Enlisting Clustering and Graph-Traversal Methods for Cutting Pattern & Net Topology Design in Pneumatic Hybrids

Phil Ayres[1], Petras Vestartas[1] and Mette Ramsgaard Thomsen[1]

[1] Centre for Information Technology and Architecture, The Royal Danish Academy of Fine Arts, School of Architecture, 1435 Copenhagen, Denmark

phil.ayres@kadk.dk

Abstract. Cutting patterns for architectural membranes are generally characterised by rational approaches to surface discretisation and minimisation of geometric deviation between discrete elements that comprise the membrane. In this paper, we present an alternative approach for cutting pattern generation to those described in the literature. Our method employs computational techniques of clustering and graph-traversal to operate on arbitrary design meshes. These design meshes can contain complex curvature, including anticlastic curvatures. Curvature analysis of the design mesh provides the input to the cutting pattern generation method and the net topology generation method used to produce a constraint net for a given membrane. We test our computational design approach through an iterative cycle of digital and physical prototyping before realising an air-inflated cable restrained pneumatic structural hybrid, at full-scale. Using a Lidar captured point-cloud model, we evaluate our results by comparing the geometrical deviation of the realised structure to that of the target design geometry. We argue that this work presents new potentials for membrane expression and aesthetic by allowing free-patterning of the membrane, but identify current limits of the workflow that impede the use of the design method across the breadth of current architectural membrane applications. Nevertheless, we identify possible architectural scenarios in which the current method would be suitable.

Keywords: Cutting pattern, Pneumatic membrane, Mesh segmentation

1 Introduction

The research project *Inflated Restraint* investigates an alternative approach to conventional methods of cutting pattern generation described in the literature. The approach favours free patterning of the membrane cutting pattern through the application of mesh segmentation approaches recently introduced to generative architectural design. This paper presents our research motivation, background and state-of-the-art, methods, results and evaluation, discussion and conclusion.

Fig. 1. *Inflated Restraint* – one of three full-scale demonstrators in the exhibition *Complex Modelling* at KADK, fall 2016.

1.1 Motivation

Our modelling approach targets the generation, analysis and fabrication of a cutting pattern for an arbitrary (non form-found) design volume with a complex surface, and the generation of cable restraint topology. Multiple models and algorithmic methods, predominantly related to mesh segmentation [Nejur & Steinfeld, 2016], are employed to support different scales of design consideration at different periods in the design cycle. In short, the design cycle is organised by the defining of the global design target, the subdivision of the design mesh into curvature regions, the subdivision of regions into suitably sized patches for fabrication, the flattening of the patch geometry and the generating of a suitable topology for the restraining cable (Fig. 2). Our focus on pattern cutting is motivated by the understanding that a primary contributing factor to the performance and aesthetic quality of architectural pneumatics, and architectural membrane structures in general, is the cutting pattern. This makes it a central design concern that spans across different scales of consideration and implicates constraints of fabrication. Within the project, we identify three inter-linked scales of consideration for the membrane – the textile (micro scale), the pattern patch (meso scale) and the overall shape (macro scale). At the micro scale (textile), we find that under typical inflation pressures (in the range of 200 -350 Pa) we do not activate the anisotropic characteristics of our coated textile membrane material. At the meso scale (patch), we find that naked edge relaxation of patch elements is essential for final surface quality. At the macro scale (complete membrane) we demonstrate that computationally derived cutting patterns, that appear to be arbitrary, can be fabricated efficiently (minimising waste) and approximate design targets that contain regions of synclastic and anti-clastic curvature.

2 Background & State-of-the-art

There is general consensus across the literature regarding design approaches for architectural membranes – both mechanically stressed and pneumatic. Design workflows tend to commence with form-finding, progress through structural analysis and conclude with the generation of a cutting pattern [Otto et al., 1982; Gründig et al., 2000; Kim & Lee, 2001; Philipp et al., 2015]. With the cutting pattern acting as the interface between design intent and manufactured reality, the process of cutting pattern generation implicates issues of design, engineering, fabrication and, not least, aesthetics [Dent, 1971; Knippers, 2011]. In general, the aesthetic of architectural membranes follows principles of regularity and minimum deviation between membrane sub-panels. In this project, we explore alternative principles of free-patterning within the constraints of achieving predefined design targets.

2.1 Approaches to cutting pattern generation

The principle challenge in cutting pattern generation is the sub-division of a target geometry into a set of sub-surfaces, with minimal distortion [Gründig et al. 2000]. This is a trivial problem in the case of target geometries that are developable, however, in practice, mechanically stressed and pneumatic membranes generally gain structural performance through double curvature – anticlastic in the case of mechanically stressed, and synclastic in the case of pneumatics. Many approaches to the problem of distortion minimisation from doubly curved sub-surfaces to flattened pattern are found in the literature. These include target surface sub-division using geodesics [Ishii, 1972], dynamic relaxation, force density method [Moncrieff and Topping, 1990], finite element method using weighted least-squares minimisation [Tabarrok and Qin, 1993] and a hybrid iterative flattening technique combined with equilibrium shape finding using FEM [Kim and Lee, 2001]. It is of note that underlying the development of methods is a change in focus in where distortion should be considered in the realisation process – initially as a problem of fabrication, then as a problem of forces encountered in construction and finally as a problem of material extension after erection.

2.2 Mesh representation and treatments

In all the aforementioned approaches and in computationally led methods in general, a mesh acts as the underlying data-structure for representing the membrane. However, their treatment in the cutting pattern generation process can vary significantly. In Gründig [2000] the representation of individual membrane segments occurs through a mesh segmentation process that alters the mesh topology. Geodesics act as cutting geometry of the mesh with additional vertices and edges added where faces are split. The implication here is a potential loss of mesh regularity.

In Tabarrok and Qin [1993], and Kim and Lee [2001] the topology of the input mesh is pre-defined as an approximation of the design target with topology maintained through segmentation and only mesh geometry adjusted in the various relaxations. This implies that a relatively clear design geometry is already present, and may therefore act as an impediment to speculative early-design iteration.

2.3 Mesh segmentation methods

In the broader field of generative architectural design, relatively recent developments in methods of mesh segmentation from the field of computer graphics are finding traction with architectural design problems, particularly in the field of free-form surface rationalisation, planarisation and discretisation [Nejur and Steinfeld, 2016]. These approaches are predicated on the use of design meshes, or typically their dual representation, to provide a weighted graph from which mesh features can be interrogated and modified [ibid.]. In this project we investigate the use of K-means clustering and Graph-traversal as methods of steering mesh segmentation for generating membrane cutting patterns. By altering parameters such as face-angle and edge-traversal-distance, fine grain control of mesh segmentation can be achieved and qualitatively different results produced (Fig.2).

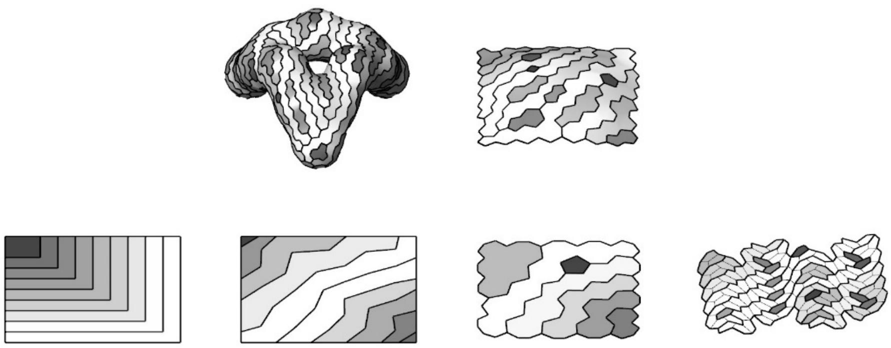

Fig. 2. Early investigations of mesh segmentation strategies demonstrating design freedom in the control of patch geometries.

3 Method

In contrast to conventional approaches of pattern cutting generation that operate on form-found geometries, we begin with an unconstrained design cycle to define a macro-scale design target mesh. This target is designed using the Cocoon toolset – a plugin for Rhino/Grasshopper. To create a spatial tension we define two pneumatic bodies – one with larger volume (approx. 8.1 m^3) and areas of high anticlastic curvature, and the other with a smaller internal volume (approx. 4.7 m^3) with predominantly synclastic curvature. Both pneumatic bodies are fully closed surfaces with no open boundary connection conditions to the ground (Fig.3, stage 1).

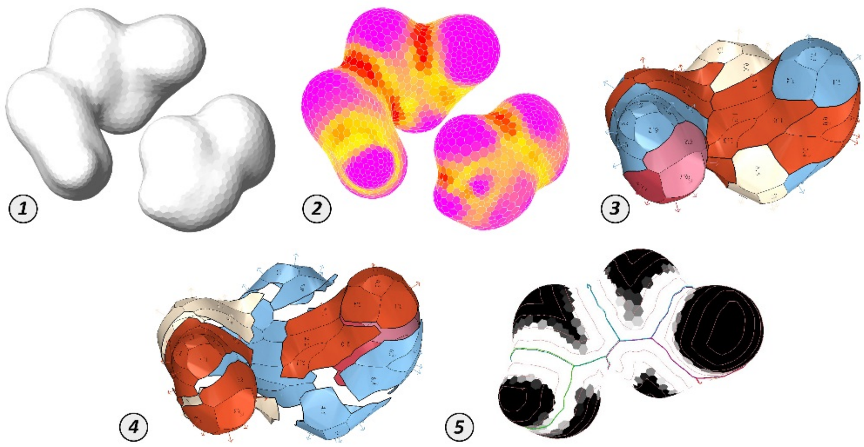

Fig. 3. Stages in the modelling workflow: 1. A defined target model; 2. curvature analysis of the design model; 3. subdivision of the surface (only the larger inflated body shown); 4. breaking into discrete models for refinement and further division into sewable patches; 5. first order cable-restraint topology generation by joining 'lowest' areas of anticlastic curvature.

3.1 The k-means clustering and graph-traversal approach

A custom mesh curvature analysis algorithm operates on the design mesh to identify areas of synclastic and anticlastic curvature. A k-means clustering algorithm is then applied to group mesh faces within the isolated synclastic curvature zones. Graph traversal methods (Depth First Search and Dijkstra's Shortest Path) are then used to subdivide the anti-clastic curvature zones into strips suitable for fabrication. New meshes are generated for all of these curvature regions and refined to increase fidelity as they are used downstream to define the cutting geometry of individual patches. The naked edges of all patch meshes are analysed to determine shared edges and these are relaxed to create smooth boundaries for unrolling. The Rhinocommon unroller class is then used to produce a developable surface patch with edge marking, indexing and patch ID added prior to laser cutting (Fig. 4). Without this process of relaxation along shared edges, 'pinch' artefacts would become evident during inflation as can be seen in early prototype studies (Fig. 7, top left).

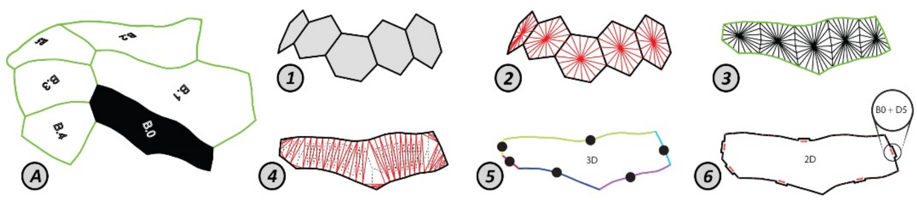

Fig. 4. Stages in the flattening of a patch (A): 1. Patch is defined by a collection of dual mesh polylines; 2. Polylines are triangulated into a ‘fan’ mesh; 3. Relaxation using Kangaroo 2 with weak inner springs (black lines) and stiff outer springs (green lines); 4. Naked edge is flattened using the Rhinocommon function ‘3D polyline to mesh’ resulting in minimum triangulation for unrolling; 5. Edge adjacency attributes are added for the transfer from 3D to 2D; 6. Rhinocommon ‘Unroller’ class is used to unroll the mesh and edge adjacency labels are added.

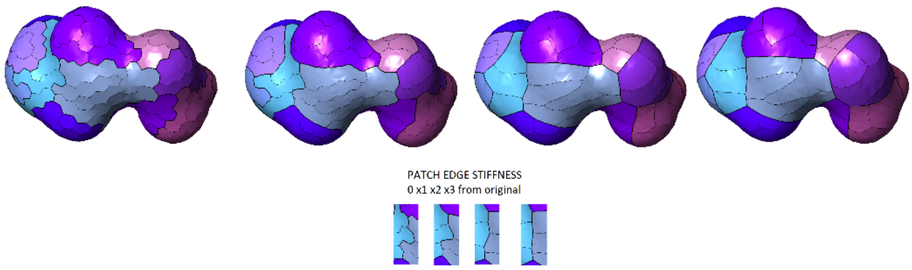

Fig. 5. Sequence showing patch naked-edge relaxation.

The topology of the cable restraints is determined from curvature analysis of the design target model. In this case, we firstly identify areas of anticlastic curvature, the ‘lowest’ points of the membrane surface, to establish the primary loops of the net. This ensures that they do not exhibit ‘slippage’ on the membrane when under tension. Further edges are added to the net topology using search criteria that combines finding areas of lowest synclastic curvature (to relieve membrane stress) and being approximately equidistant from each other (to ensure even distribution). As such, the net topology does not have any direct geometric correspondence to the sub-division of the membrane into patches, with this being exemplified by the use of a neon coloured braided rope. In simulation, we ‘inflate’ the membrane model to verify its interaction with the cable restraint model. Here, the measure of success is that the net does not exhibit ‘slippage’ and the two systems find and maintain equilibrium across the operating pressure range.

4 Results & Evaluation

The full-scale demonstrator (Fig. 1) comprises two pneu. The smaller pneu is designed to have synclastic curvature which conforms to the ‘natural’ tendency of pneumatic form. The larger pneu includes areas of anticlastic curvature, which is not a natural pneumatic form. Exhibited together, the two pneu demonstrate the role of the membrane in steering the geometric result of the pneumatic system.

With a combined volume of approx. 12.8m^3, inflation of the membranes takes approx.7 mins using a proprietary insulated duct fan (Östberg IRE 125 A1) operating at 240v with a maximum flow of 64 l/s at a maximum pressure of 300 Pa. The pneu system reaches full inflation with a pressure in the region of 200-350 Pa. At this operating pressure, membrane stresses are not sufficient to have to consider the anisotropic characteristics of the coated textile used for the membrane (Fig. 6). This is determined using the standard equation for membrane stress that relates inflation pressure to radius of curvature, and comparing to the stress/strain graph for the textile shown in Fig. 6.

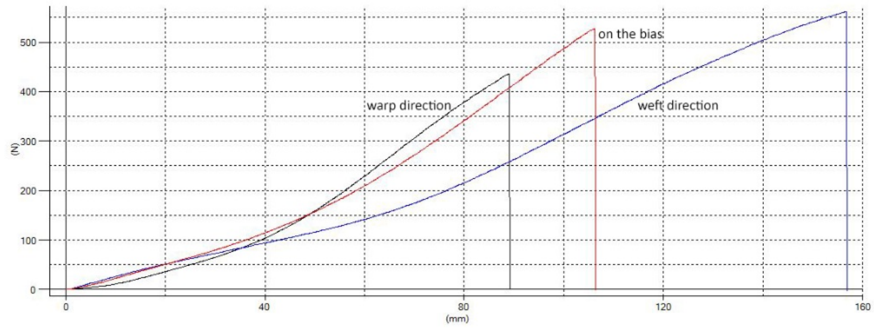

Fig. 6. Stress/strain graph for uniaxial tensile test (following Ansell & Harris [1982]) for the coated membrane textile in the direction of warp, weft and on the bias. The difference between warp and weft directions reveal the anisotropy of the textile. However, significant deviation only begins to occur after approx. 100N / 40mm of elongation.

We verify the modelling workflow by comparing the design model with the physical demonstrator. Here, the measures of success are: 1. that there is a close geometric correlation between the model and the realised pneu; 2. that the inflated surface achieves the desired curvatures; 3. that the membrane has a smooth transition across patches; 4. that the membrane is fully tensioned with no areas of compression resulting in unsightly and underperforming compression wrinkles.

In addition to comparison between the physical demonstrator and the design model, comparison with earlier physical prototypes (Fig. 7, left) provide evidence of refinement in the cutting pattern generation method (the addition of naked edge relaxation for patches as shown in Fig.4 & 5) and successfully achieving measure of success 3 & 4 in the final membrane.

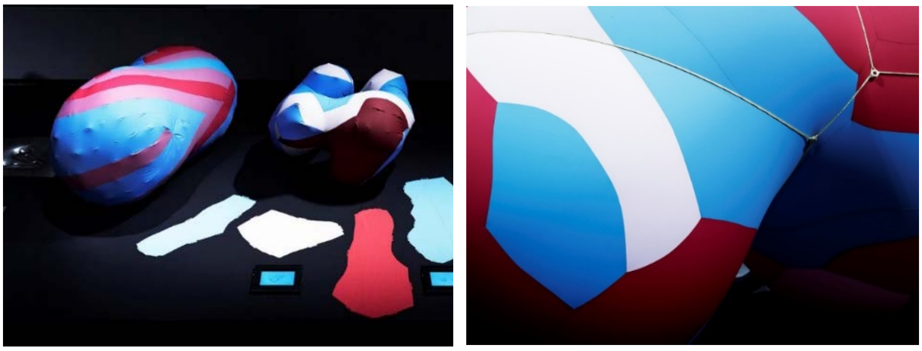

Fig. 7. Early prototypes (left) showing evidence of ‘pinches’ and wrinkling, and the final membrane (right) showing smooth transitions between patches and fully tensioned membrane.

For the measures of success 1 & 2 we compare a Lidar captured point-cloud of the physical pneu and determine the deviation from the intended model. Surface deviation shows a general tendency towards the surface being under-inflated (Fig. 8). The sectional study (Fig. 9) reveals the deviation between the realised membrane and the design intention. This was sufficient for the generated restraint net to not be compatible with the membrane. A second iteration of net production used a mesh derived from the laser-scanning data of the physical membrane. This approach of operating from ‘as-built’ data to inform subsequent construction phases is described in the literature [Brandt, 2012], and resulted in nets that conformed to surface for both pneumatic forms in the final demonstrator.

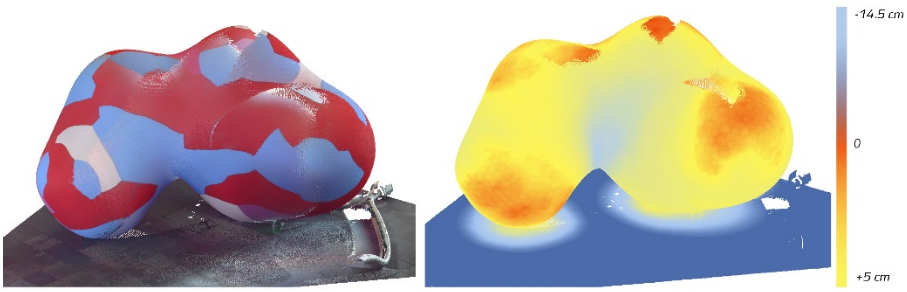

Fig. 8. 3D Lidar scan of the larger membrane (left) and surface deviation analysis of target model (right).

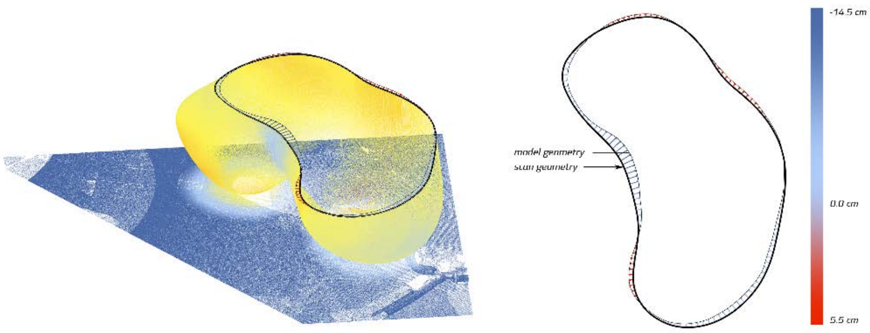

Fig. 9. Cross sectional comparison between target geometry and 3D Lidar point cloud of the larger membrane reveals larger geometric deviation in the area of pronounced anticlastic curvature.

5 Discussion & Limits

Inflated Restraint demonstrates the use of mesh segmentation methods for the generation of cutting patterns, that, despite appearing arbitrary, approximate smooth pneumatic design targets with complex curvature. However, as an internal exhibition piece, the project is limited in its architectural generalisability as it has not been designed or tested against the full domain of external architectural loads such as wind and/or snow. Designing and analysing the performance of the pneu for such operational loads remains an open challenge for the workflow we have described in this paper. Where rudimentary analysis of membrane stresses can be easily calculated given inflation pressure and membrane curvature, a more involved understanding of membrane performance at the yarn scale would be a necessary area of exploration for further work. This is due to the patchwork nature of the membrane in which yarn-to-yarn relations between patches are often highly oblique and eccentric. The literature points to such conditions as being detrimental to load transfer and recommends that, given two lengths of fabric to be joined, the angle of the edges to be joined should be mirrored [Otto et al., 1982]. Such a constraint is a challenge to implement for the cutting pattern generation method described. Currently, fabric orientation is determined through nesting of patches to minimise waste along the length of the manufactured coated fabric. However, a multi-objective optimisation aimed at negotiating this fabrication constraint with that of minimising warp/weft orientations between neighbouring patches could be considered.

Despite the limitations outlined above, *Inflated Restraint* does demonstrate architectural relevance for circumstances in which light-weight, quick to erect, quick to demount, visually engaging and formally expressive forms of interior spatial sub-divider or screen are desired. For example, interior large span contexts such as exhibition halls, foyers, atrium spaces, and, currently under investigation, as dynamically reconfigurable architectural scenography for an immersive spatial sound and visual performance.

6 Conclusion & Further Work

This paper has presented a computational approach to cutting pattern generation for architectural membranes. The approach has been refined through a cycle of iterative testing that has included the production of physical prototypes. A final demonstrator comprising two cable-restrained air-inflated pneumatic membranes has been produced at full scale to evaluate the approach. The computational approach offers an alternative method of cutting-pattern generation to those described in the literature, providing designers greater freedom in the definition of target design geometry (i.e. - not constrained to a form-finding process), and in steering the outcome of the cutting pattern generation through altering parameters of the mesh segmentation process. We have identified that a current trade-off to these freedoms is a more constrained domain of architectural application and have suggested what these might be.

Further work aims to address the limitations within the computational design process to allow designers more explicit structural performance feedback of derived cutting patterns. Testing of the method in the context of cutting pattern generation for mechanical stressed membranes also remains an open challenge.

References

1. Ansell, M., Harris, B. (1982), “Fabrics – Characteristics and Testing.” in *IL15 Air Hall Handbook*, Institute for Lightweight Structures, West Germany.
2. Brandt, J. (2012), “The Death of Determinism.” in Ayres, P. (ed.), *Persistent Modelling – extending the role of architectural representation*. Routledge, London, pp.105-116.
3. Dent, R. (1971), *Principles of Pneumatic Architecture*. Architectural Press, London.
4. Gründig, L, Moncrieff, E., Singer, P., Ströbel, D. (2000), “High-performance cutting pattern generation of architectural textile structures.” in *IASS-IACM, Fourth International Colloquium on Computation of Shell & Spatial Structures*.
5. Kim, J-Y., Lee, J-B. (2002), “A new technique for optimum cutting pattern generation of membrane structures.” in *Engineering Structures*, Volume 24, pp.745-756.
6. Knipper, J., Cremers, J., Gabler, M., Lienhard, J. (eds.) (2011), Construction Manual for Polymers + Membranes. Birkhäuser, Edition Detail.
7. Nejur, A., Steinfeld, K. (2016), “Ivy: Bringing a Weighted-Mesh Representation to Bear on Generative Architectural Design Applications.” in *ACADIA // 2016: POSTHUMAN FRONTIERS: Data, Designers, and Cognitive Machines, Proceedings of the 36th Annual Conference of the Association for Computer Aided Design in Architecture* (ACADIA), pp. 140-151.
8. Otto, F., Burkhardt, B., Drüsedau, H. (1982), “Manufacturing.” in *IL15 Air Hall Handbook*, Institute for Lightweight Structures, West Germany.
9. Otto, F., Drüsedau, H., Hennicke, J., Schaur, E. (1982), “Architectural and Structural Design.” in *IL15 Air Hall Handbook*, Institute for Lightweight Structures, West Germany.
10. Philipp, B., Breitenberger, M., Wuchner, R., Bletzinger, K. (2015), “Form-Finding of Architectural Membranes in a CAD-Environment Using the AiCAD-Concept.” in Ramsgaard Thomsen, M., Tamke, M., Gengnagel, C., Faircloth, B., Scheurer, F. (eds.) *Modelling behaviour: design modelling symposium 2015*. Springer, pp. 65-74.

11. Punurai, W., Tongpool, W., Morales, J.H. (2012), “Implementation of genetic algorithm for optimum cutting pattern generation of wrinkle free finishing membrane structures.” in *Finite Elements in Analysis and Design*, Volume 58, pp.84–90.

Acknowledgements

Inflated Restraint was exhibited together with two further projects – *A Bridge Too Far* & *Lace Wall* – as part of the research exhibition *Complex Modelling* held at Meldahls Smedie, The Royal Danish Academy of Fine Arts (KADK), over the period September –December 2016.

This project was undertaken as part of the Sapere Aude Advanced Grant research project *Complex Modelling*, supported by The Danish Council for Independent Research (DFF).

The authors wish to acknowledge the collaboration of Maria Teudt.