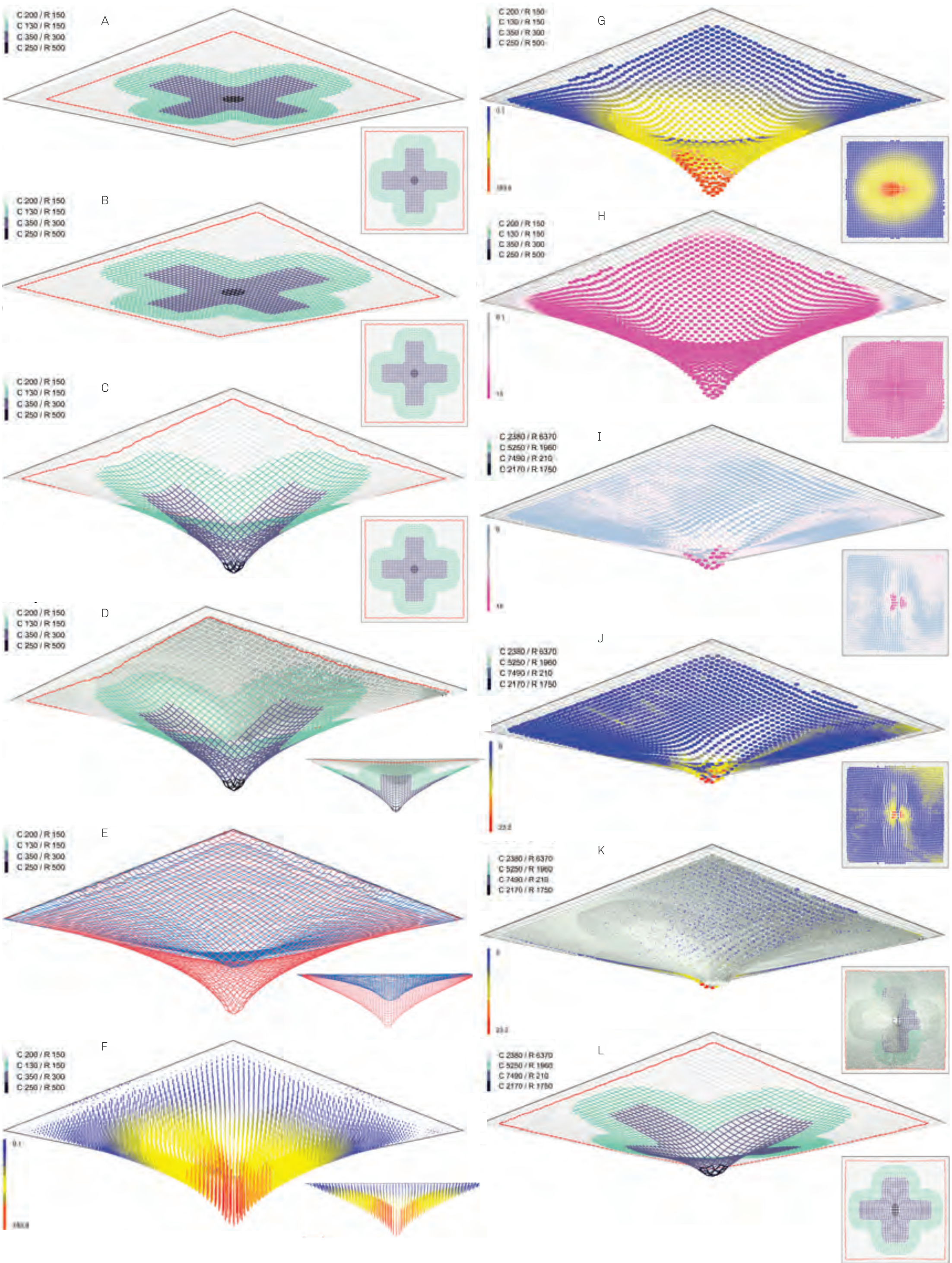
Digital Deviation Optimization

At first, when the real stiffness values are yet undiscovered, arbitrary numbers are assigned to the pattern zones in order to complete the simulation. This gives an arbitrary mesh geometry to work with.

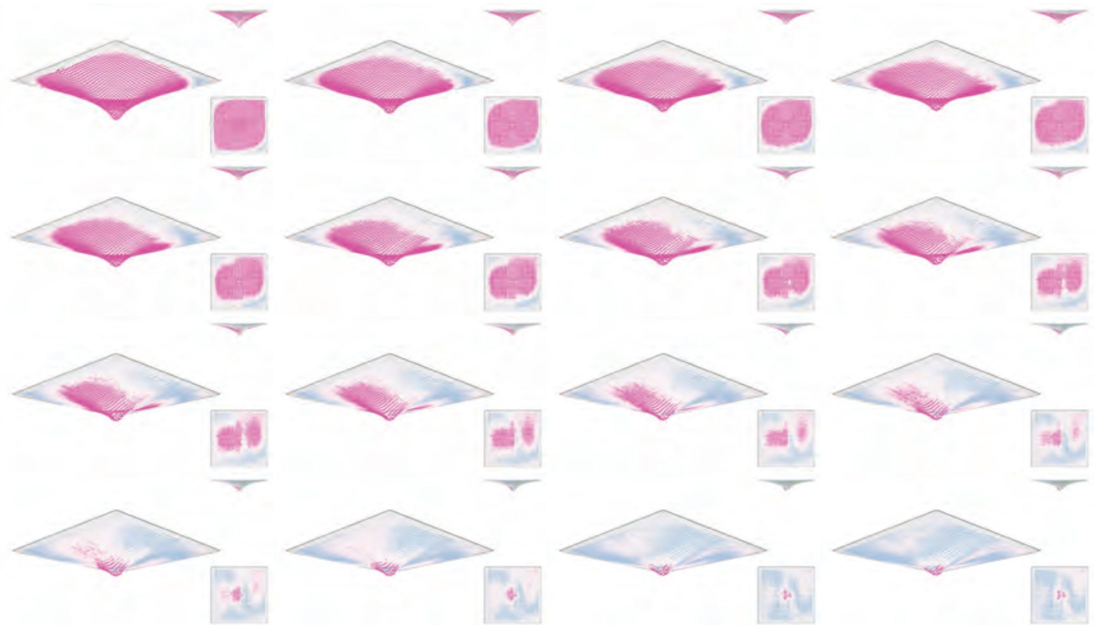
The simulation follows the same steps as in the physical installation of the fabric onto the test rig. In the beginning, the textile sample is stretched in plane with the testing frame and only then loaded with the weight. In the same way the pretension is introduced in the digital environment. These pretension values are then used in the second step of the simulation, when the pretensioned mesh is loaded with the 147 N in the z (down) direction (Fig. 6a, b, c). This allows us to build a more correct simulation of the three-dimensional geometry, corresponding more closely to the real behavior.

The point clouds are translated to the mesh geometry by projecting an arbitrary mesh (in red) to it and rebuilding the same topology mesh (in blue, Fig. 6e). This way there are two meshes with identical topologies that can be overlapped and compared. The comparison lies in calculating the distances between the mesh nodes (Fig. 6f), where it is visualized through the red-yellow-blue color mapping projected onto the simulation mesh (Fig. 6g). In the magenta mapping, the nodes are colored pink if the distance exceeds 15 mm (Fig. 6h).

At first, the mesh with the arbitrary values deviates a lot from the point cloud geometry (Fig. 6d). The prevalence of the magenta nodes (Fig. 6h) means a high degree of discrepancy between the simulation and the equivalent physical geometry. The aim of the task is to lower the distance between the red and the blue mesh by achieving



6 Step-by-step actions of graded membrane stiffness value optimization membrane design, digital setup, simulation, testing, and digital tool calibration



7 Incremental improvement of the stiffness value set by reduction of deviation value between the simulated mesh and the point cloud. 7

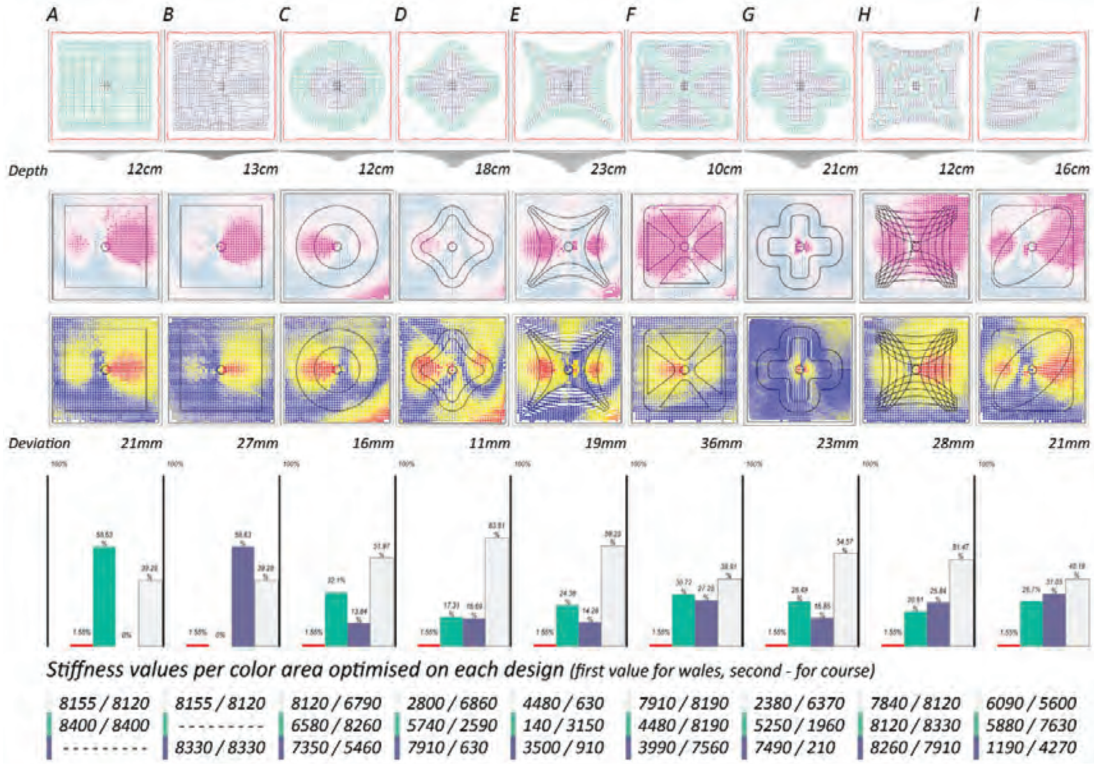
the smallest maximum distance and reducing the number of magenta nodes in the simulated mesh.

To derive the set of unknown stiffness values, a genetic optimization algorithm is used to minimize the distance between the digital mesh and the point cloud of the corresponding textiles (Fig. 5). The optimization loop is established with the Galapagos plug-in for Grasshopper Rutten 2020), integrated in a double solver simulation with Kangaroo (Piker 2017) and K2 Engineering workflows. Here the engine is going over the stiffness value combinatorics within the given boundaries (150–8500 MPa) and applying them to the mesh zones. With each stiffness value application, the algorithm is measuring the distance from the resulting simulated mesh to the point cloud. If it exceeds the maximum desired value, the search for the optimal stiffness values continues until the deviation is acceptably low. On average, the search for each design solution took 10–15 hours and an average of 20,000–25,000 iterations. Figure 7 shows the incremental reduction of both magenta nodes and the maximum distance, while the mesh is getting closer to the point cloud geometry.

RESULTS AND DISCUSSION

This paper describes the method of stiffness value determination for graded knitted membrane material. Initially, unknown mesh stiffness values are optimized, using corresponding point clouds as target geometries for minimizing the distance to the mesh. As a result of the exercise, the stiffness values that would bring the digital mesh very close to the corresponding physical model geometry have been found (Fig. 8). The tolerance between the point cloud and the simulated mesh is between 16 mm and 36 mm, which is acceptable for the expandable fabrics. Although the results for each geometry were very promising, the stiffness values for the same fabric type differ from design to design, and the cross-application of discovered values would give deviating results. This means, for example, that the stiffness values that work perfectly for design D would not work for F. This challenge provoked the authors to rethink the method and to find a potential system in the results to improve the method for the future development of the work.

For that reason all the discovered stiffness value sets are cross-applied to all the other designs. This exercise is explained in Figure 9 through D-, C-, and E-based optimized results. The results for each cross-application are sorted based on the deviation from the corresponding point cloud: from the smallest in the target design to the most deviating in the rest of them. When looking at the selection of design pairs based on their stitch ratio proportion similarity (D/G, C/E, I/H, E/H), interesting findings emerged. In the analysis of the results, the following aspects are taken into account:



8 Diagram showing (top to bottom) the tested design range, optimization results mapped onto the mesh, stitch ratio proportions, and stiffness values. 8

stitch ratio, geometry of the pattern, and the depth of the cones under the stretch.

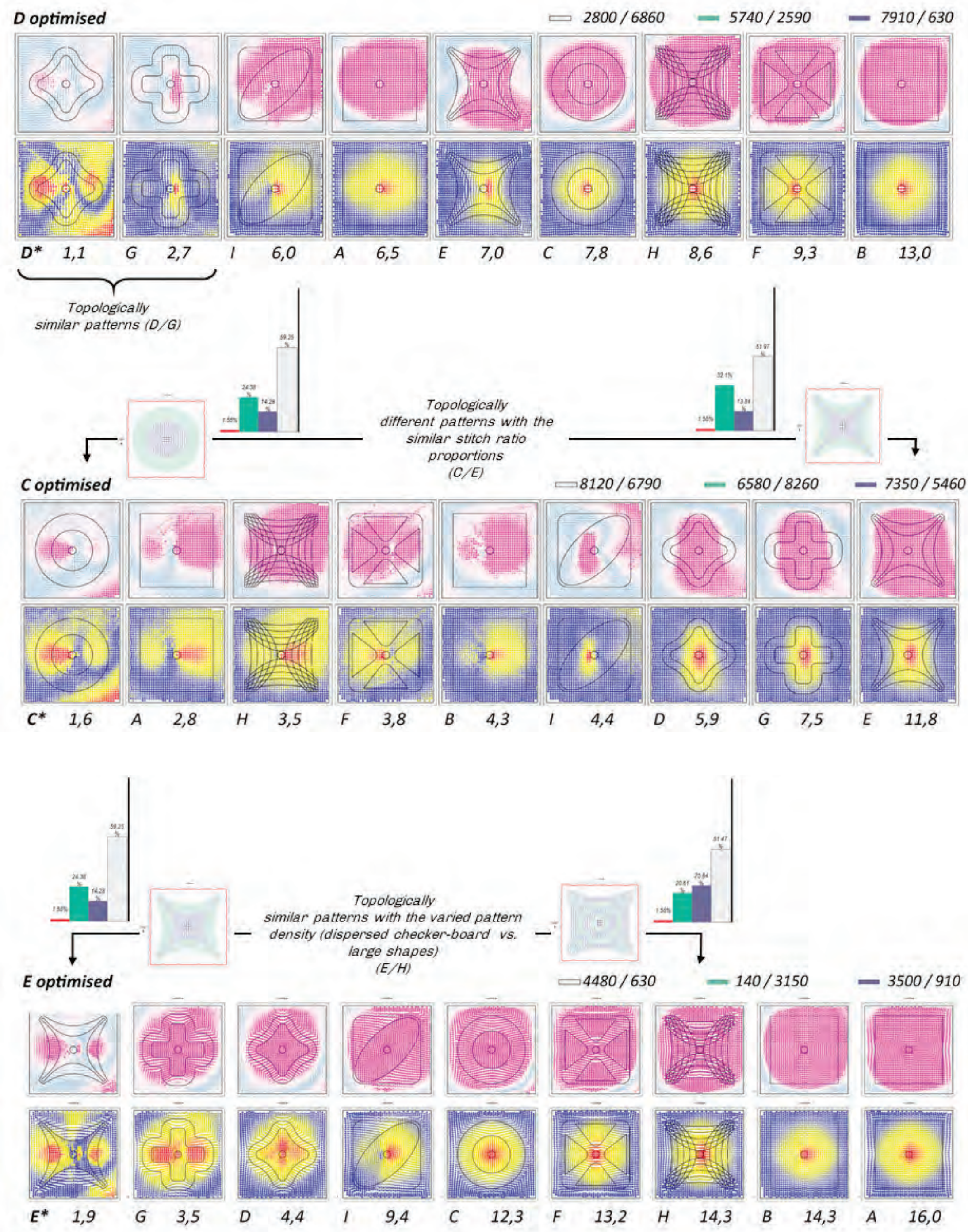
Cross-application of stiffness values between topologically similar patterns ("cross-like" in D/G) shows less deviation from the equivalent point clouds (Fig. 9 top), while topologically different patterns, although with similar stitch ratio (C/E), resulted in a larger error to the point clouds (Fig. 9 middle). Topologically similar designs with a close stitch ratio (E/H) but variation in pattern density (dispersed checkerboard vs. large shapes) performed a noncompatibility of stiffness values. The numbers resulting from optimization on the shallower designs (A, B, C, F, H) are higher, while the values trained on deeper geometries (D, E, G) are lower (Fig. 10). This is logical, as the stiffer mesh has more resilience against the load and therefore results in a shallower cone.

Overall, the value of discovered stiffness values remains doubtful, as it is unreliable to reuse them for pattern geometry other than the one that was used to train the optimization. The discrepancies among the stiffness values can be explained by the lack of pattern boundary tracing. As the pattern linework was not traced in the point clouds, it is challenging to evaluate whether the simulated mesh has taken the exact right shape. Possibly, while the overall mesh boundaries were quite close after optimization, the inner boundaries of the pattern might remain off.

Additionally, in the described optimization setup, the relations between the stitch type areas were not defined but rather left too open. The same stiffness value range condition (150–8500 MPa), introduced to all the zones, created a situation where the same stitch type zone is obtaining both the low and the high stiffness values in the different designs.

REFLECTION AND CONCLUSION

Despite the challenges encountered in the universality of the method, the presented workflow is an important step toward an understanding of the graded knit behavior. The optimization of stiffness values per design showed a high degree of precision, interlinking the pattern design, fabrication data, physical testing data, and the corresponding digital simulation.



9 Results of the cross-application of the stiffness values trained on a particular design.

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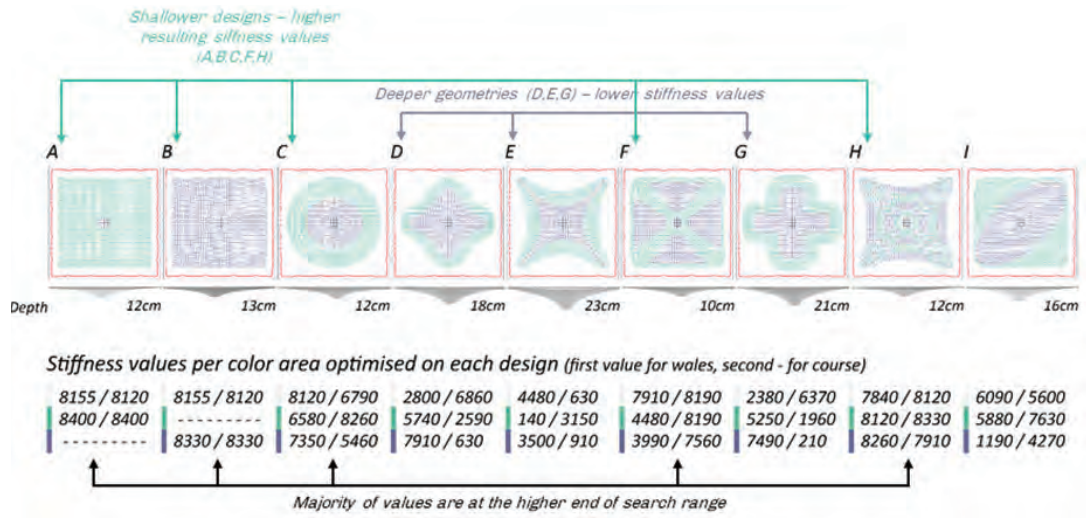

10 The resulting stiffness value sets for each panel design.

10

A future research work would imply a further increase of digital complexity, introducing a wider search range of stiffness values, finding a way to quantify the pattern density (dispersed vs. large zones), establishing the relations between the stitch types (stiff vs. expandable), and introducing additional springs for reflecting the stitch type differences. These implementations might potentially increase the method's precision, transforming it to the tool for generating stiffness values for heterogeneous knitted membranes.

A more reliable digital tool for graded knitted membranes would allow for a greater confidence in design with this challenging but high potential material for architectural applications. Predictability of graded knit material behavior would build trust in using it for large-scale architectural elements, where heterogeneous material density and elasticity can contribute to functionality and structural performance while being highly sustainable and waste-free in manufacturing.

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IMAGE CREDITS

All images and drawings are by the authors.

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Mette Ramsgaard Thomsen examines the intersections between architecture and new computational design processes. During the last 15 years her focus has been on the profound changes that digital technologies instigate in the way architecture is thought, designed, and built. In 2005 she founded the Centre for IT and Architecture research group (CITA) at the Royal Academy of Fine Arts, School of Architecture, Design and Conservation, where she has piloted a special research focus on the new digital-material relations that digital technologies bring forth. Investigating advanced computer modeling, digital fabrication, and material specification, CITA has been central in forming an international research field examining the changes to material practice in architecture.

Publication 5.2

INTEGRATED DESIGN MODELS FOR MATERIALLY DIFFERENTIATED KNITTED TEXTILE MEMBRANES:

AS MEANS FOR SUSTAINABLE MATERIAL CULTURE WITHIN MEMBRANE ARCHITECTURE

(Part II)

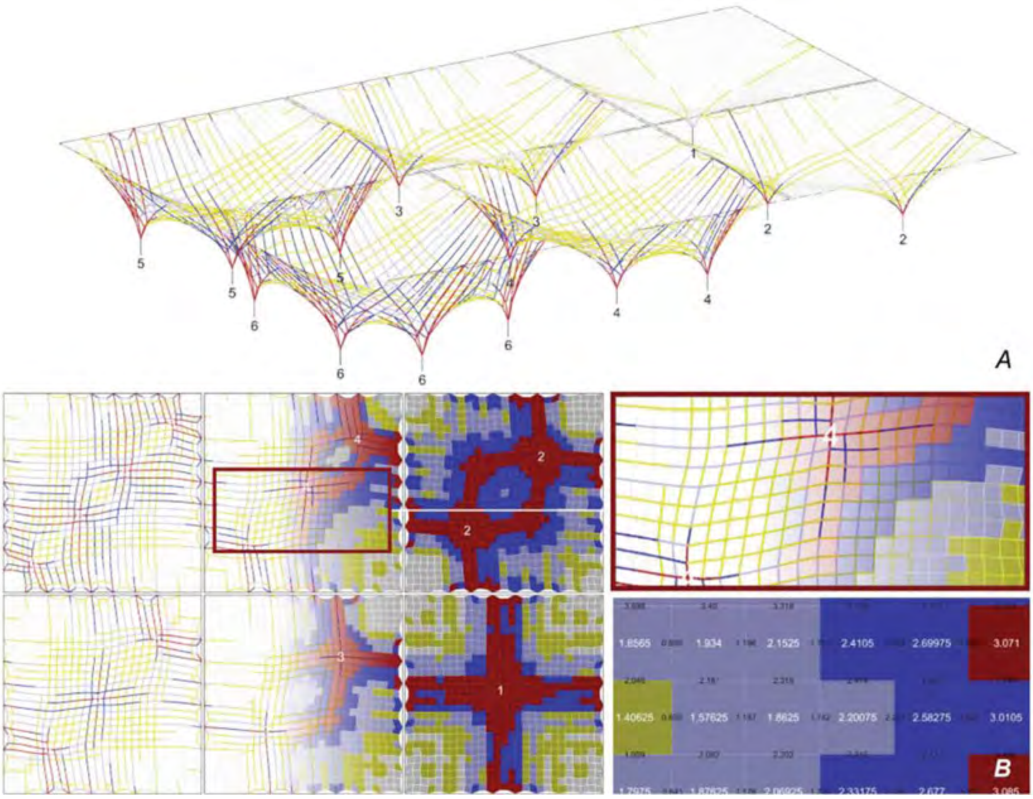

Fig. 8 Axial stress distribution in mesh cables and the translation of mesh cable tension value mapping per bar (mesh segment) to per mesh face

while the areas that experience less tension, remain dense, as they do not need to expand that much in order to achieve desired three-dimensionality.

This is counter-intuitive from the perspective of material performance for strength, as traditionally more dense textiles are perceived as more strong and expected to be in the areas of higher tensile forces. However, with the use of high-performance yarns, the integrity of the filament is guaranteed, which maintains the surface knitted strength despite stitch density. Here, the larger loops lock into their final locking position with the same strength properties as the smaller loops. Placement of larger loops in the areas of required larger deformation is very efficient in achieving material expansion and reaching required three-dimensionality with the fewer resources through the steering of material density. As the result, *cluster colour maps* are generated for each design, that are then translated to knitting machine-readable bitmaps (Fig. 9)

5 Finding 2. Structurally Informed Material Differentiation for Heterogeneous Simulation—Calibration Through Physical Prototyping with Homogeneous Membranes

With the membrane structural analysis, the cluster colour map is not only used for *material differentiation for digital manufacturing*, but also for *materially informed simulation*, incorporating these structurally derived surface gradings for more accurate digital representations of heterogeneous CNC-knitted membranes. Here each

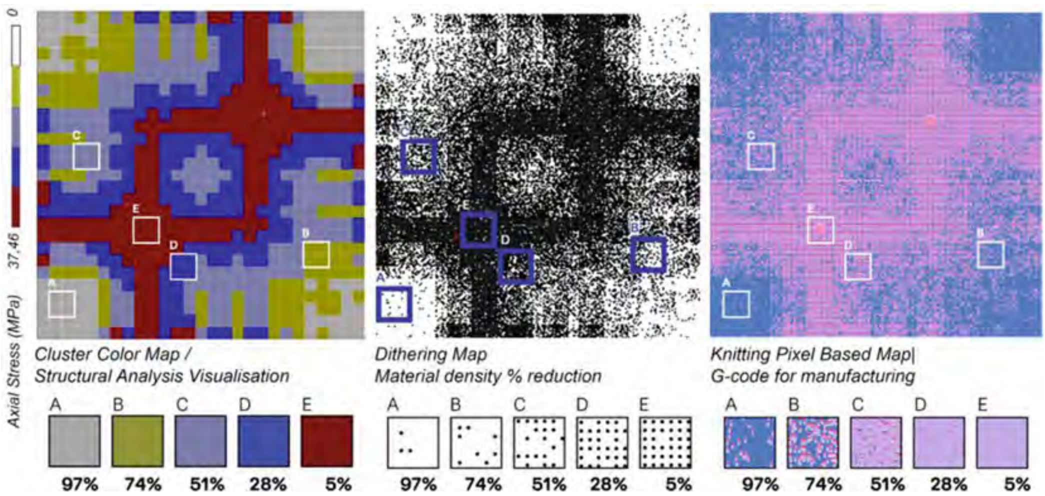

Fig. 9 Grading of the knitted heterogeneous membranes linked to the stress distribution in the surface and driven by the percental reduction of material density

colour zone of the mesh receives a specific stiffness value in relation to the corresponding material density of the knit.

The assignment of stiffness value for each area is not a trivial task, since no definitive understanding has been developed on how to transfer from an arbitrary stiffness value used in Simulation A, nor how to correlate material density in the form of stitches with a specific Young's modulus value.

Until now, the method of extensive physical prototyping has been used in order to tune the graded simulation. A 3D-scan data from the equivalent 1:1 physical prototype (Fig. 11), with corresponding graded areas as in the digital simulation, is compared to the digital simulation and in the event of deviation, the stiffness values are adjusted in order to fit the physical membrane. This can be done manually, by tuning the numbers incrementally, which is a tedious task, or with the use of evolutionary optimisation algorithms in order to find the right numeric values for stiffnesses (Sinke Baranovskaya et al. 2020; Oghazian et al. 2022). It is a valid method to gain more precise simulations. However, the need to produce the entire design first and only then be able to tune the simulation is not giving many benefits, as is expensive at first and does not inform the design, as structural deviations are only visible once fabricated. The results from such calibration also highly depend on many factors such as design topology and stitch types used, which are highly unlikely to be successfully transferrable so easily to other design topologies using alternative stitch types.

We find it important to develop a method that would aid the understanding of digital material properties of graded membranes early in the design process, without excessive 1:1 scale prototyping or the production of the final design. The aim is to find a way how to calibrate a computational system in a more generic way, that would improve the digital representation of materially graded CNC-knitted membranes. In this chapter, we present a proposal, on how to correlate the material density with the digitally assigned stiffness value with the aid of a supporting physical experiment.

5.1 Correlation of Material Density with the Stiffness Values

The differentiated knitted material has a certain limit of stretch and therefore a limit in stiffness. In order to understand the range of stiffness values possible to achieve with a certain material density, a few homogeneous panels representing

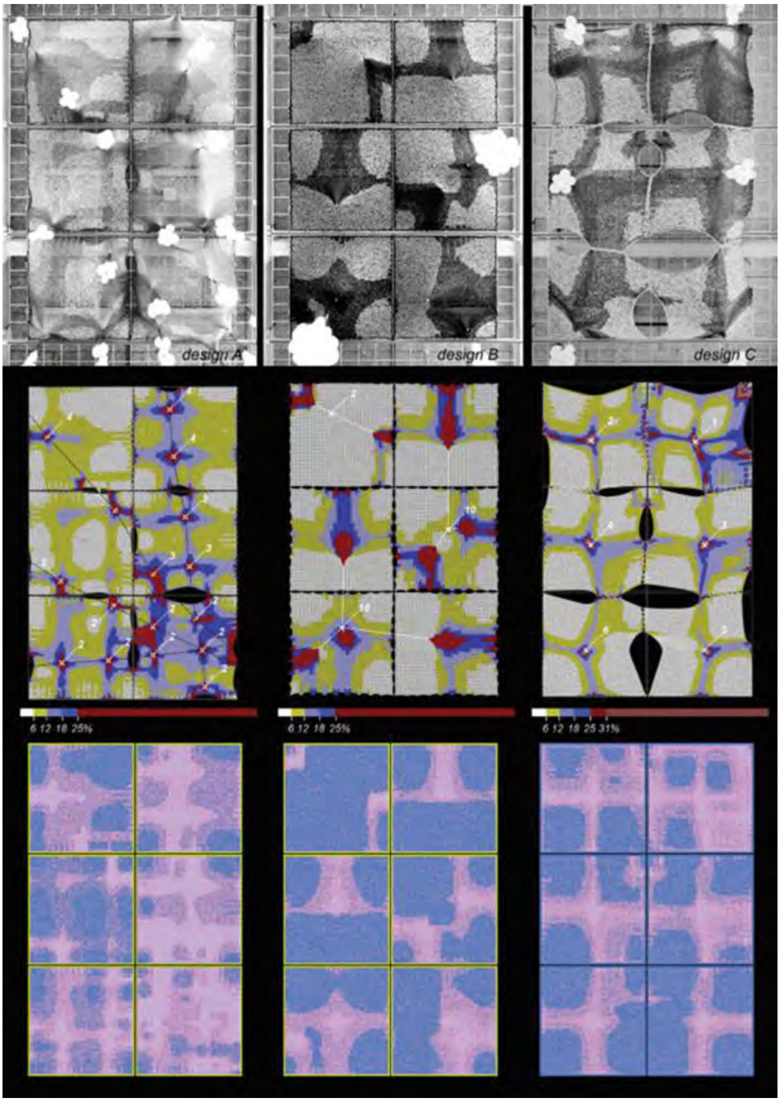

Fig. 10 Three installations of Graded Knitted Ceiling project, each with different loading conditions, reflected in variegated material differentiation of membranes (Fig. 10). Design C is used for further simulation calibration

the *maximum*, the *minimum* and the *medium* material densities are fabricated and loaded with the arbitrary weight of 2.9 kg. The exact loading value is not important here as it is important that it remains the same across all the membranes. All three membranes are produced with the same knitting machine settings, however with varied material density, reflected in the percental presence of unravel stitch—0%, 50% and 100% accordingly. The pattern density defines the textile's capacity for expansion under the load (Fig. 11). The dimensions and the material used for this experiment are the same as in the design that is intended for calibration.

5.2 Stiffness Values Discoveries

The results of the calibration of the homogeneous model through Simulation B are documented in the diagram in Fig. 12, where the digitally scanned physical samples are compared to the digital simulation B. With the aim to reduce the deviation between the scanned and the digital

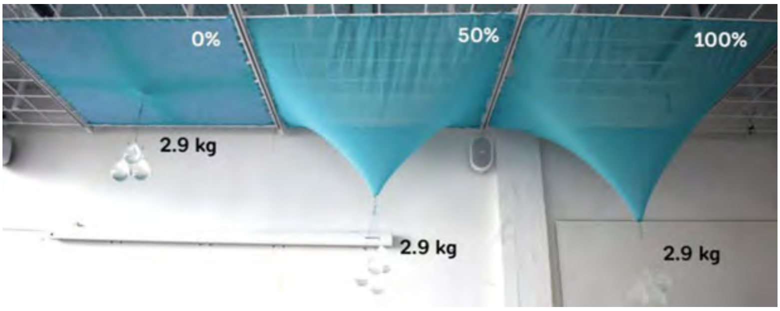

Fig. 11 Three homogeneous samples with various material densities loaded with the same weight

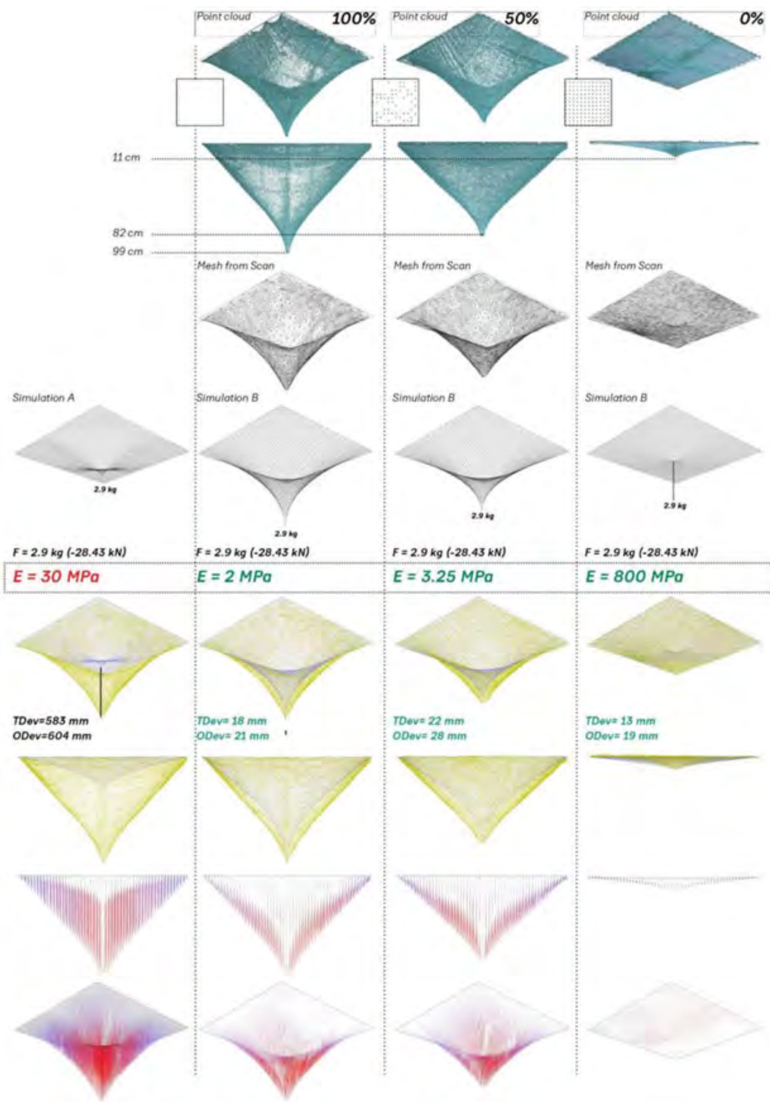

Fig. 12 Diagram showing the calibration of the model through the set of homogeneous samples, each of different material density—ranging from 0% unravel stitch reduction to 100% unravel stitch reduction. TDev—tip deviation, ODev—overall deviation

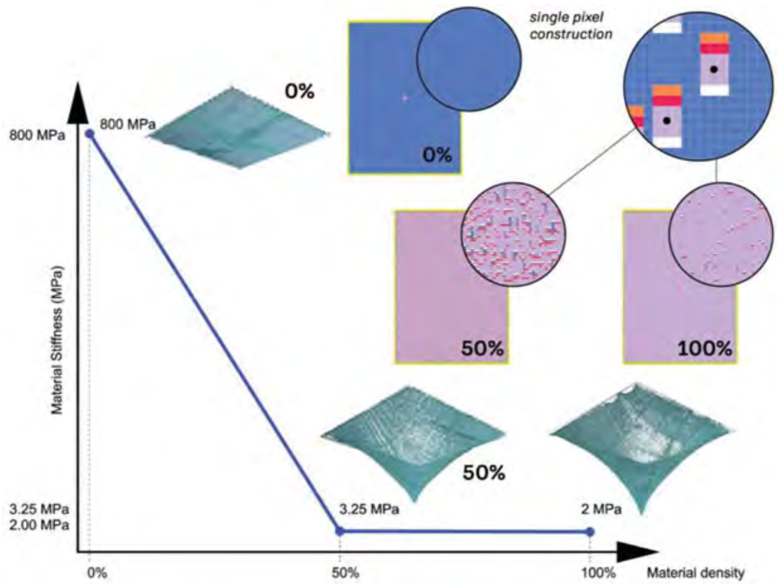

Fig. 13 The curve graph showing a non-linear relation between the material density vs material stiffness property

Fig. 14 Panels C design, used for the digital calibration of the model

mesh, the values of stiffness values are found for each corresponding membrane material density for 0%−2 MPa, 50%−3.25 MPa, 100% −800 MPa. The stiffness values discovered through this exercise demonstrate the non-linear relations between the material stiffness value and its material density (Fig. 13). Additionally, a more steep stiffness variation is expected between the 0% and 50% material density, while between the 50 and 100% the stiffness shows almost a flat curve. This can be explained through how the fabrication file is constructed, where each point from the dithering map, that is used to calculate the material density, is later assigned more pixels around it for technical reasons of executing the pattern on the machine. This results in an accumulated density of the unravelled stitch types. Despite that, the same principle is used to define the material densities in the ceiling panels intended for calibration, which guarantees the consistency of the experiment and the method (Fig. 14)

5.3 Calibration of the Heterogeneous Model

The graph of stiffness values, discovered during the homogeneous model calibration allows to estimate the stiffness values for other material percental densities (97%, 88%, 64%, 19%, 5%), present in the design intended for calibration (Fig. 15). The reapplication of corresponding intermediate stiffness values demonstrates a much more tuned digital simulation with visibly reduced deviation from the scanned data of the physical installation (Figs. 16 and 17), however, some deviation remains. Figure 16 demonstrates how resulted calibrated mesh of Simulation B correlates to the scanned data in comparison to same overlay of Simulation A with the scanned data. There it is visible that the calibrated mesh reaches much closer to the physical prototype in terms of depth, however, the curvature of the mesh is not entirely followed. This can be explained with the quad-based setup of the mesh, which lacks the springs in order to control the vertical displacement more precisely. Additionally, the method of Simulation B uses the discovered values on mesh bars, while there should be a backward method on how to translate values from mesh face to mesh bars as the latter ones are used for assigning the properties.

6 Conclusion

This paper describes a contribution on two aspects to design and fabrication of materially differentiated CNC-knitted membranes: (1) the material differentiation based on structural analysis and (2) the improved simulation of materially differentiated membranes by means of material probes.

The first contribution presented in this paper is the newly developed approach for material differentiation by using structural analysis. It allows for the introduction of free angles for membrane stretch, thereby reducing the unutilised areas of the membranes that would otherwise appear as sagging surfaces if another method for material differentiation is used (e.g. surface displacement strategy) (Fig. 18). Analysis-driven emerging patterns correspond to increased mesh geometrical complexity, while also providing pattern solutions that are not possible to predict manually or analytically. This leads to increased freedom in CNC-knitted membrane design, providing a more sustainable alternative to already employed woven textiles in membrane architecture.

Another contribution presented in this paper is a method for calibrating the simulation of heterogeneous membranes. This calibration

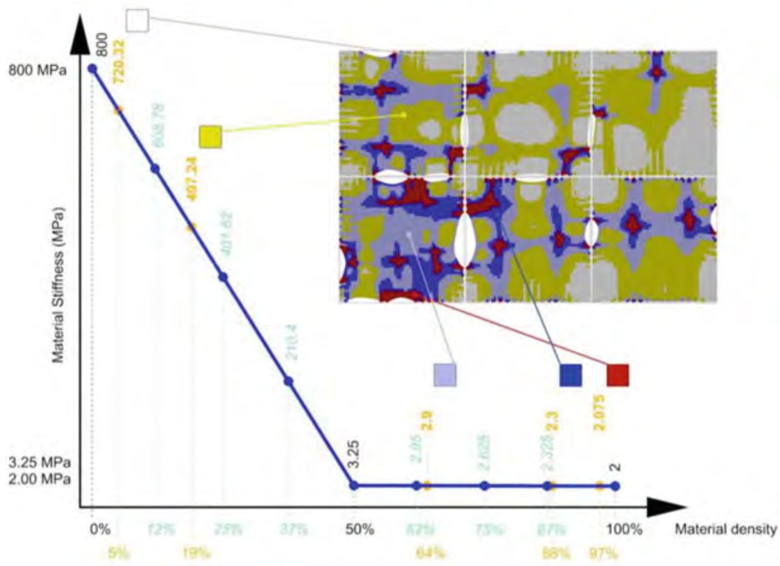

Fig. 15 Graph of correlated stiffness values related to the material density and linked with the material expansion capacity (new values for calibration are in orange)

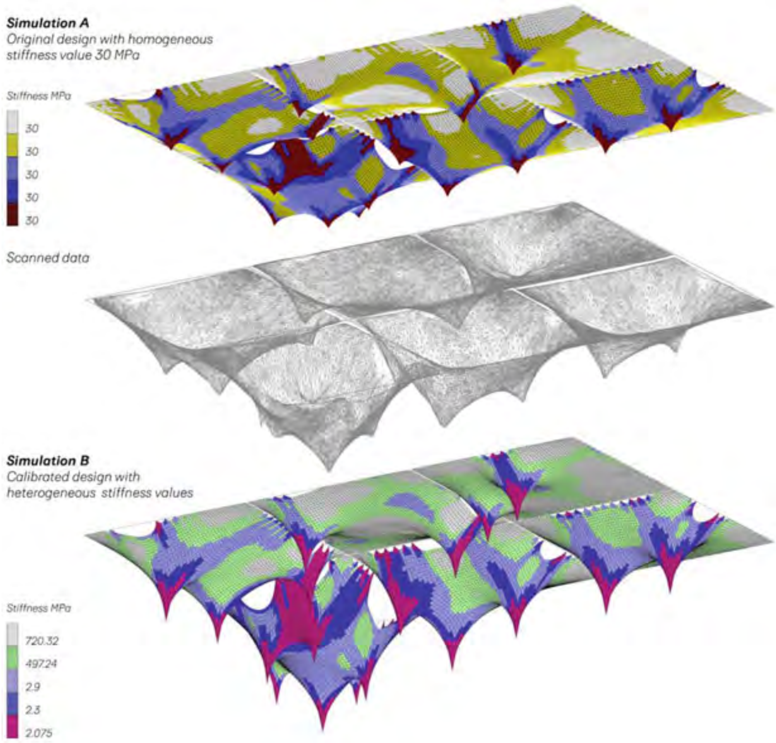

Fig. 16 Simulation A, Scanned data and calibrated Simulation B, applying discovered stiffness values, informed by the homogeneous membranes experiment

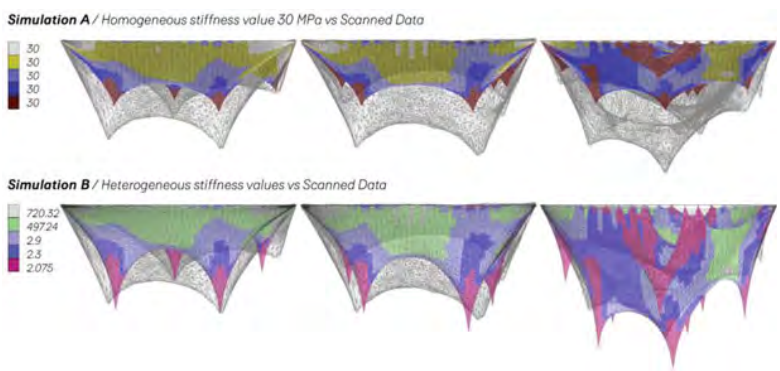

Fig. 17 Comparison of Simulation A and B to the physical prototype with the overlay of scanned data

process involves manufacturing homogeneous membranes with extreme densities, serving as reference points to determine the intermediate stiffness values required in the calibrated design. These extreme values provide reference points to understand how the material stiffness varies in relation to the density distribution within the membrane. With this knowledge, the calibration process can interpolate and determine the appropriate stiffness values for the intermediate zones of the heterogeneous membrane. Moreover, this method can be replicated with other design cases of alternative pattern combinations or employed yarns.

The found stiffness values are then used in the calibrated digital simulation to achieve more geometrically accurate outcomes. Certain deviations are observed between the calibrated mesh and the scanned data, which can be explained by the lack of prestress in the basic homogeneous samples, that were used to derive the extreme stiffness values. In other words, the

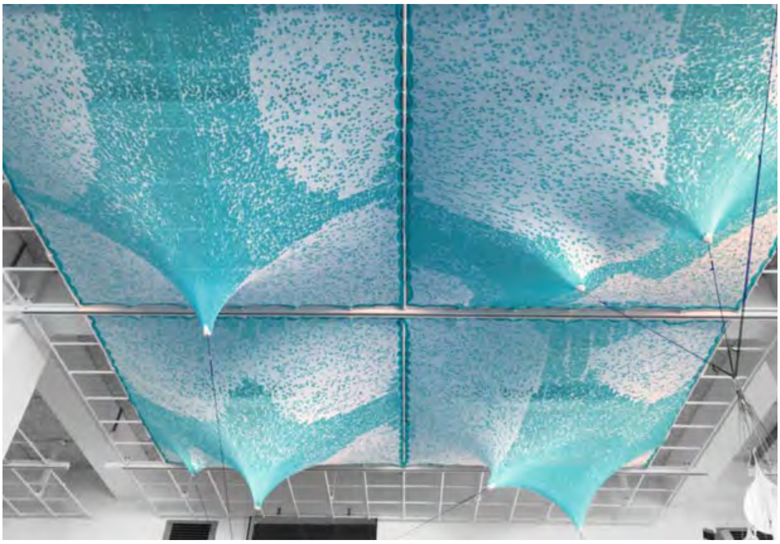

Fig. 18 The CNC-knitted textile panels design with angles loading directions demonstrates the benefits of using tensioned-based material differentiation strategy

homogeneous samples should have been loaded with the larger weight to provide sufficient pre-stress. As 2.9 kg used in the experiment might have been not enough to stretch the membranes to their maximum capacity, and therefore resulting three-dimensional geometry might be misleading from the start of the calibration process.

In general, this approach allows us to reduce excessive prototyping by avoiding creating the entire final design before we know the stiffness values that we can use to calibrate the simulation. Instead, it is sufficient to construct only three supporting samples to understand what stiffness range is possible with the given knitting setup and designed material density. To tune and confirm the values, additional 2-axis material tests of the smaller material samples of the corresponding densities can be conducted.

In the current situation of scarce resources, more materials, manufactured with additive tools will be invented. Additive technologies such as 3D printing or CNC knitting provide general access to methods of material grading. In order to be successful and efficient in designing with material gradings, we need to establish methods of how to speed up and ease the understanding and prediction of behaviour for these materials. Currently, physical sampling and prototyping can be considered the best way for understanding the material properties in order to tune simulations of FGMs. The presented method for simulation tuning uses only a few physical samples, which reduces the volume of physical prototyping and proves a better understanding of digital and physical material correlations of various material densities. The data from preliminary prototyping feedback into the construction of full representational models aid the implementation of these novel heterogeneous materials for real applications with the reduced risk of material failure. Our hybrid approach makes use of worldwide available digital fabrication technology and can in this way be used in a general way. An improvement and generalisation of the calibration of FGM simulation is part of future work.

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Publication 7

SIMULATION CALIBRATION OF DIFFERENTIATED KNITTED MEMBRANES WITH EVOLUTIONARY OPTIMISATION TOOLS

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SIMULATION CALIBRATION OF DIFFERENTIATED KNITTED MEMBRANES WITH EVOLUTIONARY OPTIMISATION TOOLS

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Abstract. Knitting offers a flexible and customizable approach in architectural textile applications, challenging traditional woven membranes [28]. CNC (computer numerical control)-knitting technology enables the creation of gradient expansion membranes through precise stitch control, facilitating large-scale production with minimal waste [25, 27, 34]. This departure from cut-pattern-based strategies typical in woven membranes allows for integration of diverse material properties in a single process. Our research focused on guiding material expansion in knitted membranes to achieve complex, non-developable surfaces through digital form-finding and structural analysis. However, the irregular material density distribution posed challenges in reliable digital simulations due to complexity and knowledge gaps. Successful simulation models require a deep understanding of material properties and abstraction strategies to balance computational feasibility and accuracy. Our study investigated these challenges through prototyping and calibration of simulation models, aiming for more geometrically accurate results in designing with differentiated CNC-knitted membranes. Here, we presented the extension of the method for simulation and calibration of graded textiles, published earlier by the authors [32, 35]. We extended previous methods for simulating graded textiles, experimenting with CNC-knitted ceiling panels of varied geometries and material gradients. Calibration involves adjusting stiffness values and mesh representations using evolutionary optimization algorithms to reduce geometric deviations between digital simulations and their physical artifacts (Figure 1).

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 [14]. 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 a 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 with those.

2020 *Mathematics Subject Classification.* Primary: 65Y10.

Key words and phrases. CNC-knitting, simulation calibration, graded materials, evolutionary optimisation.

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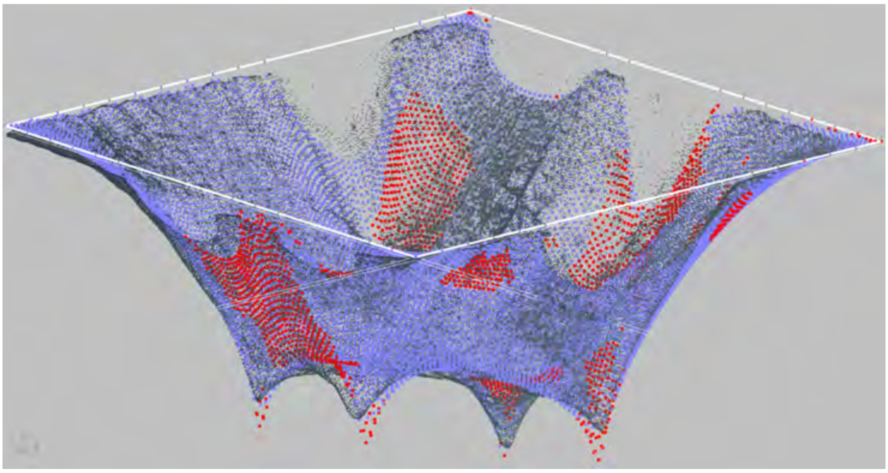

FIGURE 1. Deviations between the digital and physical artifacts

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, a very high Poisson's ratio, and a strong anisotropic behavior [30]. This capacity defines the behavior of the material and shall be taken into account early on during the design process, form-finding, and simulation [35].

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 [29, 44]. 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. **Philosophical questions within the context of simulation.** Alongside the technical aspects, simulation raises philosophical questions related to its nature as a knowledge-generating tool [43]. 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 the abovementioned 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 an abstracted simplified system.

1.5. **Abstraction and accuracy when building simulation for differentiated knits.** When simulating knitted membranes at a 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 the previously published method for simulating and calibrating graded textiles [32, 35]. 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 [35]. 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 [7, 18, 23, 27, 33, 39]. 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 [1, 11, 19]. Another approach adopts a strategy of a larger abstraction and utilizes quad-based meshes with lower complexity at sparser resolutions [2, 3, 8, 16, 18, 24]. This allows for simulations of larger structures compared to the first approach. Additionally, several mesh topologies such as quad-, triangle-, hexagon- and nonuniform ones are explored [7, 20, 26, 30, 31, 33].

2.2.2. *Abstracted mesh properties - rest length 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 [2, 8, 11, 19, 24]. With the introduction of plug-ins for Rhino Grasshopper like K2Engineering [15], Karamba [10], and Kiwi3D [13], 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.Young's modulus here is the measure of a solid material's stiffness under tension or compression along its length. 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 [16, 21, 32, 34].

2.2.3. *Difficulty in finding the stiffness value.* However, assigning stiffness values to the mesh in a 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 biaxial 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 [5, 18, 26, 30, 39, 40]. 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 [31]. 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 [25, 32, 35, 38, 41]. Although, the process 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 [9, 12, 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 [4, 6, 17, 22, 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 heterogeneous knit structures [21, 32]. Building upon mentioned research outcomes, a further improvement and alternations of the method are 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 algorithms to reduce discrepancies between physical and digital counterparts. Figure 2 shows various representations of the panel used in this study.

3.1. **Physical setup, 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. The collection consists of six materially graded textile panels forming a highly undulated ceiling installation, with each panel measuring 1.2 x 1.2m. Since the panels are knitted from high-tenacity polyester Serafil, which is expected to exhibit very low elongation under load, the variation in the panel's stretch property is achieved solely by combining two stitch types across the surface: 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). Textile expansion is activated by attaching equally heavy (2.9kg) suspended weights to the fabrics. The weight value is determined through empirical intuition and visual observation of fabrics reaching their "locking" point state, where they feel maximally stretched and exploited under the weight. Additionally, each panel is featuring either continuous or selective clamping of the perimeter to the solid support frame. Selective clamping creates larger openings in the membrane structure as well as a 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 [36].

3.2. **Digital simulation setup.** 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 [35, 36].(Fig.2, B).
- Mesh-density based clustering (dual setup). This is a novel method of mesh clustering, explored in this paper, where mesh springs are clustered into two groups, forming a dual mesh setup, 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).

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 visualized through the color mapping. Considering the scale of the observed panels (1.2m x 1.2m each), a value of 25mm has been empirically chosen as a satisfactory threshold to evaluate

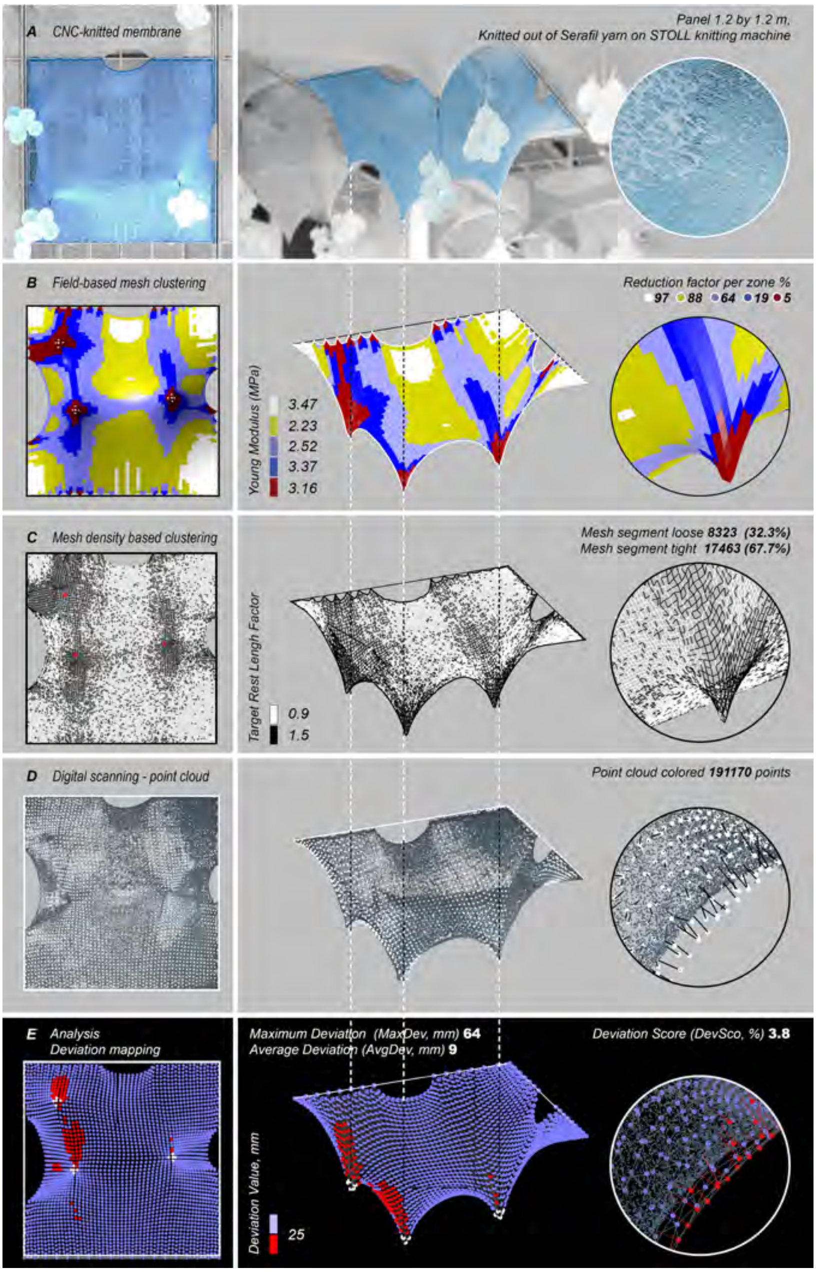

FIGURE 2. Representations modes of differentiated knitted ceiling panel. A - physical membrane, B - Clustered mesh derived from the structural analysis (field based), C - Mesh density based clustering up (reflecting material density), D - Point cloud from digital laser scanning, E - Discrepancy analysis,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

discrepancies. This threshold serves as a practical measure to assess the differences between the physical and digital representations. Achieving a target discrepancy value of 0mm between the physical and digital models presents a significant challenge due to several factors. To begin, the high degree of material flexibility inherent in knitted membranes introduces shape and surface variations that are difficult to completely eliminate. Additionally, the scans of porous lace-like fabric structures may exhibit occasional digital anomalies such as “flying points,” which can affect the accuracy of the scan data. Moreover, using the full range for deviation visualization (0 to MaxDeviation) for discrepancies mapping would result in excessive data, making it challenging to interpret and analyze effectively. Additionally, such visualizations may generate misleading images, obscuring meaningful insights. Establishing a uniform threshold range for all analyzed panels at the outset of the studies is challenging due to the unique maximum deviation of each panel and the unknown potential overall maximum deviation across all panels. Instead, the panels are mapped dually: Areas with discrepancies under 25mm are considered “satisfactory” (blue), while those exceeding 25mm are deemed “unsatisfactory” (red). These serve as visual indicators of significant discrepancies, where the mesh deviates over 25mm from the point cloud and is highlighted with the red dots (Fig.2, E). This approach permits to create a uniform graphic material, allowing for visual comparison between all panels by tracking the disbalance between the red and the blue areas through the deviation score. By visually mapping the discrepancies onto the simulated mesh, we can 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 setup.** In the experiment, the evolutionary algorithm plug-in Galapagos is utilized to search for the optimal stiffness values of the mesh. The gene pool, 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 ranges 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 optimization 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 force's distribution domain. This setup aims to achieve a smooth material differentiation gradation. For the evolutionary optimization of stiffness value discovery, five gene pools 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 optimization in Simulation C utilizes two gene pools. 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 optimization run is set up to minimize fitness value with a threshold of 10, where the evolutionary solver is set up to a maximum stagnation of 50, population 50.

4.1. **Quantitative evaluation of earlier experiments - simulation A, B, B2.** In the previously conducted Simulation A [35], 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 stiffness value, significant discrepancies between the digital mesh and the physical counterpart were observed (Fig.3, top). The average maximum deviation (Average MaxDev, mm) 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, mm) 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 [35]. The results of this calibration exercise are quantitatively evaluated further in Simulation 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 is particularly applicable with the given material setup

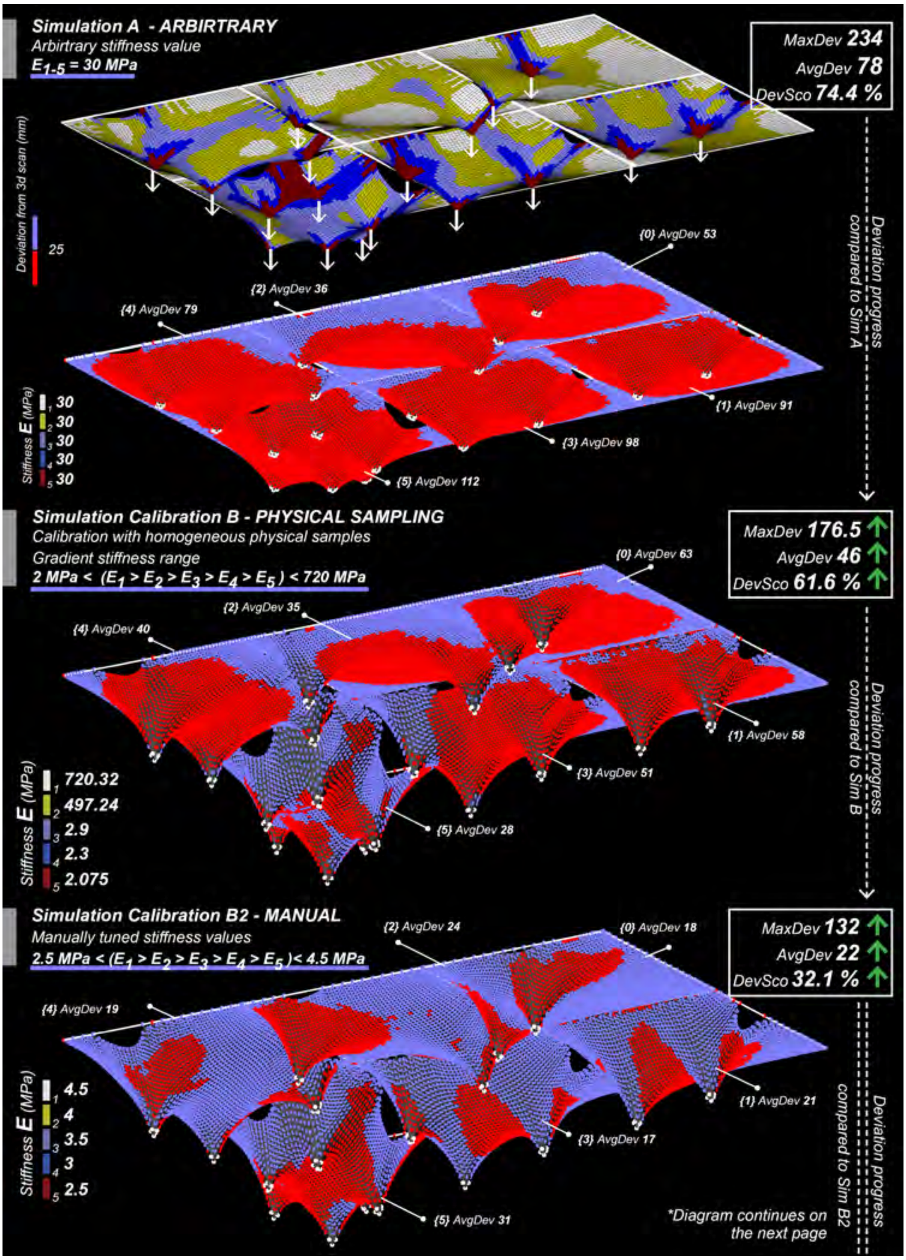

FIGURE 3. Simulation A, B, B2

of a gradient membrane density differentiation, using double jacquard (tight) and unravel double jacquard (loose) stitches.

4.2. **Evolutionary optimization 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 optimization for Simulation B3 (Fig.4, top) is conducted in the unrestricted manner, meaning that each gene pool of values is allowed to receive any stiffness value within the overall range, without any specific constraints. On the other hand, the optimization for Simulation B4 (Fig. 4, bottom) is set up in restricted mode, where gene pool values are forced to obtain gradually increasing values per each membrane field zone. Here, the optimization 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 predefined 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 incorporates a dual mesh setup that is expected to accurately capture variations in material density, while also improving optimization time by utilizing only two gene pools for the value search.

4.2.2. *Mesh density dual setup (Sim C1, C2.A, C2.B).* Within Simulation C, optimization is conducted through three exercises. The first exercise, Simulation C1, utilized an unrestricted gene pool range of 1-8 MPa, starting position at 50% - 4.4 MPa. Unrestricted search setup resulted in 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 deviation, and overall deviation score of 28.9%. Despite this outcome being quite convincing in terms of deviation lowered value, and overall similarity of digital and the physical meshes, 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 represent the varied behavior and

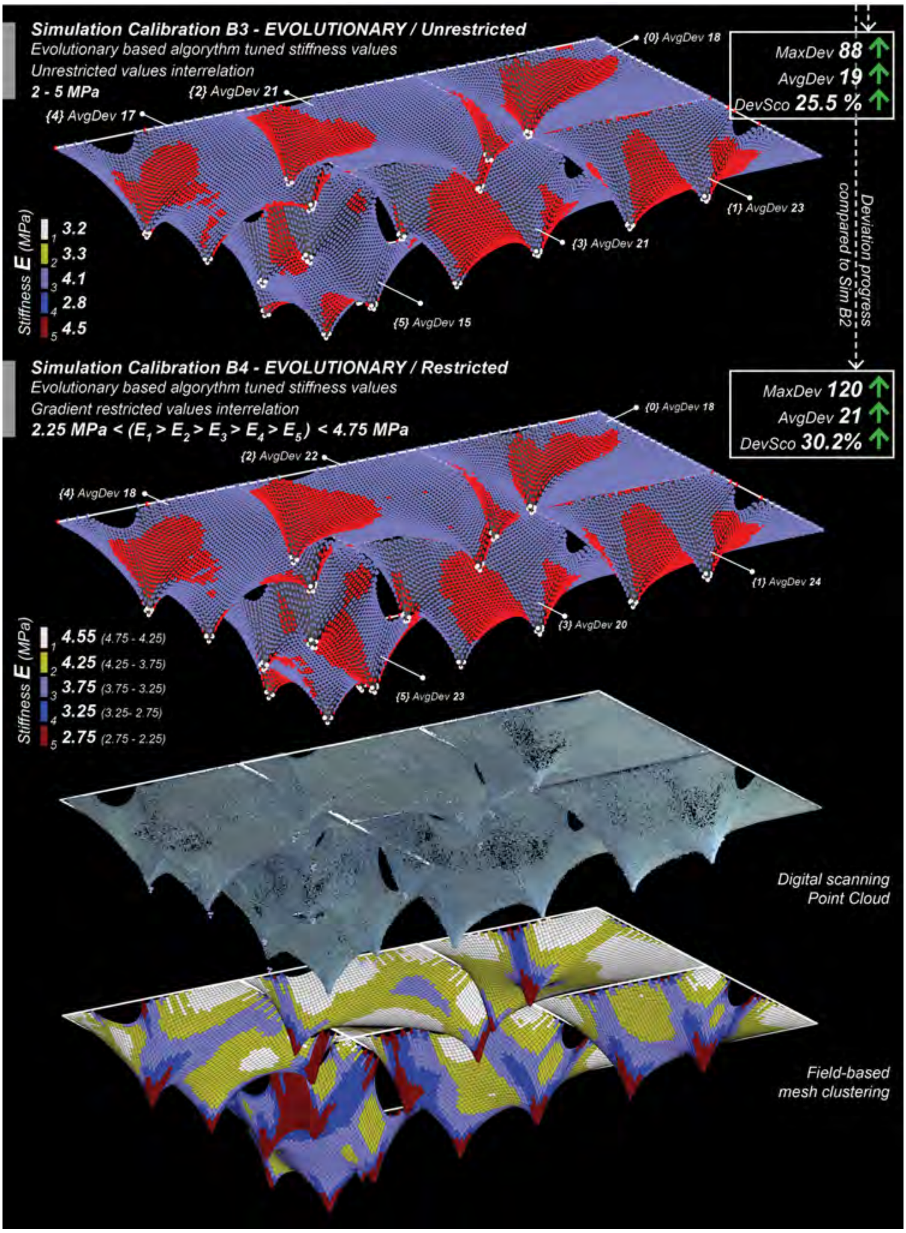

FIGURE 4. Simulation B3 and B4

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, a further optimization exercise of Simulation C2 is conducted with restricting condition to keep proposed stiffness values in

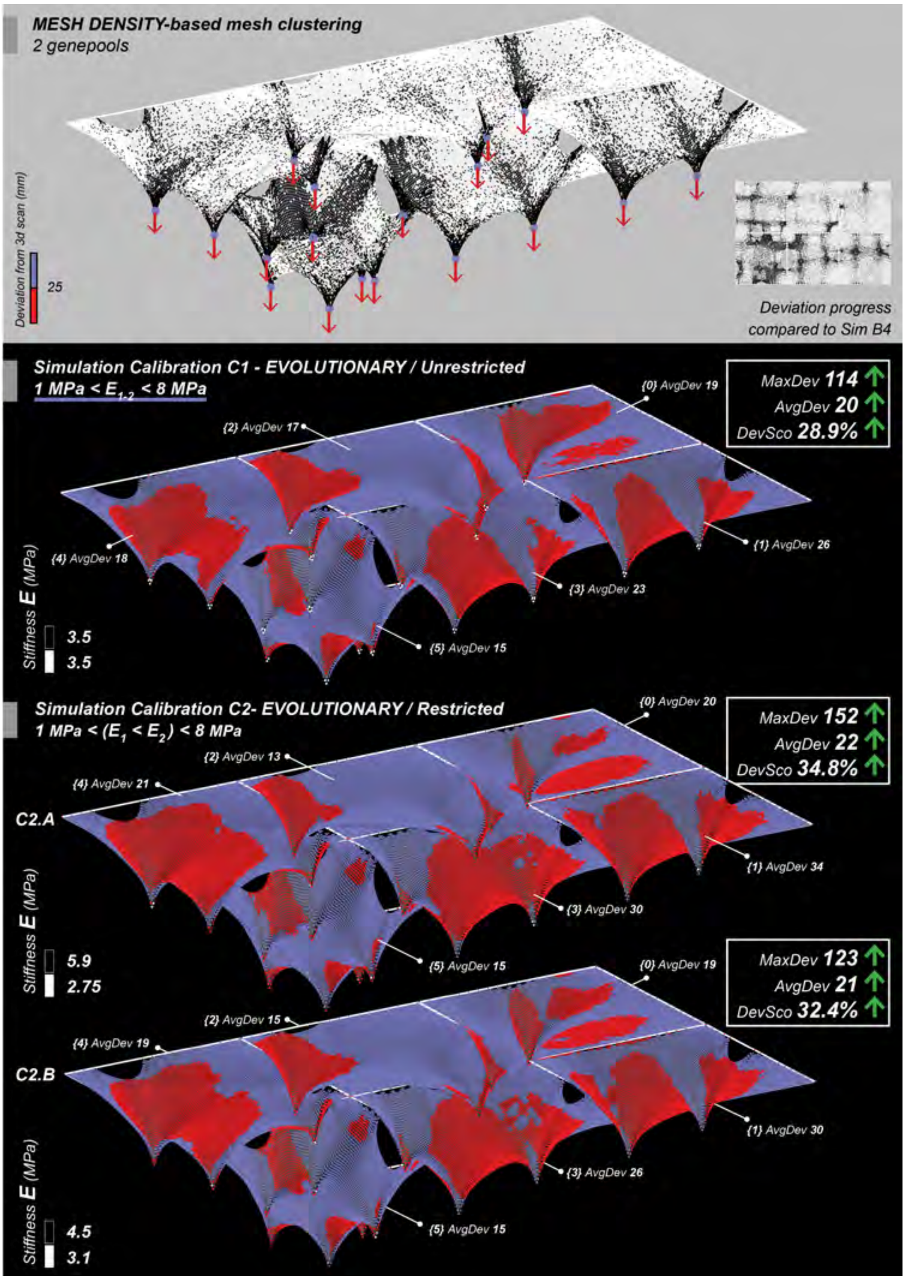

FIGURE 5. Simulation C1, C2.A, C2.B

relation of tight stitches being assigned a higher stiffness value, while loose ones - lower. Two sets of values are proposed by the algorithm, and both are tested across all the panels. In Simulation C2.A, proposed stiffness values of 2.75 MPa (loose) - 5.9 MPa (tight) result in 22mm of average deviation, 34.8% deviation score, and 152mm of maximum deviation (Fig.5, middle). For SimC2.B, 3.1 MPa (loose) and 4.5MPa (tight) proposed values resulted in slightly better results of reduced average deviation 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 gene pools to optimize stiffness values for each zone, while the mesh density-based approach uses two gene pools 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 (1200 x 1200mm) 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 summarized in Table 1 in Figure 6.

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 algorithm 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 homogeneous stiffness value across mesh areas, indicating that these can bring mesh closer to the digital scan, however conceptually questionable. While evolutionary algorithms offer great potential for design and simulation optimization tasks, they also come with several challenges that need to be addressed 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, the 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 optimization criteria are necessary 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 crucial for guiding the evolutionary search toward 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 the 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.

	Field-based mesh clustering					**Mesh-density** based clustering		
	Prelim.	Simulation calibration						
Value search	Arbitrary	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%

FIGURE 6. Summary of the calibration activities and results

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 architectural membranes. Exploring the finetuning of the operational threshold for discrepancies visualization could be a productive avenue for future studies. Rather than simply dualizing areas into satisfactory and dissatisfactory, a more nuanced approach to visualizing deviations could offer greater insights. This approach could involve subdividing the areas based on varying degrees of deviation, allowing for a more detailed analysis of discrepancies and aiding in the development of alternative methods to minimize them. However, careful consideration and adjustment of the threshold range would be necessary to ensure the effectiveness of this approach in evaluating and improving simulation results. Furthermore, establishing a better correspondence of differentiated properties of the physical mesh with the digital representation is crucial.

This could be achieved by implementing special markers that can be tracked by laser digital scanning, ensuring alignment between the digital mesh clustering and its physical counterpart. By accurately capturing the variations in material properties, this approach would enhance the fidelity of the simulation and improve its predictive capabilities.

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Chapter V

CONCLUSIONS

CHAPTER OVERVIEW

Chapter 5: Conclusions synthesizes the research findings, addressing the key research questions and contributions of this Phd thesis. The chapter is structured into five sections, each systematically analyzing the implications of the study on CNC-knitted membranes for architectural applications. It consolidates the methodological and theoretical advancements developed throughout the research, positioning them within the broader discourse of material innovation, simulation-driven design, and digital fabrication.

The opening section, **Reinstatement of Context and Research Aims**, revisits the central motivations and objectives of the thesis. It underscores the shift from standardized materials toward differentiated, functionally graded CNC-knitted membranes, advocating for an integrated approach that aligns material specification with target structural performance. The section situates the research within the broader field of lightweight architecture, articulating how simulation and digital fabrication methods facilitate material differentiation for architectural applications.

The second section, **Contributions**, presents the core research advancements, categorized into primary and complementary contributions. The primary contributions are framed within three research tracks — Design, Fabrication, and Evaluation — each corresponding to a computational model developed in the thesis. These contributions define structured workflows for designing, fabricating, and validating CNC-knitted membranes, emphasizing simulation-driven material differentiation and calibration methods. The complementary contributions extend the research beyond its immediate application, positioning CNC-knitted membranes within the discourse on functionally graded materials, sustainable fabrication, and computational workflows for digital manufacturing.

The third section, **Answering the Research Questions**, explicitly responds to the research inquiries posed at the outset of the thesis. It provides systematic answers based on the findings across the research tracks, confirming that CNC-knitted membranes can be differentiated to meet performance targets, that computational models bridge the design-to-fabrication domain shifts, and that deviations between digital models and physical artefacts can be identified and addressed through computational validation methods.

The fourth section, **Limitations**, critically reflects on the constraints encountered in the research. It discusses the computational complexity of parametric workflows, challenges in simulation precision, the scalability of CNC-knitted membrane fabrication, and the need for further refinement in validation methodologies. Additionally, it highlights the environmental considerations associated with the reliance on synthetic yarns, advocating for future exploration of sustainable material alternatives.

The concluding section, **Perspectives and Future Outlook**, outlines the potential trajectories for expanding this research. It identifies opportunities for further integration of computational design methods, hybrid simulation approaches, and machine learning-driven material differentiation strategies. It also proposes directions for enhancing digital-to-physical translation processes, refining calibration techniques, and extending the applications of CNC-knitted membranes beyond tensile structures to adaptive facades and lightweight enclosures.

Together, these sections establish the broader impact of the thesis, demonstrating how CNC-knitted membranes contribute to material efficiency, structural adaptability, and the advancement of digital fabrication methodologies in architectural design.

5.1 RESTATEMENT OF CONTEXT & RESEARCH AIMS

This thesis situates itself within the broader discourse on the environmental impact of architectural materials, highlighting the potential of shifting from standardized, homogeneous materials to a paradigm where form-matter relations drive material innovation. By fostering a dialogue between material composition and overall structural performance, this research aims to develop architectural materials that are specifically tailored for their intended functions and behaviours. This approach ensures that materials not only achieve their target shape efficiently but also optimize resource use through additive manufacturing techniques.

Rooted in the domain of lightweight architecture, this thesis focuses on tensile architectural membranes — a field closely aligned with the author's background and expertise. The **aim** of the thesis is to introduce differentiated CNC-knitted membranes as a novel class of functionally graded architectural materials, that engage in form-matter relations through their inherent differentiation, programmable material capabilities, and scalability enabled by additive industrial manufacturing. Differentiated CNC-knitted membranes offer a sustainable and design-versatile alternative to standardized sheet materials, which are conventionally used in membrane architecture.

A central objective of this thesis is to investigate the transformative strain properties of knitted materials by establishing a direct link between localized material specifications and the global performance of membranes. This is achieved through a hybrid methodology that integrates research by simulation and research by design. The combined experimental approach, encompassing the development of computational digital models and rapid digital prototyping on industrial knitting machines, has led to advancements in achieving the stated aims of the PhD project.

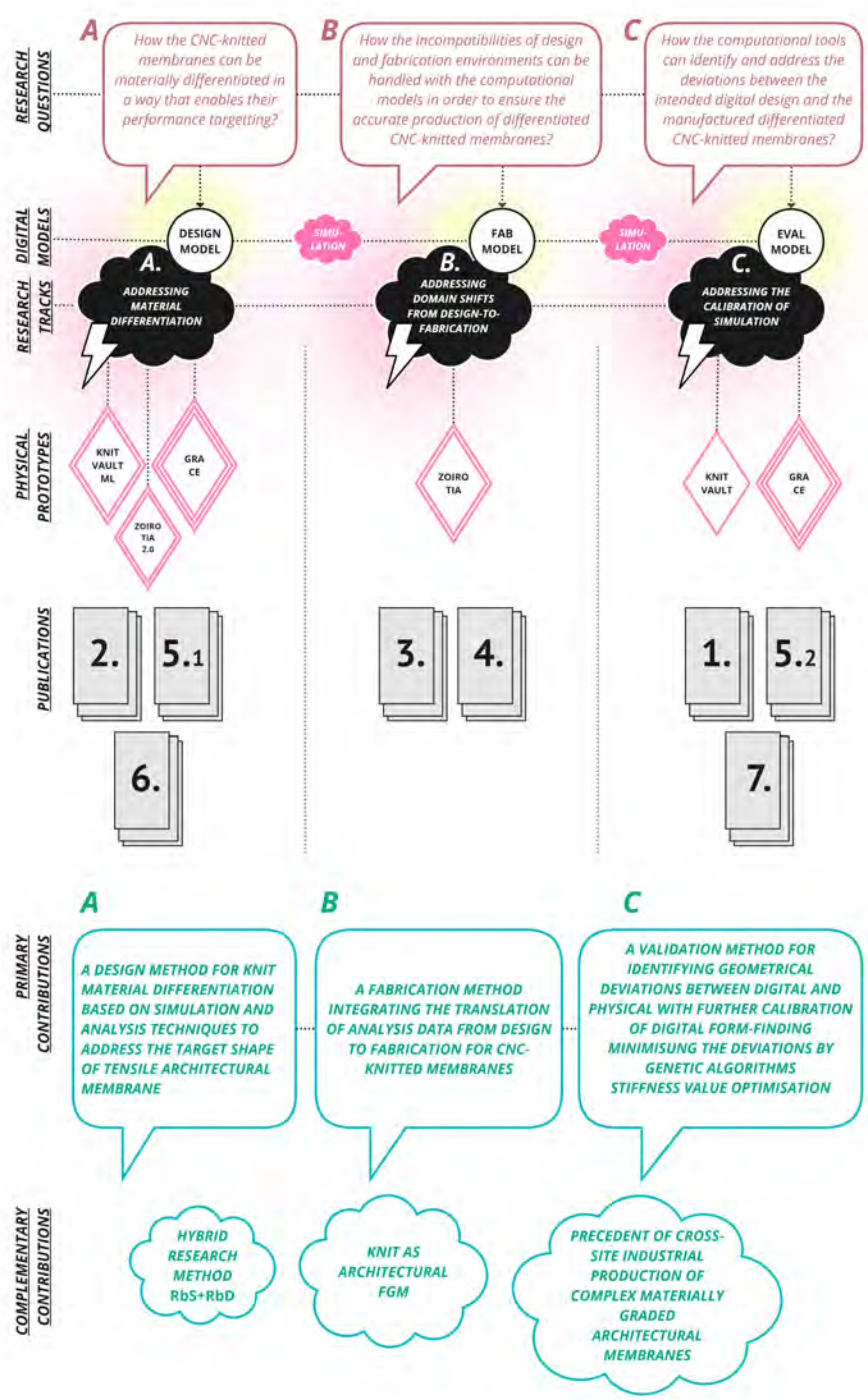
By integrating simulation-driven design and digital fabrication methodologies, this research constructs a comprehensive framework to address three key challenges: material prediction through simulation and material specification for CNC-fabrication processes. This inquiry is anchored in **three research questions**:

A How the CNC-knitted membranes can be materially differentiated in a way that enables their performance targetting?

B How the incompatibilities of design and fabrication environments can be handled with the computational models in order to ensure the accurate production of differentiated CNC-knitted membranes?

C How the computational tools can identify and address the deviations between the intended digital design and the manufactured differentiated CNC-knitted membranes?

These questions form the foundation of the thesis and are systematically explored through its fundamental contributions. The following sections elaborate on the research findings and provide answers to these critical inquiries.



F 5.1: Diagram, visualising PhD thesis research questions, digital models, research tracks, publications and thesis contributions.

5.2 CONTRIBUTIONS

This thesis contributes to the growing body of research on CNC-knitted membranes at an architectural scale, advancing both design and fabrication methodologies.

The contributions are categorized into **primary** contributions, which directly stem from the experimental work addressing the research questions, and **complementary** contributions, which emerged through the broader implications of the research, extending its impact beyond design-to-fabrication methodologies to theoretical contributions, emerged during the writing of this dissertation and tangible outcomes, as the results of methodological applications **F**5.1.

5.2.1 PRIMARY CONTRIBUTIONS

The primary contributions of this thesis are *methodological*, providing structured approaches for designing, fabricating, and validating materially graded CNC-knitted membranes at an architectural scale, and are structured according to three research tracks, each corresponding to a *research question* and a *digital model* developed within this thesis. These tracks — design, fabrication, and evaluation — provide a systematic framework for advancing the state of the art in CNC-knitted membrane development.

This research demonstrates that simulation can serve as an active design tool rather than merely a post-validation instrument. Through simulation-driven exploration, novel knit material gradings have been developed, which would have been impossible to discover through physical experimentation alone.

Drawing inspiration from both scientific and engineering disciplines, this thesis introduces a **hybrid methodology** of Research-by-Simulation & Design (RbS+RbD) that integrates simulation and experimental fabrication into a dynamic feedback loop. This iterative process allows for continuous refinement between digital and physical entities, establishing an **expanded digital design chain for CNC-knitted membranes**.

The thesis formalizes a workflow that interconnects design, simulation, fabrication, and evaluation models, facilitating a cohesive pipeline for the development of differentiated knitted materials for architecture. This methodology enhances topological membrane design, local material differentiation, and form-finding tailored for CNC-fabrication, ensuring accurate production of textile artefacts informed by simulation. Below the three core contributions, each related to the development of digital models, is reviewed in detail.

CONTRIBUTION A

A DESIGN METHOD FOR KNIT MATERIAL DIFFERENTIATION BASED ON SIMULATION AND ANALYSIS TECHNIQUES TO ADDRESS THE TARGET SHAPE OF TENSILE ARCHITECTURAL MEMBRANE

This contribution introduces a simulation-based framework that establishes a direct link between local material properties and the global structural behavior of CNC-knitted membranes. By integrating form-finding techniques with structural analysis, the **Design Model** enables precise material differentiation tailored to specific performance requirements, including targeted three-dimensional shapes. It opens up new design opportunities for the application of knits in tensile membrane architecture through waste-free manufacturing, achieving volumetric configurations, possible only with the locally graded material differentiation.

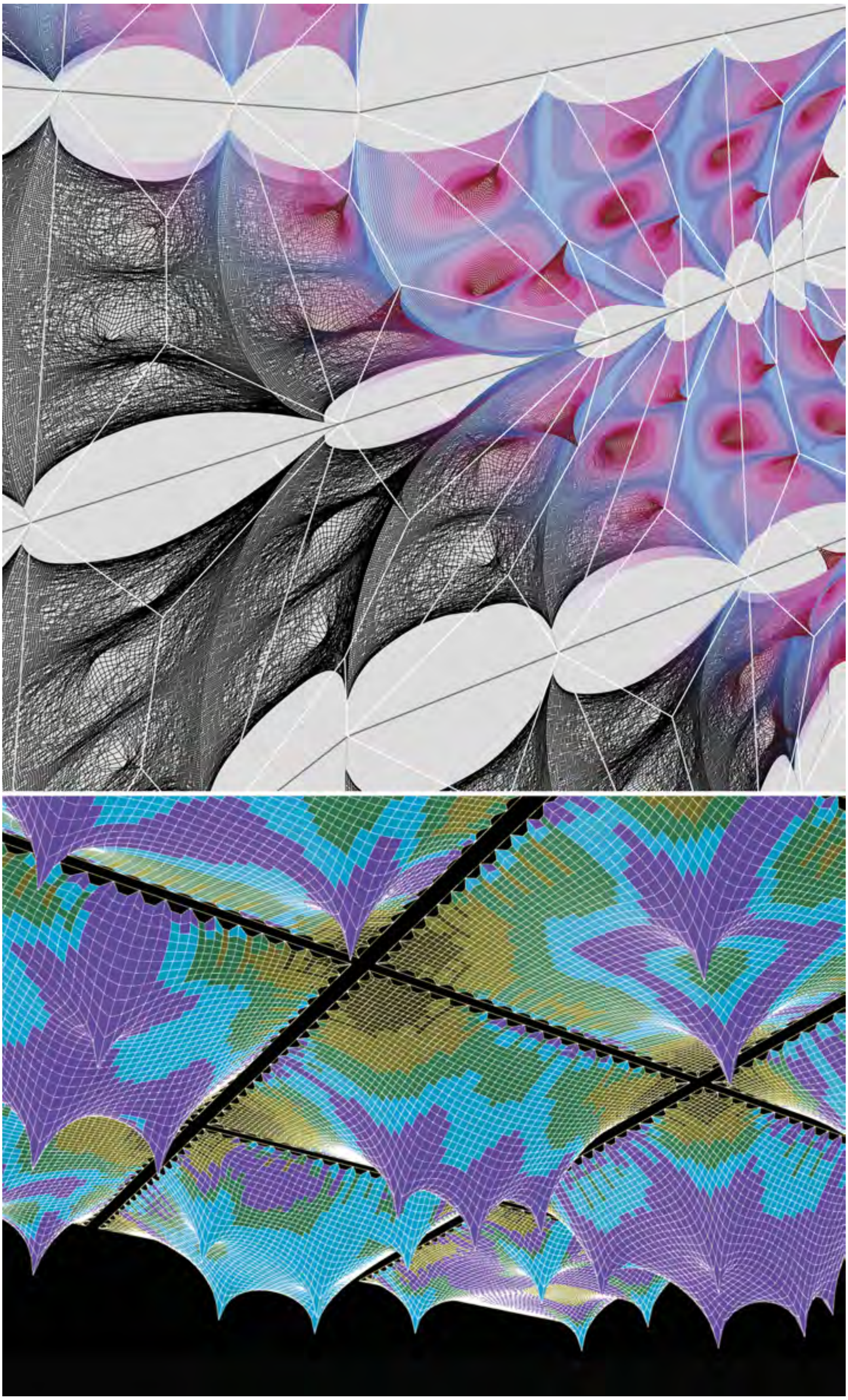
QUICK TOPOLOGICAL EXPLORATION The Design Model bridges global membrane behavior with localized material differentiation, employing advanced simulations to optimize structural and aesthetic outcomes. Its concept sub-model, a preliminary scheme for design criteria, through its simplistic abstract depiction allows for rapid adjustments, enabling quick design iterations, by modifying the membrane typology, whether by redefining the membrane boundary or repositioning hybrid integrated elements, quickly visualised by form-finding solver. For greater detail read on p.133

MATERIAL DIFFERENTIATION THROUGH ANALYTICAL TOOLS Utilizing geometric and structural analysis, the model enables localized adjustments in material properties, ensuring complex three-dimensional forms that respond dynamically to external forces. The rationale for developing both approaches lies in the complementary insights they offer: geometrical analysis focuses on external changes, such as how the membrane deforms and stretches during its pre-stress during the installation, while the structural analysis examines the internal response of material to applied forces. Together, these approaches provide a holistic understanding of the membrane's behavior, encompassing both structural, visual and installation aspects. Refer to p.141.

NOVEL STRUCTURAL LOADING CONDITIONS The grading of knitted surface, using structural analysis permitted to redirect the material density in a way that would allow to introduce unconventional for membrane design angular loading vectors. In this thesis read on p.145

INVERTED STIFFNESS DIFFERENTIATION APPROACH This thesis engages in material differentiation strategy, opposed to conventional grading focused on material redundancy and strategic local *reinforcement* for resisting the forces. Instead the thesis offers a novel approach, that embrace the material dynamics and deformation as design tools, where the material is graded locally to respond *dynamically*, transforming under the load in a controlled manner using strain properties of knit. This thesis, adopt the unravel double jacquard knitting stitch for active management of membrane three-dimensionality. This is achieved through *inverted stiffness strategy*, where areas of the membrane experiencing the highest force concentrations are assigned the lowest stiffness values. This approach leads to greater strain in the mesh under applied loads, creating a structural membrane system where the differentiated surface yields more readily to forces. As a result, the membrane undergoes greater expansion and stretching, ultimately achieving a higher degree of three-dimensionality — a characteristic, identified as advantageous for the structural performance of tensile membranes. Refer to p. 68

By integrating these analytical tools, this contribution refines the understanding of CNC-knitted tensile membranes, enhancing their ability to meet both performance-driven and aesthetic objectives. The findings related to this contribution are technically described in *articles 2, 5.1, and 6*, forming the foundation for *Research Track A*.



F 5.2: Design Model demonstrating the novel material gradings for CNC-knitted membranes

CONTRIBUTION B

A FABRICATION METHOD, INTEGRATING ANALYSIS DATA FROM SIMULATION FOR PRECISE MANUFACTURING OF DIFFERENTIATED CNC-KNITTED MEMBRANES

This contribution presents a **design-to-fabrication workflow** developed through the **Fabrication Model**, specifically tailored for CNC-knitted membranes graded for their target shape performance. It bridges the fundamental differences between *digital design* — which operates in 3D, uses metric measurements, and often runs at lower resolutions — and *knitting industrial manufacturing*, which operates in 2D, is measured in stitches, and requires high resolution. The Fabrication Model ensures precise translation of digital designs into physical artefacts by integrating simulation-driven differentiation with the constraints of CNC-knitting processes.

FABRICATION PRECISION The Fabrication Model resolves domain shifts — spatial, metric, and resolution — by employing computational processes that translate numerical analytical data from the Design Model into pixel-based representations. This workflow ensures seamless conversion from digital design to machine-readable knitting instructions. Its robustness and flexibility were validated through the successful realization of multiple physical prototypes, including one of extensive scale (Zoirotia) and complexity, demonstrating precise execution guided by the workflow.

GRAPHICS TECHNIQUES FOR KNIT GRADING By employing *data interpolation* and *dithering* techniques, the workflow effectively converts numerical data into graphical representations, addressing the binary constraints of knitting production. This enables nuanced material differentiation, enhancing both aesthetic expression and functional performance. Refer to p.203

APPLICATION OF TECHNICAL YARNS FOR ARCHITECTURE This PhD contributes to research, pioneering the application of high-tenacity yarns such as *Dyneema®* and *Serafil*, known for their exceptional tensile strength but previously unexplored at an architectural scale. Their integration ensures surface integrity, minimizes breakage during fabrication and installation, and opens new possibilities for large-scale architectural applications. Their successful implementation highlights previously uncharted opportunities for utilizing technical yarns in architectural contexts. Mentioned at p.115 and 117.

This contribution directly addresses *Research Question B* and is realized within *Research Track B*, and technically described in *articles 3 and 4*.

CONTRIBUTION C

A VALIDATION METHOD FOR IDENTIFYING AND CALIBRATING GEOMETRICAL DEVIATIONS IN CNC-KNITTED MEMBRANES USING EVOLUTIONARY ALGORITHM

This contribution establishes a validation workflow developed through the **Evaluation Model**, ensuring that deviations between digitally designed and physically fabricated CNC-knitted membranes are systematically analyzed and minimized. The

F 5.3: Fabrication Model permitted to realise the complex and large Zoirotia installation. Photo: A.Ingvartsen

Evaluation Model performs two critical functions: benchmarking deviations and calibrating the digital simulation to improve predictive accuracy. By incorporating feedback loops informed by physical testing, the Evaluation Model enhances the robustness of digital simulations, increasing their reliability in predicting real-world performance.

BENCHMARKING FOR DEVIATION MAPPING The Evaluation Model systematically compares the physical prototypes with their digital counterparts by converting laser-scanned point cloud data into mesh representations, facilitating topological deviation analysis. Benchmarking provides visual clarity and quantifiable deviation analysis, making it a powerful tool for both validation and design iteration. The colour-mapped deviation analysis offers a clear, intuitive way to see where and how the physical membrane diverges from the digital simulation. This allows to quickly assess problematic regions rather than relying solely on numerical deviation values. In this thesis read on p.248.

CALIBRATION THROUGH GENETIC ALGORITHMS The evolutionary optimization algorithm employed in this workflow offers a highly effective means of fine-tuning stiffness values in CNC-knitted membranes by systematically refining digital models to match real-world behavior. This approach searches the solution space dynamically, allowing for adaptive stiffness calibration based on actual material differentiation, represented by physical prototype. By establishing focused search criteria, tailored to graded properties of knits, the algorithm optimizes stiffness assignments in response to membrane strain performance, ensuring that simulation outputs reflect the true mechanical behavior of CNC-knitted structures. This method significantly reduces the discrepancies between simulated and fabricated membranes, providing a scalable, adaptable, and experimentally validated framework for calibrating heterogeneous material systems. Refer to p.250.

DUAL MESHING APPROACH The calibration workflow integrates two complementary meshing strategies — binary and field-based mesh clustering — to optimize the representation of differentiated CNC-knitted membranes. These approaches offer distinct yet synergistic methodologies for aligning digital models with the locally defined material properties of knitted structures. The *field-based* approach organizes the mesh according to material density gradients, ensuring smooth transitions in stiffness across the membrane's surface, while the *binary* approach maps the inherent duality of stitch types, providing a precise structural differentiation. Beyond improving simulation accuracy, this dual strategy enhances the realism of digital renders, allowing more faithful representation of material transitions and surface behavior. In this thesis read on p.253.

HYBRID CALIBRATION This research introduces a hybrid calibration method that systematically links material stiffness to density, significantly improving the accuracy of digital simulations for CNC-knitted membranes. By fabricating three reference membranes representing the full spectrum of knit material properties — minimum, medium, and maximum density — this method provides empirical stiffness values at key points within the material system. These values serve as anchor points for constructing a stiffness-density curve, enabling a structured interpolation of intermediate material properties. The strength of this approach lies in its efficiency: integrating rapid prototyping with form-finding calibration, it minimizes computational overhead while maximizing predictive precision. The force-into technique ensures that calibration is achieved with minimal input data, making the method adaptable to diverse material configurations. This hybrid approach effectively bridges the gap between digital modelling and physical testing, offering a scalable, reproducible, and experimentally validated framework for refining material behaviours in CNC-knitted membranes. In this thesis read on p.251

By integrating this validation methodology into the broader design-to-fabrication workflow, the thesis establishes a design-to-fabrication-to-evaluation digital chain, offering a structured platform for iterative refinement and further exploration of CNC-knitted membrane architectures. This contribution directly addresses Research Question C and is realized within *Research Track C*, and technically detailed in articles 1, 5.2, and 7.

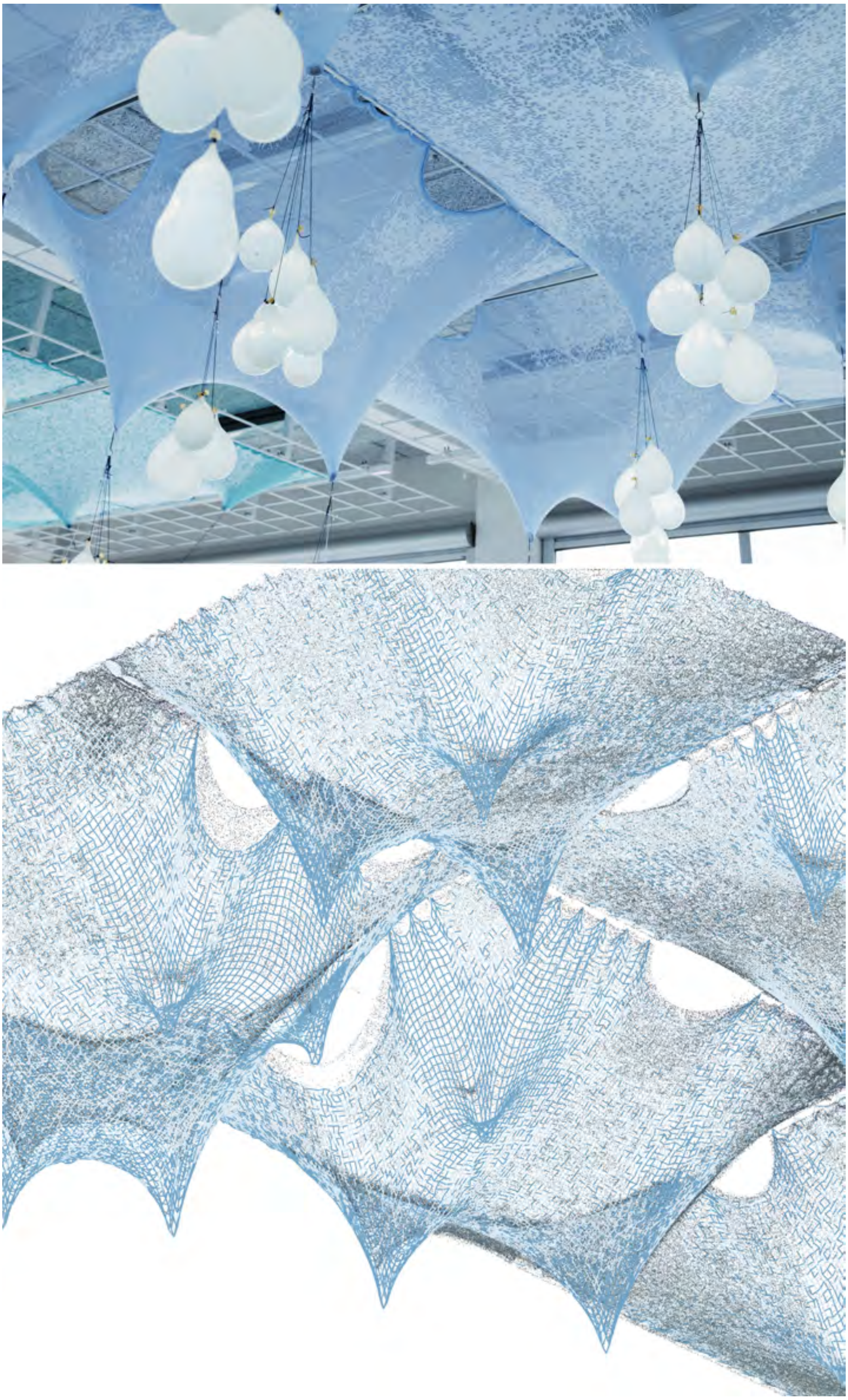
5.2.2 COMPLEMENTARY CONTRIBUTIONS

Building upon the primary contributions, which establish the methodological and computational advancements of this research, the complementary contributions extend the impact of the thesis by situating its findings within broader discourses. These contributions reflect both theoretical advancements — arising from the scholarly discourse during writing his dissertation and experimental work conducted during this research — and practical outcomes, including large-scale physical prototypes that serve as real-world validations of the developed methodologies.

The complementary contributions of this research reinforce its broader material and technological implications, positioning CNC-knitted membranes within contemporary discussions on functionally graded materials, resource-efficient fabrication, and scalable digital workflows. These contributions extend beyond knit-based systems, offering valuable frameworks and precedents that inform future research and innovation in computational material systems.

KNIT AS ARCHITECTURAL FGM This research positions differentiated CNC-knitted textiles as a novel class of functionally graded materials (kFGMs), broadening the scope of FGM classification beyond conventional composite-based systems, as outlined on p.12. By demonstrating that CNC-knitting allows for localized material differentiation, this thesis argues that knitted membranes should be considered within the larger material science framework of graded material systems, offering an alternative to traditional laminated or composite tensile structures. This shift opens up new possibilities for adaptive and performance-driven material applications in architecture.

CROSS-SITE PRODUCTION OF A LARGE-SCALE CNC-KNITTED MEMBRANE STRUCTURE The computational tools, developed in this thesis led to realisation of Zoirotia, the largest to date and highly customized form-active membrane structure made with graded knit. Due to its scale and limited time-frame of the project, production was distributed across three different manufacturing sites — two commercial knitting companies and an in-house research knitting lab. The manufacturing data was swiftly adapted to accommodate the fabrication constraints of each production partner, ensuring consistency in outcomes despite variations in machine gauge (needle density) and operational width. The ability to execute the production of complex materially graded membranes across a distributed and diverse manufacturing setup was made possible by the flexibility of the Fabrication Model, facilitating the successful completion of this large-scale project within an



F 5.4: Contribution of the Evaluation Model through the method of benchmarking and simulation calibration ambitious five-month timeline.

The Zoirotia prototype, consisting of 88 custom-knit units spanning 568m² of surface area, demonstrates the scalability, structural integrity, and material differentiation achievable through CNC-knitting in real-world applications. The unprecedented scale and complexity of both material and production management validate the computational and fabrication methodologies developed in this thesis, underscoring their applicability to tensile structures, adaptive facades, and lightweight canopies. Additionally, the GraCe prototype contributes to the expanding body of realized large-scale CNC-knitted structures, further reinforcing how simulation-driven workflows enable precise material differentiation. GraCe's sophisticated surface patterning, directly informed by the Design-to-Fabrication workflow, exemplifies this thesis' contribution to both the technical and aesthetic possibilities of CNC-knitted membranes in architectural applications.

5.3 ANSWERING THE RESEARCH QUESTIONS

With the primary and complementary contributions outlined above, the research questions posed at the outset of this thesis can now be explicitly answered. The overarching inquiry — **How can we design, fabricate and predict the behavior of the materially graded CNC-knitted membranes, based on their target performance?** — has been systematically explored through the three research tracks, each tackling a distinct phase of the design-to-fabrication-to-evaluation workflow.The answers to these sub-questions are inherently embedded in the contributions developed throughout this research and are consolidated in the summary by answering each of the research questions.

A How the CNC-knitted membranes can be materially differentiated in a way that enables their performance targetting?

This PhD research confirms that CNC-knitted membranes can be precisely differentiated to meet performance-driven targets. Research Track A addressed this through the development of a Design Model that integrates form-finding, simulation, and material differentiation strategies. By embedding analytical tools into the workflow, this model enables localized control over material stiffness, density, and geometric response, ensuring that the membrane's structural and aesthetic properties are optimized for specific performance criteria. This contribution demonstrates that differentiated CNC-knitted membranes can be computationally designed and fabricated to achieve tailored structural and material behavior — an advancement that was previously unattainable through manual design approaches alone.

B How the incompatibilities of design and fabrication environments can be handled with the computational models in order to ensure the accurate production of differentiated CNC-knitted membranes?

This PhD research confirms that design and fabrication environments can be successfully linked by computational models, facilitation the data transfer. Research Track B developed a Fabrication Model that successfully resolves spatial, metric, and resolution mismatches between digital design and CNC-knitting production. This was achieved by integrating data translation methods that convert 3D form-finding outputs into 2D machine-readable knitting instructions, maintaining the material differentiation and design intent throughout the fabrication process. The model was tested on large-scale architectural applications, such as Zoirotia and the GraCe ceiling installation, both demonstrating the scalability and adaptability of the developed workflow. Additionally, the workflow facilitated continuous prototyping, allowing for iterative testing and refinement, proving its robustness in real-world applications.

C How the computational tools can identify and address the deviations between the intended digital design and the manufactured differentiated CNC-knitted membranes?

This PhD research confirms that the deviations between the digital design and physical artefacts can be identified by computational tools of benchmarking and calibration. Research Track C, featuring the Evaluation Model, which through its sub-models, systematically benchmarks, analyses, and corrects the deviations between digital simulations and fabricated prototypes by employing the power of evolutionary optimisation. Through this iterative feedback loop, the Evaluation Model refines predictive accuracy, reducing deviation errors and strengthening the link between computational modelling and physical realization. The integration of hybrid calibration, which derives stiffness-density relationships from 1:1 scale prototypes, provides an empirical foundation for stiffness assignment, making this method reproducible and scalable for future CNC-knitted structures.

5.4 LIMITATIONS

While this thesis presents significant advancements in the design, fabrication, and evaluation of differentiated CNC-knitted membranes, several limitations emerge from the complexity of the workflows, computational constraints, and material considerations. These limitations are structured around the three core research tracks — design, fabrication, and evaluation — aligning with the developed Design, Fabrication, and Evaluation Models.

5.4.1 LIMITATIONS OF THE DESIGN MODEL

The Design Model developed in this thesis introduces computational strategies for designing, simulating, and defining the material gradings of CNC-knitted membranes. However, its applicability is shaped by several constraints, including the complexity of parametric workflows, the precision of form-finding simulations, and the limitations of data-driven approach such as machine learning. These factors influence the accuracy, efficiency of the design process, highlighting areas where alternative methodologies or further refinements could enhance the reliability and scalability of the proposed framework. The following points outline key limitations within the Research track A.

COMPLEXITY OF PARAMETRIC WORKFLOWS The parametric and simulation-driven approaches introduced in this thesis demand considerable expertise, computational power, and efficient data management across the digital design chain. While the Grasshopper environment provides flexibility for prototyping workflows, it is heavily reliant on multiple plug-ins. Dependencies on third-party tools introduce instability, as incompatibilities, version mismatches, and plug-in deprecations with time can disrupt workflow continuity. This limits accessibility for practitioners who may not have advanced computational design skills.

QUESTION OF FORM-FINDING SIMULATION PRECISION Despite extensive calibration efforts, achieving exact simulation precision remains a challenge. The quad-based meshing approach used in the Design Model simplifies the membrane's representation but introduces geometric approximations that may not fully capture the non-linear elastic behavior of knitted fabrics. Additional neglection of warp-weft direction distinction in the last calibration exercises can also explain the imprecision. The observed deviations between digital and physical models suggest that an alternative higher-resolution mesh strategy or the integration of more distinct non-linear material properties (e.g. warp-weft distinction in digital mesh) could enhance simulation accuracy. However, the complexity of knitted material behavior, particularly its response to variable strain conditions, remains difficult to fully encode within conventional simulation frameworks of using particle spring based method on meshes.

This thesis primarily employs particle-based physics solvers for form-finding, integrated into Kangaroo2 and K2Engineering, which require a lot of computational power when scaling up the simulated structures. However, alternative methods such as graphic statics projection-based methods, that rely on reciprocal relationships between force-form diagrams could offer alternative paradigms for simulating knitted structures and for controlling structural performance and material distribution with lower computational costs. These unexplored avenues may yield different, potentially more precise and faster form-finding solutions for predicting knitted tensile membrane behavior, accomplished in quicker computational processes than particle spring based form-finding.

MACHINE LEARNING LIMITATIONS IN PREDICTING KNITTING PATTERNS The thesis briefly explores the application of machine learning (ML) for predicting knitting patterns based on membrane target strain behavior, as seen in the KnitVault ML experiment F4.16 on p.150. However, this approach faced several limitations that impacted its reliability and applicability. The approach aimed to establish a direct relationship between knit surface patterns and their corresponding strain performance, using a dataset of nine physical prototypes for training. The ML model was trained on a limited dataset, meaning its ability to generalize and predict new patterns beyond the input set was inherently restricted. The dataset primarily consisted of manually designed pattern proposals, which, while guided by structural intuition, were not systematically verified against geometric form-finding methodologies. The ML-generated patterns resembled circle-like formations, which were likely influenced by the biases in the training data rather than a true structural response to material behavior. Since the training process relied on predefined manually designed input rather than computationally optimized patterns, the model's outcomes were more heuristic than structurally driven, limiting its predictive accuracy. The ML model struggled to distinguish between subtle variations in stitch types, particularly between piquet and piquet lacoste. This resulted in less pronounced material differentiation and deviations in membrane depth. As a result , the inability to establish a clear distinction between strain differences in fabric structures reduced the model's predictive fidelity.

These limitations highlight the current constraints of using ML in architectural material differentiation, particularly when dealing with complex, heterogeneous material properties like differentiated CNC-knitted membranes. While ML demonstrated potential as an exploratory tool, its ability to replace traditional simulation and analysis-driven workflows remains limited due to dataset biases, and challenges in ensuring structural accuracy.

LACK OF QUANTITATIVE PERFORMANCE ASSESSMENT OF GRADING STRATEGIES The lack of quantitative comparisons between structural and geometric differentiation techniques in this research highlights an area where physical testing and systematic performance validation could provide more concrete insights into the functionality of each surface grading strategy.While this thesis does not quantitatively compare differences in membrane performances based on these analytical techniques, it rather presents a methodological exploration of potential material gradings and their technical feasibility for fabrication.

5.4.2 LIMITATIONS OF THE FABRICATION MODEL

The Fabrication Model developed in this thesis bridges the gap between design intent and material realization, enabling the production of CNC-knitted membranes with differentiated properties. However, several constraints shape its effectiveness, including the transformations introduced in the process of translating analysis data into knitting patterns, material limitations linked to yarn selection, and challenges in scaling up for large-scale applications. These factors influence the precision, sustainability, and industrial feasibility of the proposed fabrication workflow, indicating areas where further refinements or alternative approaches could enhance its robustness. The following points outline key limitations within Research Track B.

FROM ANALYSIS DATA TO MATERIAL DENSITY While the Fabrication Model successfully overcomes design-to-fabrication domain shifts, it introduces certain transformations in the process. The dithering technique, used to translate analysis data into knitting patterns, introduces an additional layer of interpretation where thresholding, spatial clustering, and resolution upscaling decisions cumulatively affect the final pattern fidelity. While these transformations enable gradient-based material differentiation, a more systematic method for tracking these deviations could further enhance precision.

YARN CHOICES The reliance on synthetic yarns — particularly Dyneema® and Serafil — enables controlled fabrication processes but raises sustainability concerns. These high-tenacity plastics require substantial energy to produce and are not biodegradable, posing long-term environmental challenges. While the thesis explores recycled polymer alternatives, a more thorough investigation into bio-based, biodegradable, or circular textile solutions is needed. However, such materials would introduce additional uncertainties in knit elongation, tear resistance, and durability, requiring adaptations to the design-to-fabrication workflow developed in this research.

F 5.5: 100% Hemp CNC-knitted samples for RAW research project at CITA 2024, where natural based fibers are investigated for their efficient application in architectural applications. Author of this thesis continues her work with knit in this project. Photo: *Y.Sinke*

SCALABILITY FOR LARGE-SCALE ARCHITECTURAL APPLICATIONS Although the Fabrication Model was successfully applied to large-scale demonstrators like Zoirotia (568m² surface area), challenges of integration into industrial workflows persist. The computational intensity of handling extensive high-resolution knitting files can create bottlenecks in processing and production workflows. While this thesis proposes an efficient data reduction method, further optimizations in file generation, pattern compression, and data structuring are required for broader industrial adoption.

5.4.3 LIMITATIONS OF THE EVALUATION MODEL

The Evaluation Model in this thesis establishes a framework for comparing digital simulations with physical prototypes, providing insights into material behavior and calibration accuracy. However, its effectiveness is influenced by several constraints, including the omission of warp-weft directional distinctions in final calibration exercises, the specificity of the force-into calibration method, and the challenges associated with deviation mapping and benchmarking. These factors affect the precision, generalizability, and automation potential of the evaluation process, highlighting areas where methodological advancements could improve reliability and applicability. The following points outline key limitations within Research Track C.

WARP-WEFT DIRECTION NEGLECTION IN FINAL CALIBRATION EXERCISES Despite recognizing the importance of warp and weft directional behavior in earlier calibration exercises, this distinction was not accounted for in the final calibration of GraCe. As the complexity of surface differentiation increased and the scale of the structure expanded, the calibration process prioritized achieving preliminary stiffness values over maintaining directional material distinctions. While this approach facilitated a first-round validation of the hybrid calibration method, it introduces a limitation in precision, as knitted membranes exhibit anisotropic behavior that varies significantly along different thread orientations.

AMBIGUITIES IN "FORCE-INTO" CALIBRATION The force-into calibration method used for stiffness value discovery has proven effective but remains non-universal. The stiffness-density relationship, derived through physical prototypes, is specific to the tested material configurations. While the hybrid calibration method developed in this thesis offers a pragmatic empirical approach, a more rigorous mathematical formulation linking knit density to material stiffness would provide greater generalizability. Additionally, sample testing methods from textile engineering — which are traditionally designed for homogeneous woven fabrics — need adaptation to accommodate the heterogeneous properties of differentiated CNC-knitted membranes.

CHALLENGES IN DEVIATION MAPPING AND BENCHMARKING The Evaluation Model provides a visual benchmarking method by comparing laser-scanned physical prototypes with digital models. While this approach is valuable for qualitative deviation analysis, it lacks an automated deviation correction mechanism. Current deviation mapping requires manual visual interpretation, introducing subjectivity in how tolerances are defined and addressed. The potential integration of machine-learning-based deviation recognition could provide a more automated and scalable approach.

5.5 PERSPECTIVES & FUTURE OUTLOOK

This thesis establishes a methodological framework for the design, fabrication, and validation of differentiated CNC-knitted membranes, yet its findings also open several avenues for future research and technological refinement. While the developed workflows offer significant advancements, further investigations could enhance scalability, expand material options, and refine simulation accuracy. Future research directions are structured around three primary domains — design, fabrication, and simulation calibration — aligning with the thesis' core contributions.

5.5.1 FUTURE DIRECTIONS IN DESIGN OF CNC-KNITTED MEMBRANES

EXPANDING ARCHITECTURAL APPLICATIONS The scalability and adaptability of CNC-knitted membranes suggest broader applications beyond the prototypes explored in this research. While this thesis primarily focused on tensile membranes for spatial enclosures, future investigations could explore adaptive facades, responsive interior partitions, and lightweight outdoor structural components. The integration of computational design engines, such as evolutionary solvers and generative design methods, could further automate and expand the design space exploration, allowing for topological diversity and novel form-finding strategies that go beyond current manually driven approaches of conceptual scheme adjustments within the design model as done in this thesis. More intense design morphology exploration through setting up a generative engine to Concept sub-model that would generate automatically the pre-simulation schematic models, opens a great window of design exploration potential, leading to new topologies for membrane architecture.

NEW SUSTAINABILITY ANGLE FOR MEMBRANE ARCHITECTURE This Phd research opens new avenues for investigating sustainability in tensile membrane architecture by introducing material efficiency through programmable and differentiated CNC-knitted textiles. While existing approaches within membrane architecture primarily emphasize the material selection and recyclability, future studies could systematically evaluate the sustainability impact of this thesis method through Life Cycle Assessment (LCA) analyses. Such evaluations would provide quantifiable insights into waste reduction, design and production efficiencies, membrane structural efficiency, and resource optimization, strengthening the case for CNC-knitted architectural membranes as a commercially viable alternative. By demonstrating a scalable and adaptable fabrication approach, this thesis perspective lays the groundwork for integrating sustainable solutions into the broader membrane industry, offering a pathway toward more efficient and responsible tensile structures, specifically targetting medium scale applications.

HYBRID DIFFERENTIATION METHODS: INTEGRATING STRUCTURAL AND GEOMETRIC ANALYSIS Although this thesis developed grading strategies as parallel approaches, exploring their integration and overlap presents an exciting opportunity for future research. This thesis employed parallel grading strategies, informed by geometric and structural analysis independently. However, future research could investigate integrated hybrid models that combine both approaches, allowing for a more refined and structurally driven differentiation strategy, build on the development for multi-dimensional grading combining colour and structural performance leading to novel more optimised patterns both for pre-stress sequence during installation and the structural performance long-term. This dual approach enables targeted material differentiation, balancing flexibility, strength and surface three-dimensionality. During the membrane's erection process, geometric transformations are especially significant, making geometrical analysis critical at this stage. For long-term performance under sustained loads, however, structural analysis becomes indispensable, ensuring that the design is not only visually compelling but also structurally performing. By integrating both geometrical and structural analyses, the Design Model achieves a balance between form and function. This dual analytical framework supports the membrane's structural integrity while enhancing its ability to perform as a differentiated material system that meets both aesthetic and performance-driven objectives. The interplay between these methods establishes a powerful design workflow that bridges conceptual exploration with practical application.

CONSIDERATION OF OUTDOOR ENVIRONMENTAL FACTORS IN KNITTING PATTERNS The strategies for material grading in architectural knitted membranes developed in this thesis have been primarily designed for indoor applications, focusing on structural differentiation rather than environmental performance. Future research could investigate how outdoor climatic forces—such as wind, rain, UV exposure, and temperature fluctuations—particularly when using yarns based on natural fibers, influence the long-term durability and behavior of differentiated CNC-knitted membranes. This could inform new strategies for local material differentiation, such as grading porosity to channel water flow or adjusting membrane density to mitigate wind loads.

MACHINE LEARNING INTEGRATION Machine learning (ML) presents opportunities to streamline material specification and fabrication processes by combining it with simulation. By automating pattern recognition and optimizing material properties, ML could make workflows more adaptable and efficient. A hybrid approach, combining ML and simulation, could be particularly valuable when traditional simulation methods struggle to predict sophisticated material systems, where the behavior of a system depends on both well-defined mechanical rules (textiles in general) and unknown material interactions (knit fine specification). Future research could explore how trained ML models could complement physics-based solvers, offering potentially a faster and more responsive system for material differentiation and structural optimization.

BEYOND KNITTING - TO OTHER GRADED MATERIAL SYSTEMS While this thesis focuses on CNC-knitting, the methodological advancements developed — particularly in simulation integration, design-to-fabrication workflows, and calibration methodologies — hold potential beyond the textiles. The principles established in this research can be potentially adapted to other additive manufacturing processes, including multi-material 3D printing, where material properties are similarly graded and computationally controlled based on global performance targets. By demonstrating a structured and iterative workflow for heterogeneous materials, this research contributes to broader discussions on computationally controlled material differentiation across architectural and industrial applications.

LIMITED CONSIDERATION OF ENVIRONMENTAL LOADING While this thesis did not integrate external environmental factors—such as wind loads, UV exposure, temperature fluctuations, moisture absorption—or the structure's self-weight into its simulation and evaluation models, these aspects could be incorporated in future refinements of the methods. Such advancements would facilitate the application of CNC-knitted membranes in more permanent structures. Furthermore, the knowledge developed in the *Isoropia* and *Hybrid Tower* projects through bi-axial material testing and FEA analysis, which formed a foundation for this research, could be further expanded and integrated with the enhanced material grading methodology introduced in this thesis. This integration would enable a more sophisticated approach to adaptive material differentiation while accounting for real-world constraints.

5.5.2 FUTURE DIRECTIONS IN FABRICATION OF CNC-KNITTED MEMBRANES

EXPLORATION OF BIO-BASED AND SUSTAINABLE YARNS This research relied on synthetic high-tenacity yarns, such as Dyneema® and Serafil, for controlled fabrication and predictable performance. However, bio-based alternatives could provide more sustainable solutions. Future research could explore biodegradable or circular fiber options, while also addressing the challenges of variable fiber behavior, such as elongation over time, durability, and resistance to environmental degradation. Since bio-based materials exhibit less predictable mechanical properties, developing adaptable fabrication workflows that accommodate these uncertainties would be necessary.

ENHANCING DATA TRANSLATION FROM ANALYSIS TO MATERIAL DENSITY While the dithering technique used in this research effectively translates analysis data into material differentiation patterns, it introduces multiple transformation steps, each adding parametric complexity. Future research could improve the precision of the translation process by tracking these transformations more rigorously and developing systematic evaluation criteria to measure how computational interpolation affects material performance.

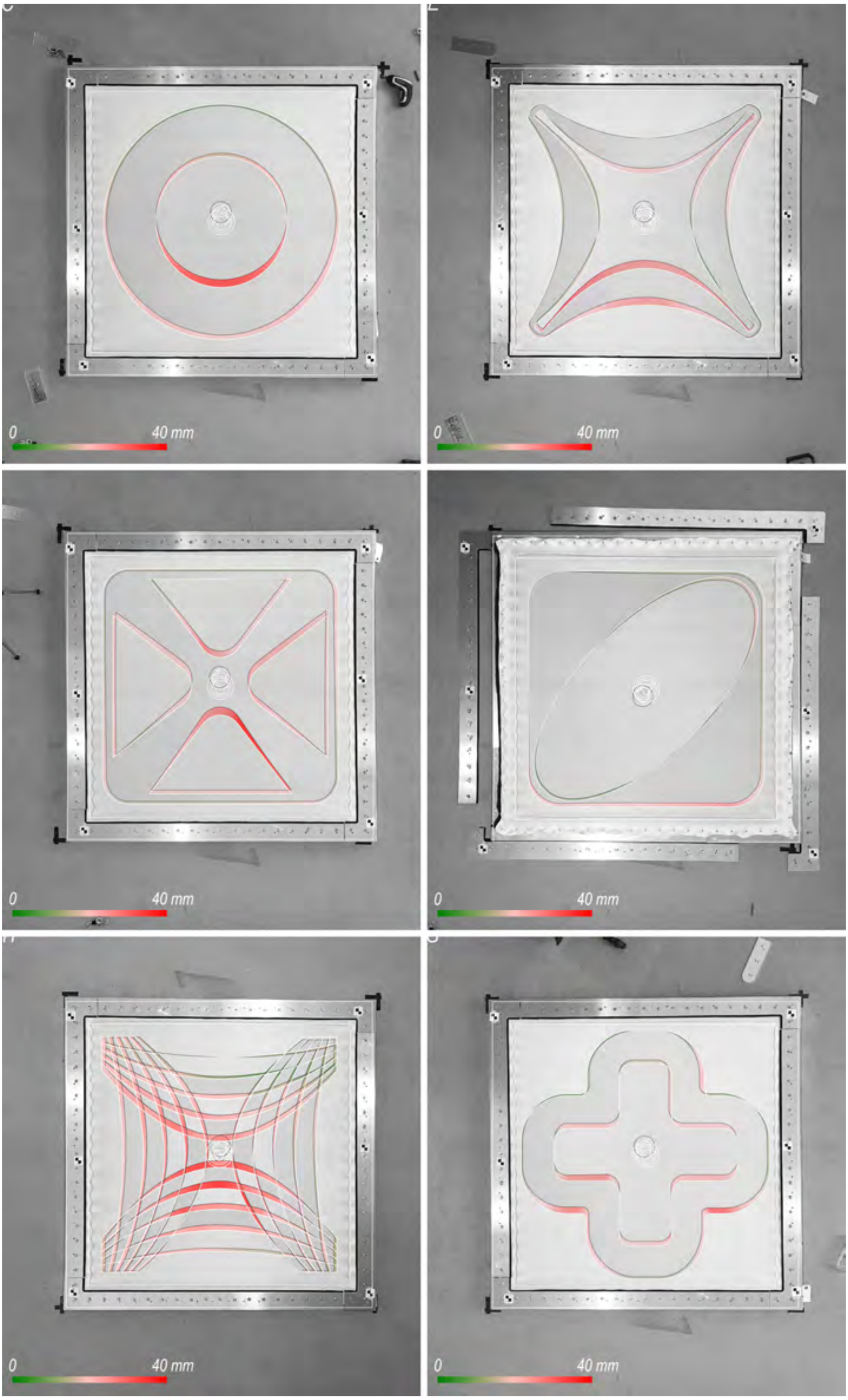
SCALABILITY AND INDUSTRIAL ADOPTION While large-scale prototypes, such as Zoirotia, successfully demonstrated CNC-knitted membranes at an architectural scale, further research is needed to make these workflows *industry-ready*. Automating the data-to-machine translation process and improving file generation efficiency will be key to making CNC-knitted membranes a viable alternative for broader architectural applications.

F 5.6: Knitted samples representing five distinct material density gradations used in the GraCe structure. Samples are knitted with Serafil yarn

5.5.3 FUTURE DIRECTIONS IN SIMULATION AND CALIBRATION OF CNC-KNITTED MEMBRANES

BI-AXIAL TENSILE TESTING FOR CALIBRATION VALIDATION The current hybrid calibration method relies on force-into mapping to derive stiffness-density relationships for calibrated simulation. However, further integration of bi-axial tensile testing on knitted samples **F**5.6 could provide a more rigorous validation of material stiffness values, enabling a more structured and empirical foundation for simulation calibration. Additionally, future calibration efforts should reintegrate warp-weft distinctions, ensuring a more materially accurate and structurally informed calibration process for large-scale CNC-knitted membranes.

ADVANCED CLUSTERING OF POINT CLOUD DATA FOR CALIBRATION The limitation of the Evaluation Model is that the mesh derived from the physical prototype recording lacks heterogeneous subdivisions. Future research could explore automated clustering methods for point cloud differentiation, implying the use of physical prototypes with coloured differentiated areas or use of some markings for better identification of differentiated zones, transferring them from real world back to digital, enabling a more granular tracking of localized material behaviours and improving the calibration process.



F 5.7: Exercise of aligning the pattern between the digital design and physical membrane

HYBRID APPROACHES: COMBINING SIMULATION AND MACHINE LEARNING Future simulation models could explore hybrid methodologies where ML assists in refining simulation predictions. Traditional simulation methods struggle with high-dimensional material variation, while ML could act as an interpolator, predicting behaviours across unexplored material configurations based on prior physical data. The interpolator role of ML here would help to learn the hidden relationships between material properties, material density and structural behavior without hopefully needing explicit equations for every possible combination.

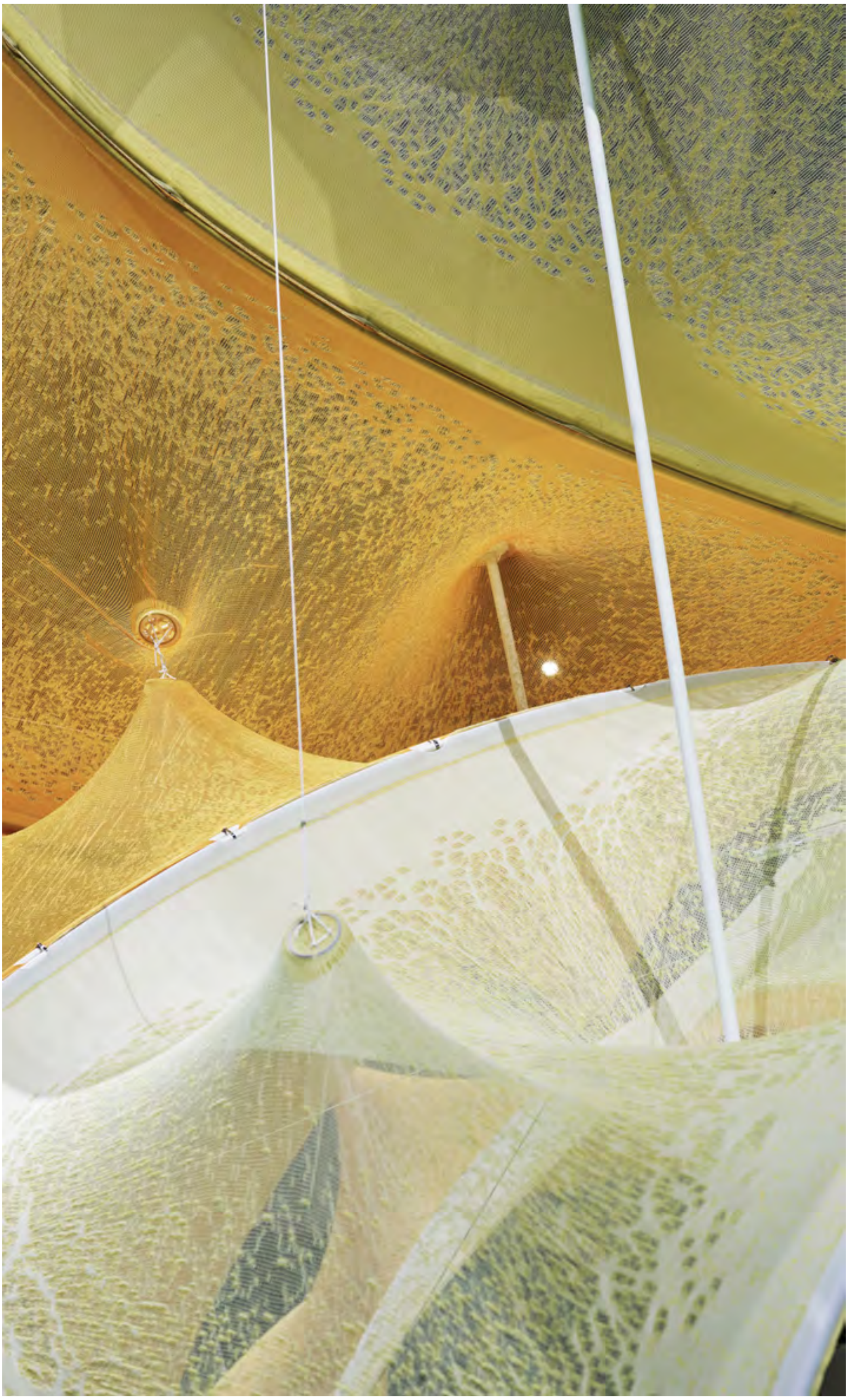
5.5.4 FINAL REFLECTIONS

This thesis marks a significant step in the advancement of differentiated CNC-knitted membranes, establishing a comprehensive design-to-fabrication-to-evaluation framework. By addressing key challenges in material differentiation, digital-to-physical translation, and simulation calibration, this research provides both theoretical insights and practical methodologies that contribute to the broader architectural discourse on computational design, digital fabrication, and material innovation.

The developed Design Model proves that CNC-knitted membranes can be precisely differentiated, linking local material properties to global structural behavior through form-finding and integrated simulation. The Fabrication Model successfully resolves design-to-manufacturing domain shifts, ensuring that digital differentiation strategies translate accurately into physical artefacts. Finally, the Evaluation Model introduces a hybrid calibration method that refines simulation predictions through benchmarking, deviation mapping, and evolutionary algorithms, enhancing predictive accuracy for graded knit structures.

Beyond its methodological contributions, this research positions CNC-knitted membranes as a viable alternative to conventional tensile structures, offering a sustainable, customizable, and scalable approach to material differentiation. It also expands the definition of functionally graded materials (FGMs) within architecture, demonstrating that knitted textiles can serve as structurally responsive systems.

As architectural applications of CNC-knitted membranes continue to evolve, this research lays the groundwork for their broader integration into adaptive facades, lightweight enclosures, and dynamic material systems. By refining design methodologies, fabrication techniques, and validation tools, future work can unlock new possibilities for CNC-knitted membranes, making them an integral part of the next generation of sustainable and performance-driven architectural materials.



F 5.8: CNC-knitted membranes of Zoirotia by CITA 2022. Photo A. Ingvartsen

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LIST OF FIGURES

All illustrations are by the author unless otherwise referenced.