Dansk 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 i 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 designet 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.

English Resume

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 utilized, 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 behavior 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 textile 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 optimization 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 prototypes 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 facades, 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.