

Knit as bespoke material practice for architecture

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ABSTRACT

This paper presents an inquiry into how to inform material systems that allow for a high degree of variation and gradation of their material composition. Presenting knit as a particular system of material fabrication, we discuss how new practices that integrate material design into the architectural design chain present new opportunities and challenges for how we understand and create cycles of design, analysis, specification and fabrication. By tracing current interdisciplinary efforts to establish simulation methods for knitted textiles, our aim is to question how these efforts can be understood and extended in the context of knitted architectural textiles. The paper draws on a number of projects that prototype methods for using simulation and sensing as grounds for informing the design of complex, heterogeneous and performative materials. It asks how these methods can allow feedback in the design chain and be interfaced with highly craft-based methods of fabrication.

1 Tower' at Danish Design Museum, 2015.

INTRODUCTION

Current architectural research practice is investigating the design and making of new material systems in which advanced CNC fabrication technologies allow for the precise control of material performance (Oxman 2007, Menges 2012, Palz 2009, Gramazio & Kohler 2008). This interest interfaces the design and fabrication of materials with that of buildings, allowing the conceptualisation of new structural systems that optimise material use and enable the realisation of lighter and smarter buildings (Nicholas 2013). While still experimental, the creation of new graded materials that respond to changes in site or use has become an overriding design paradigm by which the field aims to understand how we harness the potential of design for and with material performance.

Key aspects in this emerging design practice are the ability to determine the relevant design criteria and assign specifications for these new material systems while at the same time building solid models of their performance. This paper assembles conclusions across a series of CITA's interdisciplinary collaborations that examine knit as a material for architectural application. Learning from experiments using simulation and sensing, our interest is to examine how design criteria can be elicited, tested and fed back to the design system. We ask how these systems can be interfaced with knitted textile design systems and CNC fabrication technologies to understand, design, evaluate and fabricate new bespoke architectural textiles. The paper includes a discussion of the cultural interfaces that these interdisciplinary collaborations entail, querying how design, modelling and simulation are understood in the fields of architecture, textile design, technical textiles and engineering.

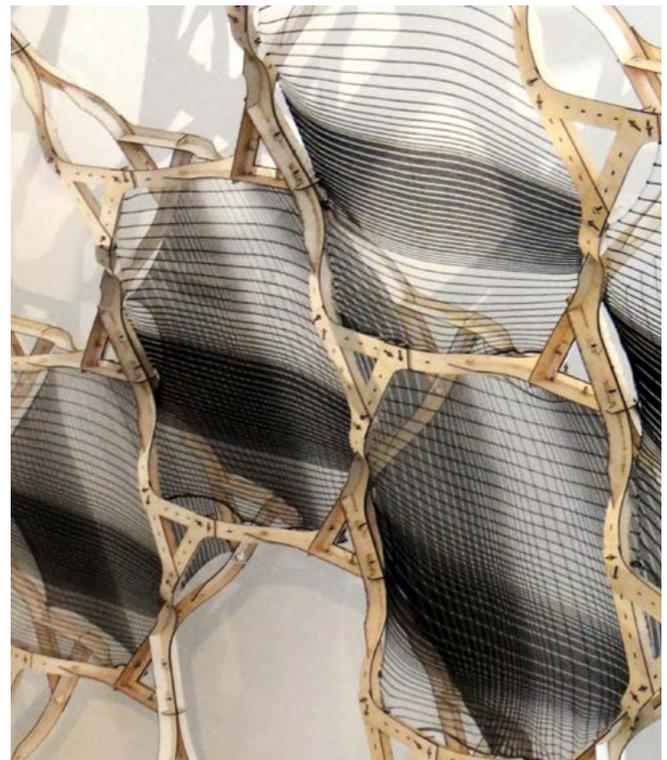
MATERIAL AND STRUCTURAL OPPORTUNITIES OF KNIT

The interest in knit lies with its particular ability to be both structurally and materially determined. Knit is fundamentally a highly flexible textile structure, which can be radically changed by controlling the composition of stitches. The control of stitches can happen across the entire fabric, which enables the fabrication of continuous materials with highly variegated performances. While knit is essentially a continuous yarn structure, the introduction of multiple yarns, in combination or replacing each other, enables further performance control. As such, knitted textiles embed interesting interactions between structural and material performances, thus making them highly singular and infinitely variable.

In CITA, experiments exploring the detailed fabrication of highly graded textiles—interfacing the parametric design and control of structure, material and pattern with CNC fabrication—examine knit for different classes of architectural textiles. 'Knitted Skins[i]



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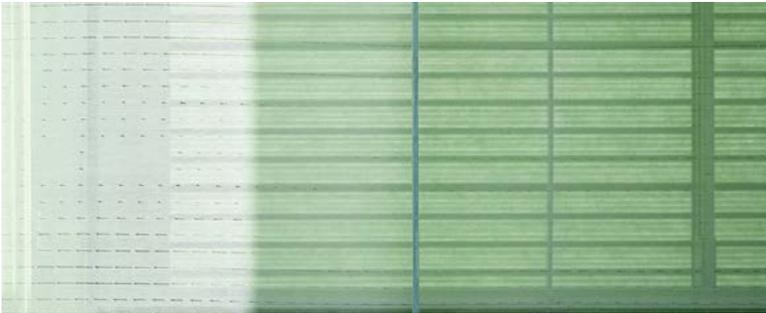
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2 'Sifter' at Architecture House, Copenhagen, 2016.

3 'Derma' grading transparencies in knit-to-shape skins., RMIT, 2013.



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and 'Slow Furl' [ii] investigate the manufacture of bespoke spacer fabrics for interior wall membranes grading the structure, thereby controlling their thickness and pliability (Ramsgaard Thomsen 2008). 'Listener' [iii] explores the embedding of sensing and control into architectural membranes (Ramsgaard Thomsen 2011). 'Derma' [iv] examines the making of a building skin with bespoke transparencies that knit mass-customised textiles to shape. 'Shoji' [v] combines the interest in the interior wall with the lightweight screening device.

These investigations have led to an inquiry of how local variation can be informed and how design criteria are developed, analysed and fed back into the process. In the following we will discuss two main strategies to generate design feedback—simulation and sensing—using the two central investigations 'Tower' [v] and 'Sifter' [vi] as examples.

INFORMING MATERIAL THROUGH SIMULATION

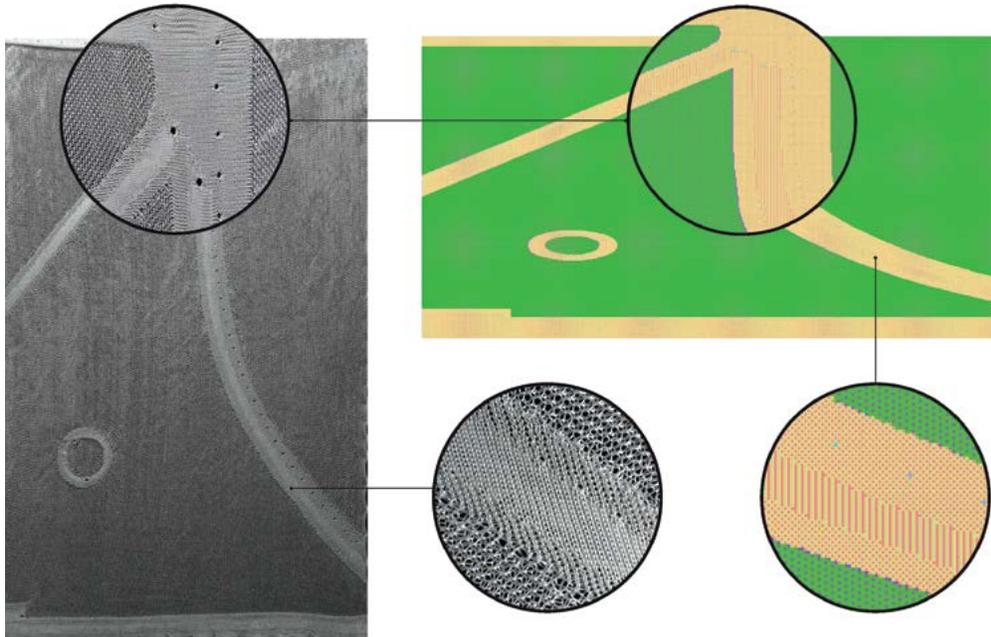
'Tower' investigates knit as a structural membrane in which active bent GFRP rods are embedded into a bespoke knitted textile (Ramsgaard Thomsen 2015). The relationship between skin and structure is a central question in the field of architectural textiles, positioning the textile membrane either as a cladding skin, or engaged in hybrid dependencies in which membrane and scaffold act as an integrated structural system. The latter requires a high degree of control and understanding of the membrane's material behaviour. 'Tower' develops new modelling practices needed to devise hybrid behaviours. The project develops a simulation process that interfaces a projection-based relaxation

method with a finite element (FE) simulation (Ramsgaard Thomsen 2016). This approach extends the work of Lienhard (Lienhard 2015) and is able to effectively simulate the interaction of the constraining fabric, the many pretensioned actively bent GFRP rods and external forces.

The 'Tower' simulations rely on new models for testing and simulating knitted fabrics. The application of knitted fabrics on an architectural scale requires a prediction of the overall structural performance in order to guarantee stability. This requires not only an understanding of the behaviour of the knit, but also its interaction with other components and forces within the structural continuum. This complexity of these interactions and the sheer size of architecture prohibits a simple scaling up of existing techniques which are used for the simulation of smaller textile artefacts.

Cultural interfaces

There are two cultural contexts for textile design of knitted fabrics; the knitwear garment industry and the technical textiles field. Both sectors define design criteria for textiles mainly through 1:1 sampling, the 'sample' being a 2D panel that visualises and tests the surface quality (yarn, colour and stitch structure) and behaviour of the fabric. This method has its embedded problems. Theoretically, samples translate to larger fabrics directly. However, a fabric may not behave homogeneously across its entire width. When under tension, the distortion of the stitch loop varies relative to local conditions at the edge of the fabric compared to the centre. Furthermore,



- 4 Examples of CITAs investigations into architectural knitting: 'Knitted Skins' 2008.
- 5 'Listener' 2010.
- 6 'Shoji' 2016.
- 7 'Tower': Integrated detailing and corresponding knitting files.

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small variables in machine set-up, slight changes in needle movement and tensioning can lead to large performative changes across the fabric (Renkens 2010). When scaling materials up to architectural scale, these imprecisions are amplified, which makes them difficult to control or assess before production.

The engagement with knit as an architectural material questions how predictability can be established in the design chain and how alternative measures of generating material understanding can be developed.

Different kinds of simulation

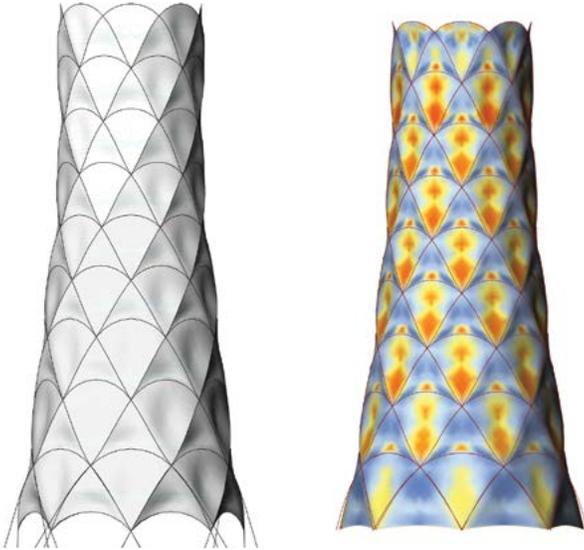
For the fashion and textile industries, simulations of textiles fabrics and 3D garments are an important area of development. In the garment industry, simulation is used for design, performance evaluation such as drape, tension and pressure points associated with fit and comfort, through to supporting virtual shopping experiences. Depending on scale and area of application, different approaches for the simulation of textiles have been developed for the capture of the multiscale relations between material, structure and patch in order to simulate the overall global behaviour of the textile.

In the area of 3D virtual garment design, programs such as V-Stitcher, Marvellous Designer, and Opti Tex are developing sophisticated programming tools that work with a range of data inputs related to body dimensions, material and garment design (Kennedy 2015). All have developed extensive libraries of material knowledge based on standard fabric types commonly used in the

fashion industry. However, with the material knowledge tied up in predefined software libraries intended for visualisation, there is limited possibility to directly interface with textile fabrication tools. Moreover, most software is limited in scope and only simulates textiles with highly simplified models of behaviour. The focus of these simulations is to understand the visual quality of the resulting textiles rather than their performative behaviour.

Knitting machinery companies such as Stoll and Shima Seiki have developed tools that integrate the design, visualisation and virtual prototyping of textiles; build on extensive material libraries of yarns, stitch structures and patterns; and create the technical file (G code) required for running the knitting machine. This currently applies to 2D flat fabrics in a relaxed state. As in virtual garment design software, the virtual 2D fabric can be draped across a 3D surface of an avatar, with a pattern mesh being laid across a specified garment type. Design options for 3D form are limited to predetermined garment types and the geometric tolerances (sizing and shaping) achieved in this type of simulation do not apply to architectural scale.

Yarn-level models are used for the precise simulation of knitted technical textile. They are based on complex mathematical models which simulate the behaviour of the overall fabric by analysing yarn geometry at loop scale. This includes issues such as non-circular yarn cross-sections, which affect fabric bending and draping characteristics (Kyosev 2005). FE simulation (Döbricha 2013) or specialized force models, such as bending and crossover springs in hexagonal patterns (Araújo 2004), spline



or volumetric representations, as in Fibre FEM by Fraunhofer, are used for the simulation of the mechanical behaviour of textiles. Volumetric representations of the knit structure are used for estimating the physical properties of textiles, such as air resistance and water absorption, through simulation (Renkens 2010, Kurback 2016). However, yarn-level models in textile research focus on small fabric sizes in controlled experiments (Cirio 2015).

A further class of textiles simulations come from CGI. Advancements of spring simulations (Stam 2009) and physics based solvers allow modelling techniques that achieve yarn-level models at the scale of complex knitted garments for virtual characters (Yuksel 2012). These cinematic effects are however decoupled from the architectural concerns of material performance, specification and fabrication.

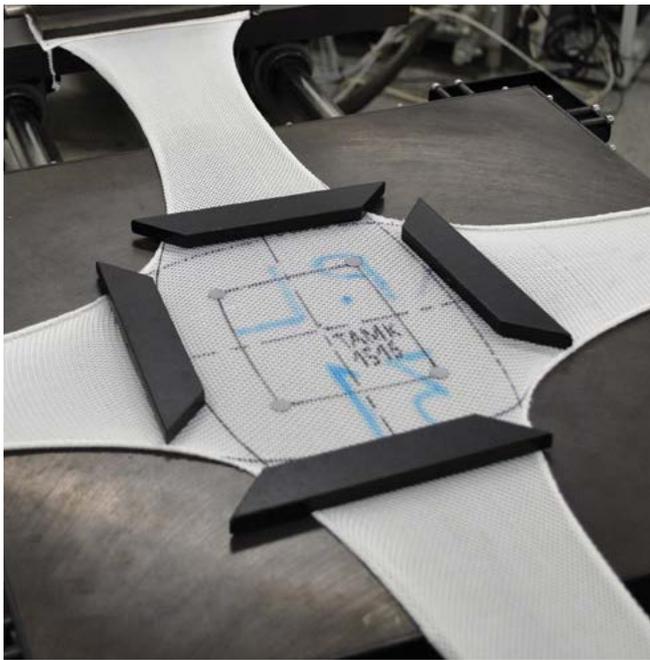
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A call for a new model of simulation

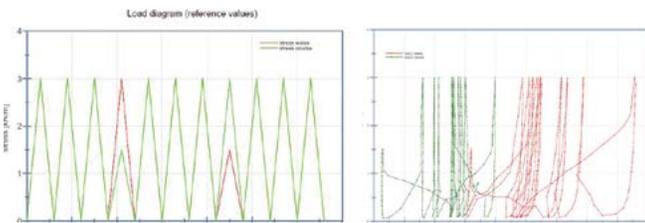
In order to create informed architectural scale design models that engage material performance, we need to develop a new class of simulation models. Where simulation in the garment industry is limited to small patches, the design and specification of textile structures in architecture has to tackle a wider geometrical range, larger scales and be able to consider the textile as part of a structural continuum. The ability to produce bespoke materials, shapes and details with CNC knit demands a tighter coupling of these currently discreet processes.

In architecture, the state of the art of textile structures can be found in membrane design. Current methods are based on material models for a limited range of laminated weaves and a two-step approach towards design and simulation that separate design and analysis. FE simulations are challenged by the inherent high degree of anisotropic and nonlinear elastic behaviour of knitted materials. These are hard to model with current methods for FE, which favour constant stress-strain ratios. It is therefore necessary to determine rough fictitious constants as an approximate simulation of materials behaviour. Finally, existing membrane materials have a relatively high degree of shear stiffness, which is not present in knit.

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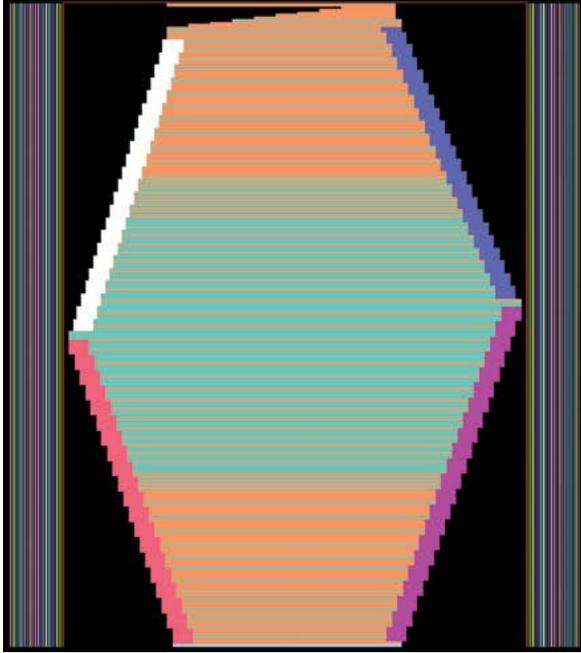


8 'Tower' as lightweight simulation and FE analysis.

9 Biaxial testing of the CNC 55 tex knitted fabric [© ELLF].

10 Exemplary loading sequence according to MSAJ/M-02-1995 without the 1:0 and 0:1 load ratios (left) and the stress-strain-diagram as a result of the biaxial test (right) [© ELLF].

In 'Tower,' the challenge is to simulate the high strains and transverse contractions under load in both directions. In order to inform the simulations, we developed new testing methods to determine the material properties of the designed textiles. The testing procedure of MSAJ/M-02-1995 defines five different stress ratios (1:1, 2:1 1:2, 1:0 and 0:1) that are consecutively applied on a cruciform shaped test specimen. The result of this procedure is a stress-strain-diagram (Figures 8, 9). From this complete set of test data, ten stress-strain-paths can be extracted. A single design set of elastic constants from the



11 Derma knit to shape interface files.



extracted stress-strain-paths can be determined stepwise in a double step correlation analysis.

Existing methods are limited in terms of the scale and precision needed for architectural application. Extending knitting practice to architectural scale must therefore include the invention of new practices by which the simulation of knitted fabric can be undertaken and by which these data are fed back into the design chain. The method developed here allows us to assess the structural stability of Tower and bears the potential for further feedback into the specification of the knit, which could inform us about local requirements for stiffness or isotropy.

INFORMING MATERIAL THROUGH SENSING

The 'Tower' investigation into simulation is contrasted with the 'Sifter' (Figure 11) investigation into sensor feedback. In 'Sifter,' local sensor data, in the form of light readings, inform the making of a site specific curtain. 'Sifter' further extends the idea of directly informing material making with data by directly interfacing design environments with the physical realm.

The integration of sensors in the actual material fabric of the built environment is becoming increasingly commonplace. Embedded into materials such as concrete, steelworks and fibre glass, sensors are used for monitoring material performance and decay (Ramsgaard Thomsen 2012.) The information collected by these strategically positioned sensors generates valuable data that reflect material behaviour, environmental impact as well as

human interaction intensities.

'Sifter' aims to understand how materials could be designed directly for their context, using the scenario of a site specific curtain developed for the Architectural House, Copenhagen. The material design is informed by sense data captured while using a prototypical material in which a field of light sensors gathers the fluctuating lux values across the façade. The data is inputted into a parametric model in turn generating the perforations. The data informs both the length and the amount of perforation in areas which are mapped back onto the location of the referenced sensor. The underlying assumption is that minute changes of the lighting conditions across each window frame can be expressed by the data.

'Sifter' prototypes the means by which material design can be informed through local environmental data. By speculating that building materials belong to lifecycles in which they are replaced and renewed, 'Sifter' asks how such materials can be incrementally optimised. If 'Sifter' retained the incorporation of the sensor field as part of its own material make up, it would embody the first of multiple future cycles of material adjusting.

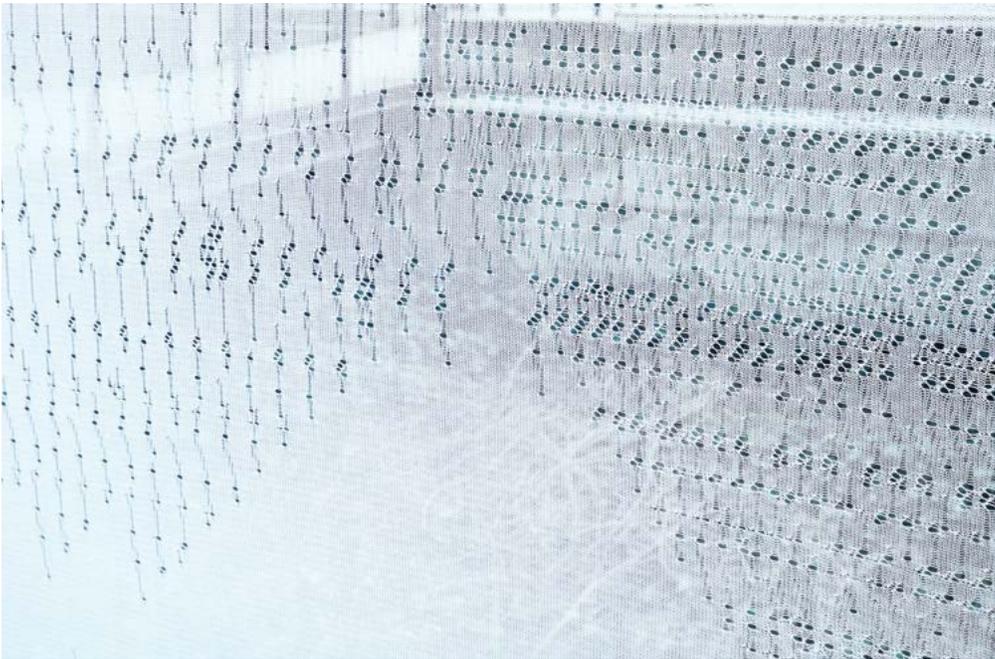
MATERIALISING THE DESIGN

When simulation or sensing is used to generate highly graded design criteria for material specification and fabrication, it becomes paramount to develop interfaces by which these can be transferred directly to the fabrication tools. In our practice,



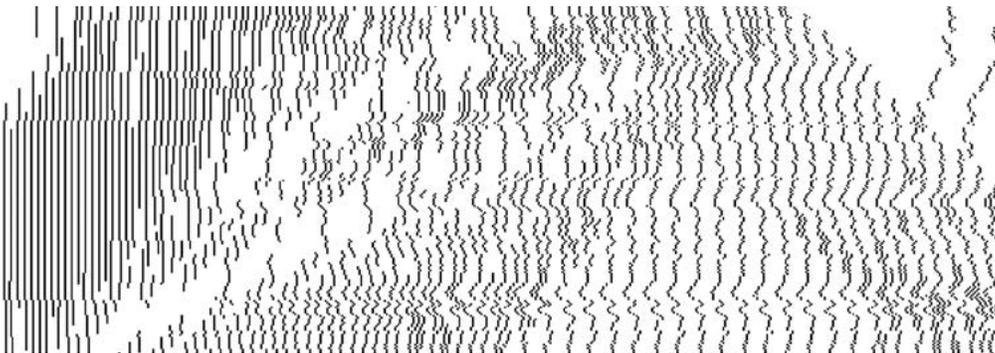
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12 'Sifter' Architecture House, Copenhagen, 2016.



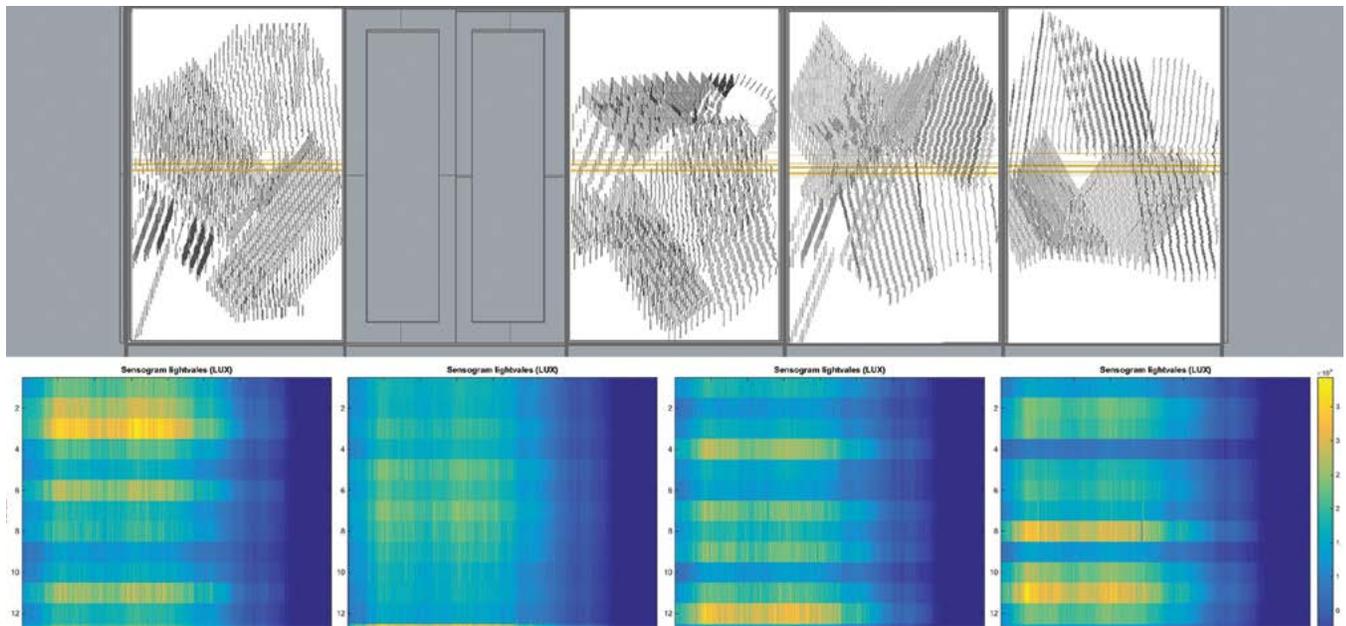
13 Detail 'Sifter'.

14 Generated knitting pattern for 'Sifter'.



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15 Correlation of generated pattern with sensor field. Sensograms visualising varying intensity in the sensor reading over time.

the interfacing between architectural design tools (rhino/grasshopper) and the CNC knitting machines has been a central focus to enable the projects' realisation. Compared to other more predictable fabrication systems such as 3D printing or CNC milling, knit necessitates a highly iterative process of prototyping. The geometrical space of design is infinitely more flexible than the material-based machine-driven knit, which depends on structurally coherent and technologically feasible combinations of knitting instructions. Therefore the creation of knitting code requires in-depth understanding, knowledge and proofing.

The development of our interfacing tools span both Stoll and Shima Seiki machines. In 'Listener,' we developed methods of directly creating the BASIC machine code consisting of patterns of letters defining the knitting beds, the yarn carries and holding patterns, and thereby controlled the formation of the knitted textile. In 'Derma,' 'Sifter' and 'Tower,' the interfacing is controlled by the generation of pixel-based files in which the controlled colour coding of each pixel denotes the particular structural and material information for each stitch. The files interface directly with the machine software. Here, tiff files are imported into the knitting software, which allows direct control of the structure, material and shape. The complexity of the design specification is controlled through bespoke definitions in Processing (Derma) or Grasshopper ('Sifter' and 'Tower') in which matrices are used to define the linear production of each knitting row (Figure 11).

In 'Tower,' this design process allows us to control sizing as well as the placement of details and reinforcements. Here,

differentiations between the base structure and its edges result in a highly differentiated knit pattern (Figure 7). In 'Sifter,' the structural pattern remains very simple. Instead, it is the drastic multiplication in the hundreds of thousands of individual perforations and their non-systematic patterning that makes up the complex and highly individualised textile.

CONCLUSION

Designing with textiles is inseparable from designing their behaviour. Architecture, engineering and textile design are struggling to find the right set of digital tools and procedures that can allow a transition from a sampling-based method towards digital processes that fully integrate and formalise unique interactions between structure and material performances. In these emergent practices, external information about material behaviour and environmental performance is fed back into the design chain, thus enabling the steering of material systems.

Knit is a valuable material technique for testing the integration of software for design, analysis, sensing and fabrication. Knitting is unique and substantially different from more commonly discussed computational techniques for material deposition such as 3D printing and enables the study of complex buildable systems with distinct properties that can be computationally steered.

The problem addressed in this paper is how to inform the design of highly detailed material systems. By presenting two strategies—design integrated simulation and sensing—our aim has been to discuss the possibilities of such strategies, their different

backgrounds and the embedded complexity and limitations of their current state. However, while sensing and simulation are presented as alternative strategies, it is important to understand that these should be seen as complementary systems, where sensing informs simulation and allows an embedded and concomitant correction. This raises new questions regarding the interfacing and use of sensing for simulation. What kind of sensing can be used to understand material performance across the multiple scales that characterise architectural structures, and how do we develop new simulation types that can correlate generalised material models with highly localised data capturing?

The second aim is to understand how these highly specified designs can be interfaced with existing fabrication software and tools. Our aim is to open up the design environment by enabling a higher degree of flexibility for interfacing between multiple computationally driven environments. We have been successful in developing our own interfacing methods and establishing the necessary interdisciplinary dialogues by which the much broader possibilities of CAD and parametric design environments can be linked to the material and structural knowledge that informs CNC knitting. As such, the project spans multiple disciplinary divides combining concerns of design (architecture, textile design) with concerns of analysis (membrane engineering and virtual garment design development) and fabrication (CNC knitting).

ACKNOWLEDGEMENTS

- [i] 'Knitted Wall': (listed as 'Knitted Skins' in text) CITA and Toni Hicks, Brighton University and Tilak Dias, Manchester University, 2008.
- [ii] 'Slow Furl': CITA and Toni Hicks, Brighton University, 2008.
- [iii] 'Listener': CITA and Shenkar College of Engineering and Design, 2010.
- [iv] 'Derma': CITA and Jane Burry, Mark Burry and Jenny Underwood, RMIT, 2013.
- [v] 'Shoji': CITA and KHR Architects, 2016.
- [vi] 'Tower': CITA, UDK, Fibrenamics, AFF and Uni Duisburg-Essen, 2015.
- [vii] 'Sifter': CITA and Shenkar College of Engineering and Design with Jan Larsen, Danish University of Technology, 2016.

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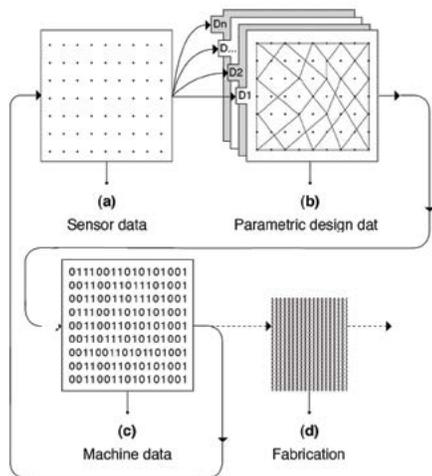
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16 Flow chart for materialising the design.

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IMAGE CREDITS

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Figures 9–10: © ELLF

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