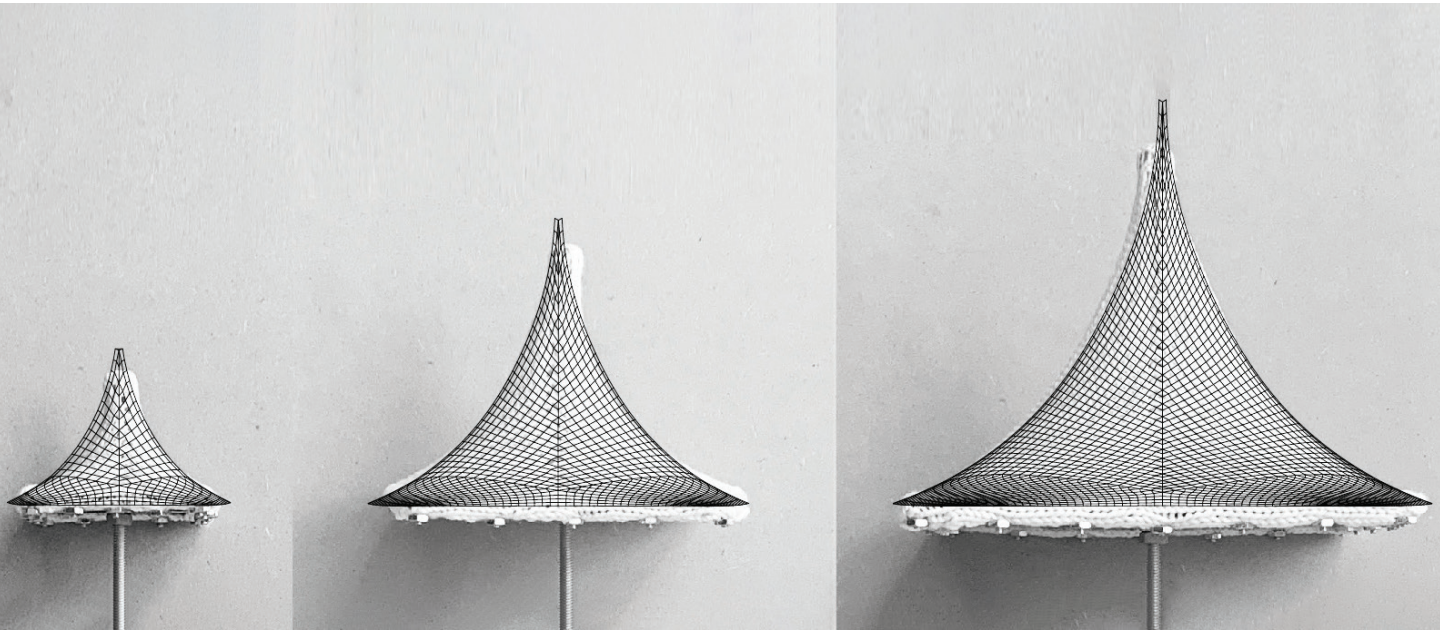
Form-finding of Architectural Knitted Tensioned Structures

An Investigation on Form-finding and Analysis of Knitted Tensioned Structures in Architecture

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ABSTRACT

This study discusses the form-finding process of tensile structures and specially knitted tensioned structures. The performance of different plugins in Grasshopper is investigated for behavioral simulation of architectural knitted tensioned structures. Whereas multi-directionality and flexibility are the main characteristics of knitted textiles and allow these materials to be used to develop more complex architectural shapes, such characteristics also make digital simulation of knitted textiles more challenging. We explore the extent to which available tools can assist during the design process. Firstly, the theoretical aspects of the form-finding of tensile structural systems are discussed. Secondly, the form-finding and analysis of knitted textile structures are explored using Kangaroo2 along with K2 Engineering and Kiwi!3D. The performance of these tools is judged by comparing the digital form-found model against the actual physical model behavior and shape. Results shows that Kangaroo2 is a faster tool than Kiwi!3D when the actual stitch distribution is applied to generate the initial shape; additionally, tuning the length of the mesh edges to replicate the physical model behavior is easier in Kangaroo2. On the other hand, Kiwi!3D is a faster tool if a rough initial simulation for gaining insights into overall form. While Kangaroo2 yields a more detailed and accurate form-found shape, for the FE structural analysis it needs to be coupled with K2 Engineering, or the output of the form-finding from Kangaroo2 can be used as an input for FE analyses using Kiwi!3D. Rather than competing with each other, these software environments are different problem solving approaches; the process requires alternating between these plugins to achieve the project goal. The research shows that in using materials such as knitted textiles to develop architectural forms, successful digital modeling can be obtained by form-finding through the material instead of form-finding onto the material.

1 Comparison of physical and digital models at different scales

INTRODUCTION

Tensile, especially textile, structures are one of the main categories in building construction. For many years, lightweight structures made with technical woven systems have been one of the dominant methods of developing such designs. Within the last decade, however, other techniques of textile development, such as knitting, have found their way into architecture. Recent improvements in CNC knitting and computational design have increased the viability of knitted fabrics in architecture and enhanced the research in this field of study (Tamke et al. 2021; Thomsen et al. 2016; Ahlquist and Menges 2013; Sabin 2013).

Several potentials of knitted textiles, such as flexibility and seamless knitting, allow for the development of complex architectural shapes and composite systems. Additionally, knitted fabrics made of organic yarns enable architects to apply these materials to create sustainable structures. However, the successful implementation of knitted textiles in architecture requires developing a digital model that accurately represents the material's behavior (Oghazian, Brown, and Davis 2022).

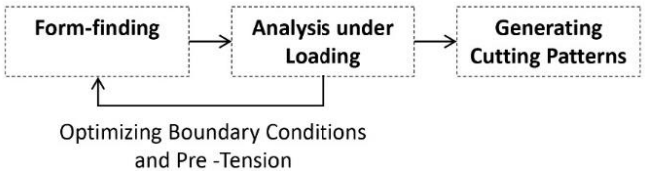
Literature shows that tools already developed for simulating the tensile behavior of the fabrics are essentially focused on the two-directional characteristics of the woven fabrics. Although these two main directions can also be recognized in knitted textile structures—course and wale—knitted textiles are multi-directional materials. Studies have already been conducted showing the comparison or integration of multiple tools during the design process of developing different types of tensile structural systems. For example, the behavior of rods in bending-active forms is compared in three plugins, Kangaroo, Kiwi!3D, and SOFiSTiK, by Bauer et al. (2018). Magna et al. (2018) implemented different tools such as Kangaroo, Kiwi!3D, and SOFiSTiK at various design stages for bending-active structures, including rods and fabric. In another study by (Cuvilliers et al. 2018), two common algorithms of Kangaroo1 and Kangaroo2 are compared regarding the reliability, speed, and accuracy of the form-finding process by defining numerical calculation from physical model measurements and comparing them with the form-found models.

However, few studies have been conducted to understand the potential of the available computational tools for simulating the behavior of 3D knitted architectural tensioned structures. This research focuses on comparing existing solvers to demonstrate each one ability and limits and suggesting improvements for simulating the behavior of tensioned knitted structures. The selected approaches are Kangaroo2 (Piker 2018), K2Engineering (Brandt 2019), and Kiwi!3D (2020), and for future investigation, we will also add SOFiSTiK. The chosen tools are not competing with one another and could be beneficial at different stages of the design process. Alternative software solutions in the field of knitted tensioned structures that are commercially available or presently under development are not covered here since they are either in beta testing or not fully functional.

FORMFINDING OF TENSILE STRUCTURES, COMMON TOOLS, AND POTENTIALS

In general, the current design process of the tensile structures includes three main steps: the first step is form-finding (defining initial shapes and boundary conditions); the second is adding material properties, loading, and analysis; and the third step is generating cutting patterns (Figure 2) and sometimes compensation (Puystiens et al. 2016).

The form-finding step includes creating an initial shape based on the boundaries' condition and prestress in the textile. The output of the form-finding step is an equilibrium form. The next step is to analyze the form-found model considering loading effects, membrane stresses and displacements, material, and geometric properties of the flexible fabric. If computed stresses and displacements are not within allowable limitations, the form-finding process should be repeated, modifying boundary conditions and initial prestresses (Dutta and Ghosh 2019).

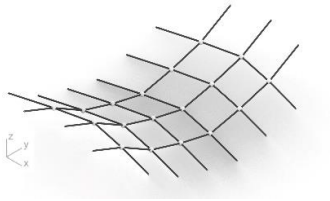
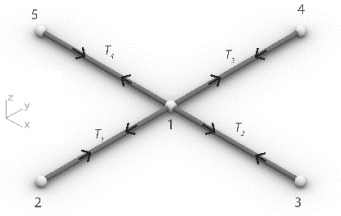


2 Methodology for the design of membrane structures (Puystiens et al. 2016)

The most popular form-finding methods are transient stiffness, force density, and dynamic relaxation (Lewis 2008). Iterative computation for producing shapes in static equilibrium is the primary goal of the three approaches (Figure 3):

- The Transient Stiffness method is dependent on the small displacements and rotations of elements. To discretize the surface in this method, lines in two directions intersect in a node. Stiffness resulting from the prestress changes the nodal forces and consequently alters the surface geometry (Lewis 2008).

- Force Density uses surface discretized as a system of branches. The boundary conditions are assumed, and the only factor affecting the structure's shape is the force density value (Lewis 2008). Force density is defined as force per unit of the length of the discretized membrane network.

Form-Finding Method	Definition	Features	Surface Discretization Method
Transient Stiffness	Assumption of small displacements and rotations based on the forces	No material properties are required for the form-finding step The ratio of force to length or stress to surface area is central in this method (Veenendaal and Block 2011)	 Lines in two directions that intersect in a node
Force Density	The boundary conditions are assumed. The value of the force densities determines the shape of the structure	No material properties are required for the form-finding step Only geometric stiffness is required for the form-finding (Dutta and Ghosh 2019)	 Branch of elements
Dynamic Relaxation	Equilibrium state in the structural system over time under the influence of the damping	Analogy with motion	Triangular mesh of points for constant tension membranes and the forces are independent of the shape of the triangular meshes

3 Three main approaches for form-finding in tensile structures

- In the Dynamic Relaxation method, the mass of discretized continuum is supposed to be concentrated at the surface's nodes. A small number of arithmetic operations is required because computations for nodes will be in turn instead of analyzing all the nodes simultaneously. This method is more efficient than the Transient Stiffness method. In Dynamic Relaxation method, equilibrium will be obtained over time and under the damping influence (Dutta and Ghosh 2019). This method uses the motion approach, which means residual forces are converted to the nodes' velocities, and mass determines the acceleration (Veenendaal and Block 2011).

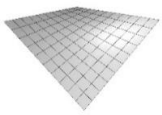
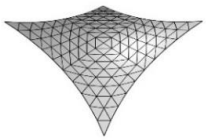
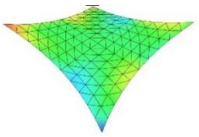
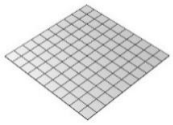
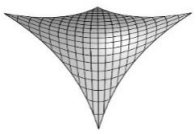
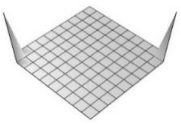
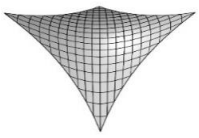
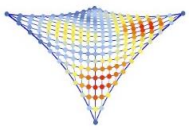
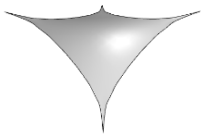
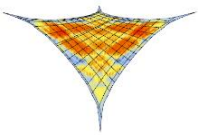
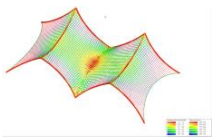
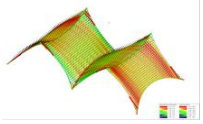
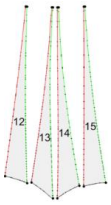
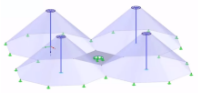
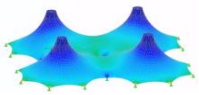
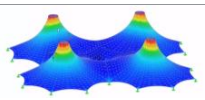
It is apparent that in all of these approaches, the problem of form-finding is geometric and thus material-independent (Dutta and Ghosh 2019). Digital platforms for the design and analysis of tensile structures adopt one of these form-finding approaches. As presented in Figure 4, most software applications freely available to architects and architecture students are plugins embedded in Rhino and Grasshopper, such as Rhino Membrane, Kangaroo2, K2Engineering, and Kiwi!3D. Some other software applications require subscription and are mainly used for structural analysis and construction of tensile structures, such as K3-Tent, Tensyl, Easy, Touch Cad, and RFEM (DLUBAL n.d.).

All software applications mentioned in Table 2 are designed for cable-net and tensile structures using technical woven composite fabrics. How we can adopt the current platforms to simulate knitted textiles is the central question of this research.

FORMFINDING OF TENSIONED KNITTED TEXTILES AND CHALLENGES

Knitted textiles are new materials in architecture. As discussed in the previous section, not many studies have been conducted to simulate these materials' structural behavior and shape. Different processes for the simulation of these materials should be considered compared to common woven tensile structures because, in knitted textiles, the textile and overall form will be shaped simultaneously. Therefore, the properties of the knitted textile will inform the shape and size of the initial as well as the final form that will emerge after post-tensioning.

Regarding simulations of the behavior of the knitted materials in architecture, springForm, developed by Ahlquist and Menges (2013), is a tool that uses physics-based simulation in processing for simulating knitted textiles shapes. In a study by Schmeck and Gengnagel (2016), a grid with hexagonal cells that substitutes stitches in a knitted textile structure for a planar shape is studied using Kangaroo2 for the form-finding.

Software/Method/Structures	Initial Shape	Form-Finding	Analysis	Cutting Pattern
Rhino Membrane/ Natural Force Density Method/ Tensile and cable net structures, Woven textiles	 Mesh			No
Kangaroo2/ Dynamic Relaxation Method/	 Mesh			No
K2Engineering/ Dynamic Relaxation Method/ Cable nets and Grid shells	 Mesh			No
Kiwi3D/ Finite Element Methods and Isogeometric Analysis (IGA)/	 NURBS			No
K3-Tent (LLC)	Yes	Yes	No	Yes
Tensyl (Shepherd 2007)	Yes	Yes	Yes	Yes
Easy (GmbH)/ Force Density Method/ lightweight structure design (Ströbel and Singer 2005) [Images from Easy website]	Yes	Easy. Form 	Easy.Stat 	Yes Easy.Cut 
Touch Cad (Lundström-Design)	Yes	No	Yes	Yes
RFEM (DLUBAL) [Images from RFEM website]				Yes

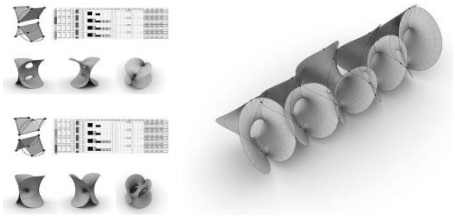
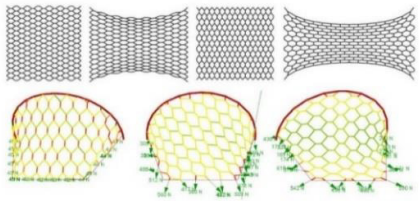
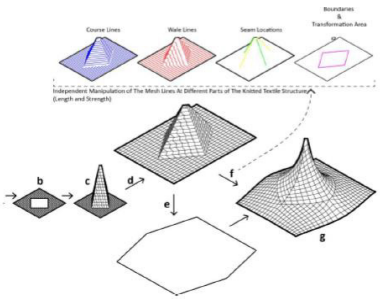
4 Common plugins for the form-finding process and designing tensile structures

In another study by Oghazian, Farrokhsiar, and Davis (2021), a 3D knitted shape is used as an initial shape, and through manipulation of the length of the mesh edges, the methods for inputting the material characteristics are explored. The table in Figure 5 illustrates some of these studies in the literature.

METHODOLOGY

This section represents the form-finding and analysis of a conical knitted tensioned structure as a case study using Kangaroo2 in conjunction with K2 Engineering and Kiwi!3D. The conical shape is selected as one of the most common tensioned structure models we could knit seamlessly using our lab's simple hand-held knitting machine (Silver Reed SK 840, standard gauge). Figure 7 and 8 show a series of conical models made with wool yarn. The first section of Figure 4 also shows the simulation results for another common form in tension structures known as hypar.

In all of the plugins, the main steps of form-finding are: defining the initial shape, determining the boundary conditions, applying forces, and inputting knitted textile material characteristics. The potential and limitations of the tools for simulation of the 3D knitted tensioned structure are highlighted in the following sections.

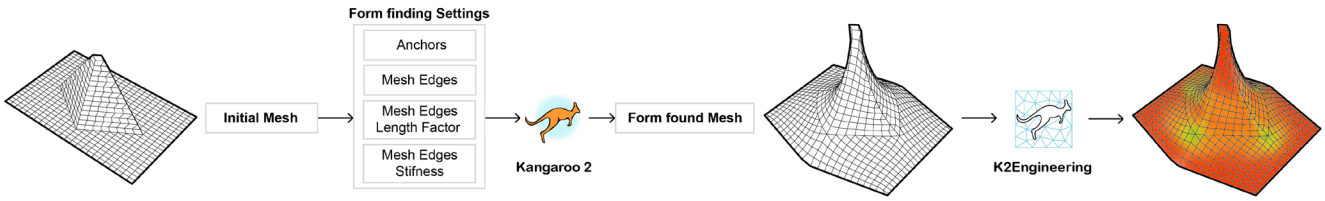
Reference	Software/ Interface/ Logic	Pictures
(Ahlquist and Menges 2013)	springFORM/ Processing/ Spring particle-based Knitting	
(Schmeck and Gengnagel 2016)	Kangaroo2/ Grasshopper/ Spring particle-based Knitting	
(Oghazian, Farrokhsiar, and Davis 2021)	Kangaroo2/ Grasshopper/ Spring particle-based Knitting	

5 Software and plugins that are designed or used in literature studies for analyzing knitting behavior

Kangaroo2 and K2 Engineering

The Dynamic Relaxation (DR) approach for solving structural problems was initially created in the 1960s (Day 1965) and has since gained widespread acceptance in various areas. DR is often related to stiffness-independent membrane shape discovery in the built environment (Barnes 1999) or with the distribution of architectural grids across curved surfaces (Williams 2001). Instead of using the usual force-based technique, where added forces at nodes produce accelerations, the Kangaroo solver works based on the configuration of the vertices with various degrees of freedom. While Kangaroo1 uses Dynamic Relaxation, Kangaroo2 logic is based on the Projective Constraints method (Cuvilliers et al. 2018). Hooke's Law is used in Kangaroo for determining axial stiffness and bending stiffness is based on the Barnes/Adriaenssens model (Barnes, Adriaenssens, and Krupka 2013).

Since Kangaroo accepts mesh as an input for the initial shape, one advantage of using such a tool is that the mesh can replicate the initial form that should be knitted with each mesh face as a substitute for a stitch. Also, the sizes and number of these mesh faces can be controlled so that the shape and size of this initial shape correspond to the actual material properties. As it is illustrated in Figure 3, the initial mesh of a cone is simulated, and the mesh faces are distributed to correspond to the knitting patterns. Then the form-finding settings should be determined. One advantage of the Kangaroo2 is that the initial and final positions of the anchors can be different. It is crucial because in simulating materials like knitted textiles that possess elasticity obtained from their unique structure, the stretchability of the material and extent to which the material could be stretched can be simply simulated by assigning points from the initial mesh as an initial anchor state and points from the final destination. Another advantage of the Kangaroo2 is that a length factor can be assigned to the mesh edges that represent the stretchability of different sections of the model. In working with knits as a flexible and multi-directional material, stitches will behave differently in different areas of the model. Assigning different length factors to these various areas allows having better control over the length change of the meshes to correspond to the actual material behavior. More details about the model's simulation and the automated process can be found in the authors' previous papers (Oghazian, Farrokhsiar, and Davis 2021; Oghazian, Brown, and Davis 2022).



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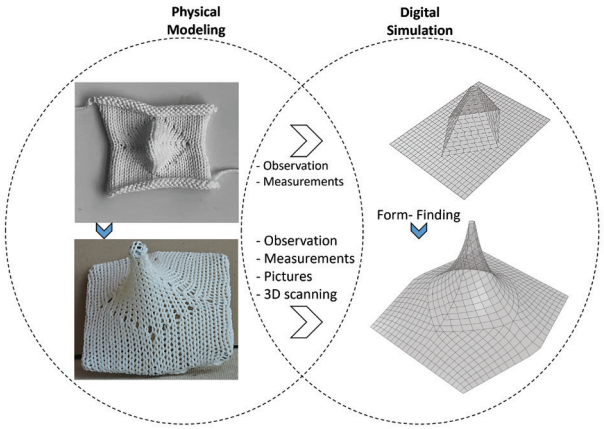
While Kangaroo can perform the form-finding process, K2Engineering can be used for the further structural analysis of the form-found shape (Figure 9). K2Engineering for Kangaroo is a plugin developed by Cecilie Brandt-Olsen that contains a set of customized Kangaroo2 Grasshopper components that can be used for calibrating goals regarding the structural performance of the tensioned fabric structures (Brandt 2019). Both form-finding and analysis can be performed within the Grasshopper environment using a combination of Kangaroo2 and K2Engineering. Figure 10 shows a series of simulations under the self-load of the knitted textiles of different *E* modulus. While at the form-finding step, the length factor of the meshes is the essential element in determining the overall form, at the analysis step, the features such as the *E* modulus determine how the structure performs under the self-weight or external loads.

Kiwi!3D

Kiwi!3D is another plugin for Grasshopper/Rhino that uses Isogeometric Analysis (IGA) techniques developed by Hughes et al. (2005) for finite element analysis. The advantage of this approach is that it uses Non-Uniform Rational B-Splines (NURBS) as the basis of the analysis. It is essential to consider because most form-finding tools perform on mesh as the initial shape, while in Kiwi!3D control points play a role in form-finding; therefore, remeshing and element discretization is not required. While this is an advantage in a working environment such as Rhino, it would become problematic—when simulating knitted textiles—to substitute each stitch with a simpler shape to have better control of the stitch itself and the combination of stitches that define the overall form. Each stitch can, however, be simulated as one brep, and the joined B-reps can be fed into the form-finding algorithm. One manipulation required at this point would be to change the polynomial degree of individual B-reps to one so that each B-rep edge can be treated as a line. One drawback of this method is that it would be computationally more expensive than using meshes in Kangaroo. Thus Kiwi!3D would be a good method if simulating the stitch distribution is not the case. Otherwise, Kangaroo performs much faster. Figure 11 illustrates a simulation process that takes the output of Kangaroo2 simulation for further non-linear analysis of the model under self-load in Kiwi!3D. Another advantage of IGA during the design process is the independence of the parametrization for boundary conditions such as loads, supports, and coupling entities. This allows the user to seamlessly integrate



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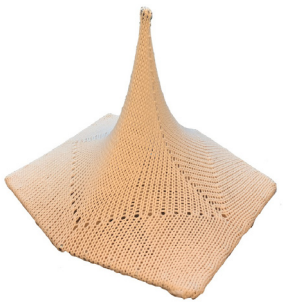
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6 Form-finding with Kangaroo and displacement analysis with K2Engineering

7 A series of conical knitted samples

8 Single conical shape used as a case study of the simulations

9 Correlation between physical and digital simulation as well as initial and final form-found mesh

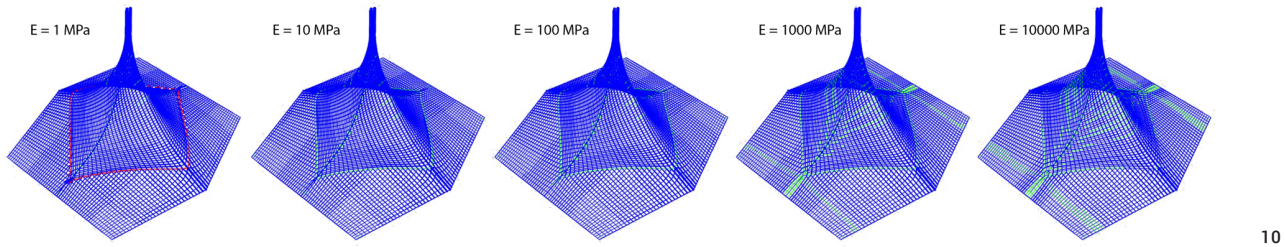


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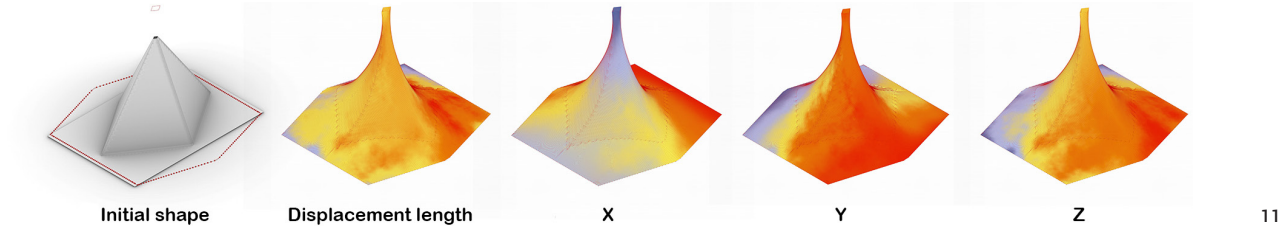
different design elements and have better assessments without losing or needing to estimate the stresses and displacements (Bauer et al. 2018).

PHYSICAL MODELING/DIGITAL SIMULATIONS

To have a reliable model, the digital simulations should always be compared against the physical models. Since the dimensions and shape of the initial mesh are according to the actual knitted sample, if we could predict the length change of meshes at different sections of the models, then we can get a form-found model that represents the actual material behavior. Figure 9 shows the interrelated connection between the physical and



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digital model as well as the initial and final form-found mesh. Additionally, the simulations are done for a series of models of the same shape but at different scales to understand the behavior change across the scales. As we scale up, the number of stitches in the actual physical model increases, as does the number of mesh faces in the digital model. This increases the computational process time. One solution would be to pack a series of mesh faces into one mesh face. How reliable to model would be is the topic of another ongoing research.

CONCLUSIONS AND CONTRIBUTION

This research study shows the potential of different Grasshopper plugins for simulating and analysis of knitted textile structures. The main contribution of this study is elaborating the form-finding and analysis of knitted tension structures using Kangaroo2, K2Engineering, and Kiwi!3D, emphasizing the material behavior and shape of the knitted model. The results show that Kangaroo 2 is a faster tool in case the stitches' exact distribution is to be applied during the simulation process. Having a mesh with such a mesh face configuration is essential because it allows the users to have control over the individual stitch. This becomes more helpful, especially when dealing with knitted textiles with a gradient pattern. Additionally, having a mesh that represents the actual stitch distributions allows the designer to get more accurate feedback after the analysis step.

The main takeaway of this study is that these tools suggest a new way of practicing that incorporates software that allows for multiple behaviors from a 'material,' a craft, rather than a design being imposed on an abstract 'material' (hylomorphic and Albertian) (Ingold 2009). With the drafted algorithms using the aforementioned plugins, we now have a way to be in conversation with the formation, thus conducting form-finding through the material, not form-finding onto the material.

10 Analysis with K2Engineering; *E* modulus is the variable, and colors show the axial force

11 Kiwi!3D analysis with different force factors

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IMAGE CREDITS

Figure 2: Redrawn after Puystiens et al. (2016); figures in the tables are referenced according to the sources used; images in Figure 3 are redrawn from associated sources.

All other drawings and images by the authors.

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Session Introduction

New Ecologies I: Biomaterials / Biotech

Laia Mogas-Soldevila, Chair

These texts unfold the complexities of biomaterial-driven design and fabrication at all scales of the architectural discipline. Underwater landscapes are scrutinized, and their sedimentation dynamics redesigned in favor of coral reef restoration; new grid shell logics are derived by embracing baboo growth eccentricities in favor of performance heterogeneous structures; to make walls, cellulose and other soft waste materials are combined into pastes to manufacture modules able to interlock despite their brutal shrinkage dynamics; column-making mycelium is guided to achieve intricate surface geometries by growing within printed lost formwork, and finally; extruded fibrous hydrogels restore wooden window frames while augmenting aesthetics with in-situ pigment diffusion dynamics.

In all projects, the role of material heterogeneity is refreshingly celebrated as a design driver instead of traditionally discarding it as a nuisance. The multiagent dynamics of oceanic sediment deposition directly inform new solid-to-porous geometries that redirect geological shape to protect corals from humans and their effect in the environment. Intrinsic non-regular biological geometric properties that make the section of bamboo vary throughout its length are direct inputs to develop a digital design workflow. Cellulose pastes' hygroscopicity and shrinkage are carefully harnessed to derive cyclopean stacking as materials harden becoming compression stable. New solutions arise when facing micro-fibrillated cellulose's segregation within its carrier hydrogel and when discovering mycelium's bonding to certain 3D printing materials.

The generation of new data is a crucial aspect in these investigations as biomaterial-aware digital design and fabrication is still in its infancy and new datasets globally devised by researchers become bodies of knowledge to push the discipline further. Contemporary digital design platforms are already able to account for and accurately simulate complex phenomena such as fluid dynamics, finite element analysis, energy transmittance, computer-aided-machining etc.; however, they yet do not have the ability to design with the properties of natural materials. The authors unveil specifically relevant new information on evaporation-driven self-shaping, beams' section eccentricity, differentially distributed porosity, time-based digestion, or pigmentation during hydrogel drying. Importantly, they can encode it within digital design to fabrication workflows or are able to parametrize it for others to do so in a joint effort towards an inevitable era of biomaterial-driven tools.

Finally, works hint at the creation of a new aesthetic. One that results from bringing the organic into the digital world; from guiding unruly, curly, meandering, soft, and flowy matter into dry robust structures and systems. In collaboration with biology, our built environment will soon embrace currently uncommon phenomena of digestion, flow, deformation, wicking, shrinkage, or decay. Efforts presented next, contribute to its much needed cultural and disciplinary acceptance.