Computer-Aided Design 149 (2022) 103263

Contents lists available at ScienceDirect

Computer-Aided Design

journal homepage: www.elsevier.com/locate/cad

Rapid Sketching of Woven Textile Behavior: The Experimental Use of Parametric Modeling and Interactive Simulation in the Weaving Process

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ARTICLE INFO

Article history:
Received 2 April 2021
Received in revised form 7 March 2022
Accepted 19 March 2022

Keywords:
Woven textiles
Parametric modeling
Textile simulation
Design methodology

ABSTRACT

Woven textiles are typically designed with methods and software that demonstrate the graphical aspects of fabric but are limited in their representation of fabric behavior. The category of textiles that undergo shape changes in the finishing phase is well suited to alternate design approaches that incorporate predictive modeling. In this paper, we describe a methodology that uses parametric modeling and simulation to ideate, refine and inform physically produced woven fabrics with specific dimensional qualities, shifting the iterative work inherent to textile design into a digital space.

1. Introduction

The weaving process is notoriously labor, material, and time intensive, with considerable effort and reliance on arduous physical sampling in order to make the decisions critical to the successful development of a woven textile. The goal of this project is to develop a methodology for rapidly sketching potential forms for woven fabrics in a way that is compatible with the parameters that textile designers take into consideration during the weaving process. We show how the “off-label” use of a surface modeling software with parametric and physics form-finding capabilities to model surfaces that reasonably represent woven textiles, with a range of behaviors consistent with physical fabrics, can enable quick and meaningful experiments rarely enjoyed in the typical weaving process. In this paper, we focus on fabrics that relax or change shape after weaving, especially those that assume non-planar surface forms and have non-rectilinear edges when released from tension off loom. While the weaving process typically results in flat, rectangular fabric panels, the use of yarns that shrink, twist or otherwise move during finishing is a well-established method of manipulating shape in both hand and industrial-scale weaving. Differential shrinkage, typically resulting from the combined use of variable weave structure and active yarns, may be used to create decorative textured surfaces, specific dimensional changes, or both, but often requires numerous rounds of physical sampling before the desired effect is captured.

The methodological framework for our experiments makes use of the parametric modeler Grasshopper for Rhinoceros and the interactive simulation plug-in Kangaroo, software that has seen widespread adoption for architectural and design application but has limited uptake in the textiles community. In addition to existing components that could be considered analogous to controlling parameters translatable into a plan for weaving, this platform was chosen for its dynamic visual depictions of surfaces changing in response to user inputs and physical forces. Quick iteration and discovery of new design features were key priorities, given the time and material intensive nature of prototyping on a loom. This methodology considers potential textile applications in which unique boundary shape and texture of woven fabrics are desirable, for example, one piece construction for upholstery seat covers, engineered panels in sound-baffling systems or whole-garment weaving [1]. While considerable effort has been made towards the computation and construction of complex knitted textiles [2–7], current weaving software has not enjoyed a comparable level of advancement and the constraints of weaving limit approaches to engineered form. The parameters and methods we deploy closely consider common working practices of textile designers, in which the visual composition of elements on a woven surface form and its overall behavior is fundamentally tied to material choices and construction techniques that make up the weaving process.

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https://doi.org/10.1016/j.cad.2022.103263
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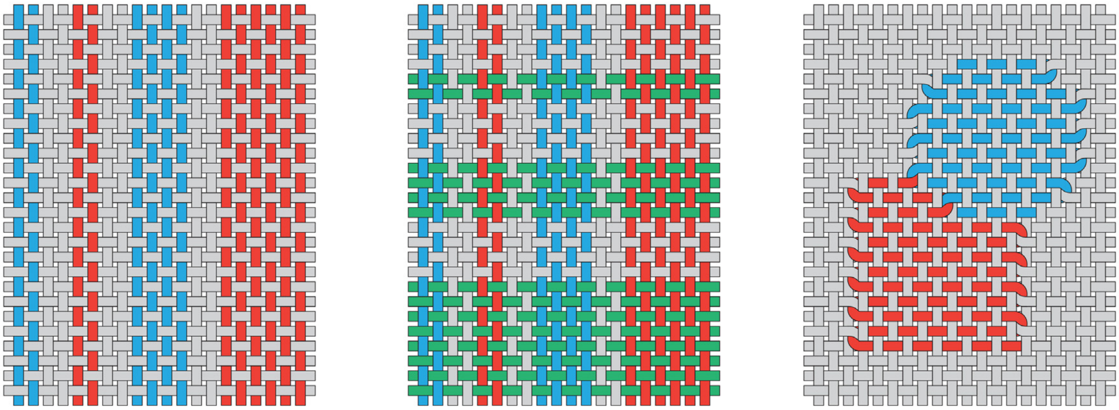


Fig. 1. Woven fabrics with warp striping; with warp and weft striping; with weft tapestry.

2. Elements of the weaving process

2.1. Weaving basics

Woven fabrics are composed of warp yarns and weft yarns interlaced at 90° angles. In the weaving process, warp yarns are wound onto a beam under uniform tension and threaded through heddles on the harnesses of a loom, with each harness controlling a group of warp yarns that can be raised independently of other groups. Weft yarns are inserted through the shed, or the space between raised and non-raised warp yarns. The pattern in which warp yarns are raised over weft yarns forms the weave structure, represented by a weave draft.

Warp yarns are continuous throughout the length of the fabric. Multiple yarn types can be combined in the warp, resulting in vertical stripes: the arrangement of warp yarns is made during loom set-up, prior to weaving, and cannot be changed. Weft yarns are usually continuous across the width of the fabric; tapestry, a handweaving technique, is an exception in which wefts are woven through a section of warp yarns to create patchwork-like areas of fabric containing that weft yarn. Multiple yarn types can be used as wefts, resulting in horizontal stripes. The sequence of weft yarns can be changed at any point in the design phase prior to weaving (see Fig. 1).

Warp and weft striping can be used to control the placement of active yarns in a fabric: alternating weft stripes of shrinking and non-shrinking yarns, for example, will result in a fabric with differential shrinkage in horizontal bands across its entire width. Due to the continuous nature of weft and warp yarns, placing an active yarn in a small or curvilinear region requires time intensive supplementary processes. Where differential shrinkage is required in fabric regions of this type, designers can instead use localized placement of certain weave structures that modify the degree to which a yarn's properties are expressed as fabric behavior.

2.2. Yarn properties

Yarns used in woven fabrics can vary significantly in diameter, fiber content, twist, surface texture and overall appearance. These qualities, as well as the mechanical properties of yarns such as tensile strength, elasticity, and stiffness, influence the appearance and behavior of fabrics. Elastomeric yarns (such as spandex) can be stretched to several times their original length and quickly recover; other yarn types, such as wool and some thermoplastics, shrink permanently by as much as 50% when heated or washed. Nylon monofilament is a yarn with relatively high resistance to bending, which increases with its diameter, while many other yarns (such as cotton) have low stiffness and bend easily. Measuring and accurately representing these properties is a crucial part of textile simulation: in its current stage, the process described here does not include yarn-level specifications, instead depicting mechanical properties of a surface representing a sheet of material as specified by the user.

When multiple yarn types are combined, the resulting fabric properties are determined by the proportion of each yarn present and the weave structure used. A fabric with a weft sequence of 1 pick (insertion) elastomeric yarn and 4 picks cotton yarn will have a lower degree of horizontal stretch than an identical fabric with only elastomeric yarn wefts. Both fabrics will stretch to the same maximum width, but the fabric containing cotton will have a greater width in its relaxed state, due to the cotton yarn limiting the ability of the elastomeric yarn to contract.

2.3. Weave structure

The simplest weave structure, plain weave, involves warp yarns alternately being raised and lowered over each weft, producing the maximum possible number of interlacings. Other common structures such as satin and twill have fewer interlacings, enabling them to shear and drape more easily. Weave structures with floats, or long spans of yarn without interlacings, likewise have a lower level of inter-fiber friction, and some yarn behaviors (notably shrinkage) are more pronounced in long floats, where the yarns are unconstrained. The density of warp yarns (ends per inch, or EPI) and weft yarns (picks per inch, or PPI) can also be modified: lower-density ("open" or "sparse") weaves tend to have lower stiffness and allow yarns to move more freely. EPI and PPI are not represented in the weave draft but are necessary to understand how a chosen weave will behave.

Woven fabrics may also have two or more layers, produced by weaving weft yarns through subsets of warp yarns that do not intersect. In doubleweave, warp yarns are divided into two sets, e.g. with all yarns on odd-numbered harnesses in the upper layer and all yarns on even-numbered harnesses in the lower layer. The upper layer is woven by lifting selected odd harnesses to create the desired structure, keeping all even harnesses down. The lower layer is woven by lifting selected even harnesses in addition to all odd harnesses, raising the upper layer out of the way. A separate weft yarn is typically used for each layer. This method treats each subset of warp yarns as a single-layer fabric to be woven, and maintains the order of fabric layers by keeping unused warps either above or below the layer currently being woven. Three or more layers can be woven in a similar fashion (see Figs. 2 and 3).

Layers can be woven simultaneously without joining, resulting in separate pieces of fabric; they can be selectively joined at a

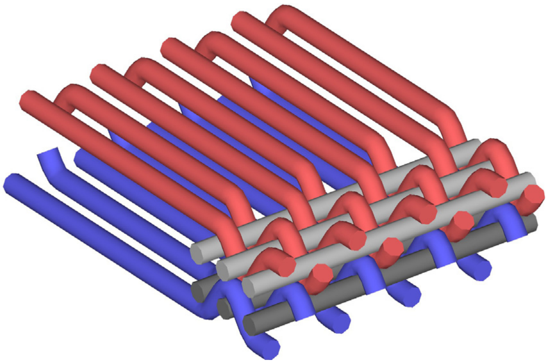


Fig. 2. Two layers of plainweave, woven by dividing the warp into upper and lower layers.

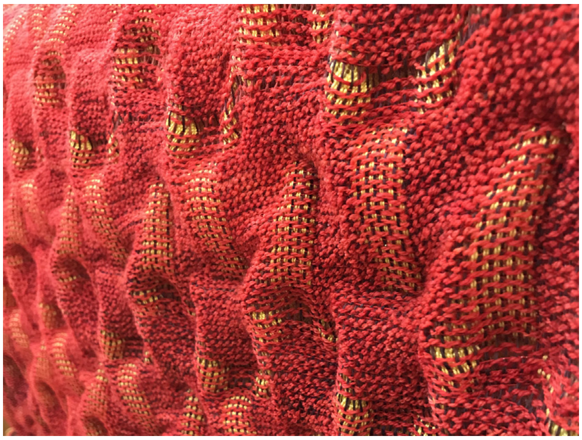


Fig. 3. A three-layer fabric with differential shrinkage and tie-downs in a chevron formation, resulting in a repeating pattern of surface texture.

single point (called a tie-down), along a line (called a stitch), or in a region of any shape, unifying that area as a single layer. Layers of fabric can also exchange positions within shape regions, resulting in boundaries defined by different combinations of warps and wefts. The use and composition of linkages in multi-layer fabrics results in complex textile architectures and permits manipulation of visual and mechanical properties.

2.4. Designing woven behavior – a textile practitioner's perspective

Textile designers have developed a number of strategies in order to design for structural and behavioral possibilities in woven fabrics. Many of these are empirical approaches, largely defined by good practice gained from years of experience or borrowed from precedent work. While not exhaustive, a number of these textile-specific design strategies were assessed in developing a methodology for sketching woven behavior using digital modeling and simulation tools that would align with the working practice of textile designers.

To achieve certain fabric appearance or behavioral qualities, a textile designer may evaluate a host of related considerations – graphic legibility, textural range, structural, material and end-use performance – before making the key decisions on yarn types and weave structure central to the construction of woven fabric. These considerations are often weighed simultaneously and have been absorbed into common design strategies wielded by textile practitioners, such as the following examples:

- Making a composition of different fabric behaviors, often represented by a graphic image with color-coded regions corresponding to regions in the weave draft.
- Testing several variations of a design simultaneously (for example, using warp striping and weft striping to create a matrix of all possible yarn combinations). The resulting fabric, known as a sample blanket, generates options including those that the designer may not have envisioned, and is used as a reference when selecting qualities to incorporate into a fabric at full scale.
- Using systems of contrasts to create texture: woven fabrics can be considered in terms of their paired elements such as upper and lower layers of doubleweave, or their distinct behaviors in warp and weft directions. Applying opposing properties to each element in a pair, or to two adjacent regions of a fabric, is an intuitive method of creating dimensional surface effects. A doubleweave fabric with polyester wefts on one layer and mohair wefts on the other will have significantly different tactile qualities on the face and reverse: if layers are exchanged in select regions, a variegated surface of smooth and textured areas is formed.

Just as good practice and precedent study can spawn informed design strategies, these can also reveal common limitations. Foremost amongst these limitations is the material, labor and time intensity of the physical sampling process. Experimentation can be costly when it takes repeated adjustment of variables and subsequent observation for the designer to visually understand the causal relationship between input value, such as material attributes and yarns per inch, and surface appearance. Material waste may be significant, for instance, in the case that the designer wishes to experiment with effects that are irreversible, such as felting (which causes shrinkage of wool yarns) and which can greatly distort the initial loomstate fabric. Additionally, reliance on good practice and precedent study alone rarely permits exploration of potentially innovative design solutions that depart from known cases.

2.5. Woven textile design software

Weaving fabric, whether on a manually controlled loom or industrial loom, requires a weave draft or card image to specify which warp yarns to raise for each weft. Pointcarre is a textile-design software in which weave structures can be allocated to regions of a graphic image based on color, creating a corresponding card image or file that can be fed directly to an industrial loom [8]. Composing the fabric visually and then substituting structure is convenient and intuitive for designers, but the system's 2D depiction of woven fabric limits its usefulness in predicting the dimensional appearance of multi-layer fabrics, and does not address yarn or fabric behavior. Any sketching of more complex fabric architecture, such as the formation of pockets through placement of single-layer and multi-layer weave structures, must be done outside the software space.

Weavecraft is a relatively new tool for design and simulation of 3D-woven fabrics that can also be used in 2D weaving: multi-layer fabrics are represented in a much more legible manner, allowing the user to quickly make and verify structural changes, and complex card images can be generated by "stenciling" weave structures into regions of an image [9–11]. Its simulation capabilities [9–11] provide additional insight into how the modeled fabric will relax. With regard to the category of shape-changing fabrics described here, which may have 3–4 layers but are not 3D-woven, Weavecraft's current limitation is that yarn properties in simulations can only be specified globally. Multiple yarn types are typically needed to produce self-shaping effects such as differential shrinkage in fabrics, and would require specification of properties at a group or individual level to simulate accurately.

Another relevant category of software for our focus on dimensional fabrics is 3D modeling platforms that incorporate interactive simulation. Real-time physics-based simulation of fluids, rigid bodies and fabric is used extensively in the computer graphics community and is available for programs for animation, modeling and rendering (e.g. Maya, 3DS Max, Cinema4D, Blender) and, more recently, popular CAD environments such as Rhinoceros. The Kangaroo plug-in for Rhinoceros is a good example of this type of software, and its dynamic relaxation type (more specifically, projective constraint-based) solver makes use of projections ("goals") as defined as functions acting on a set of points, which can describe geometric constraints, elastic material elements, applied loads and forces [12]. These goals include components such as stiffness, stretch and shear, which are then applied to geometry, describing how they will behave in a relaxed state. A more fabric-focused approach is found in CLO3D and Marvelous Designer, programs in which panels of fabric can be joined, fitted onto a model and simulated, showing the effects of gravity, compression and the wearer's movements [13]. The user can import and adjust fabric properties, and observe the simulation while modifying fit and appearance by manipulating garment pattern outlines.

The accessibility and speed of these real-time physics solvers for 3D tools is an advantage for non-experts in numerical modeling for structural analysis to experiment with relatively high-quality outcomes; used together with parametric modelers, iterative workflows involving shaping, simulating and refining have resulted in a number of impressive fabric structures [14–16]. The role of such tools in designing such hybrid textile architectures – comprised of structural "bending-active" elements like GFRP rods and an elastic knit fabric membrane – shows tremendous promise for shape-changing woven fabric, which, as we will see, often derives its dimensional surface behavior through a hybrid architecture of weave structure and active yarn. The potential role of these tools in the weaving process, largely untapped, is to use woven fabric not just as a material in complex constructions but as a complex material itself.

3. Towards a methodology for sketching woven behavior

The development of an approach to facilitate decision-making and exploration in the weaving process using modeling and interactive simulation started from identifying a class of fabric behavior previously explored through extensive physical weaving experiments. The class of shape-changing fabrics that we focus on here encompass behavioral effects such as folding, rigidity, stretching and shrinkage, which could be controlled in the weaving process through a combination of variable weave structure and localized placement of active yarn. Work was initiated in the following phases: (1) setting up a parametric model to establish the connection logic of variables to properties of physical woven samples; (2) calibrating the simulation to behavior from physical experiments; (3) using the modeling and simulation workflow to generate concepts for new woven designs; (4) producing physical fabric samples with specifications determined by surface parameters. Coming full circle in this process enabled us to develop and tune a new working process which could be compared for predictive accuracy to woven results from the loom, thereby assessing the usefulness of this methodology for rapid sample behavior sketching in the textile design process.

3.1. Modeling fabric behavior

We sought an integrated platform to model geometry that could act as surrogate for woven fabric, specify properties dynamically with visual feedback, and simulate the fabric behavior as deformed geometry. Rhinoceros is a 3D modeling environment which is popular in architecture and design communities and has become a diverse ecosystem through interoperability and numerous plug-ins that has extended its reach beyond digital modeling of free-form curves and surfaces to digital fabrication, physical computation and data visualization, amongst other applications. Grasshopper is a visual-programming plugin for Rhinoceros that enables parametric design by building code from components. Kangaroo and Grasshopper are often used together for form-finding, for example, simulating a draped sheet of material in order to design a rigid shell or visualizing how structures with many elements will behave. In the work described here, the programs are used to simulate the relaxed shape of a sheet of fabric with varying behavioral qualities, as part of the design process and as a precursor to physical fabrication.

A rectangular grid was used as an abstraction of a single-layer woven fabric, with vertical line segments representing groups of warp yarns and horizontal line segments representing groups of weft yarns. With this method, weave structures and interlacings between individual warp and weft yarns are not depicted: instead, behaviors are assigned to line segments using Kangaroo goal components, and the output surface is indicative of how a physical fabric might appear. Specifying fabric properties, rather than yarn properties, is a quick and direct way to both validate models of existing fabrics and sketch new forms, but requires subsequent work to reverse-engineer the desired properties into a plan for weaving. Future additions to this process may include guidelines for matching structure and material combinations to values for each component.

The Grasshopper definition was created by selecting previously woven fabrics, mapping their behaviors onto regions of a grid, visually comparing the relaxed grid to the fabric and fine-tuning repeatedly. The selected fabrics contain multiple yarn types with contrasting properties: shrinking yarns (elastic) and stiff yarns (nylon monofilament), with each fabric demonstrating a unique behavior such as sharp folding or smooth buckling. The weave structure includes short elastic weft floats placed either over or under a densely woven base fabric, arranged in vertical columns and diagonal bands. When the fabric is relaxed, the elastic floats contract and the base fabric does not, instead buckling in regions where the floats are located to produce mountain and valley folds. These fabrics were chosen because the way they self-fold when released from tension on the loom, transforming from a flat rectangle to a form with periodic height variations, is comparable to a modeled surface approaching a converged state in Kangaroo. The tensile forces that drive this transformation in physical fabric are analogous to goal components that dictate the modeled surface's appearance (see Figs. 4 and 5).

The calibration process consisted of first determining the appropriate Kangaroo goal components to produce a surface topography that reflected a physical fabric behavior, then adjusting their relative strengths until each model's converged state closely resembled the physical fabric. During this stage, with each iteration taking a few minutes to evaluate in its converged state, the core components for modifying surfaces were established. Shrinkage, controlled by the *Length* goal with inputs ranging from 0 to 1, can be applied to any individual line segment, and dictates the fraction of its original length that the line segment will contract to. Stiffness, controlled by the *ClampAngle* goal with inputs ranging from 0 to 1, can be applied to any pair of consecutive line segments, and reflects the degree to which the fabric in

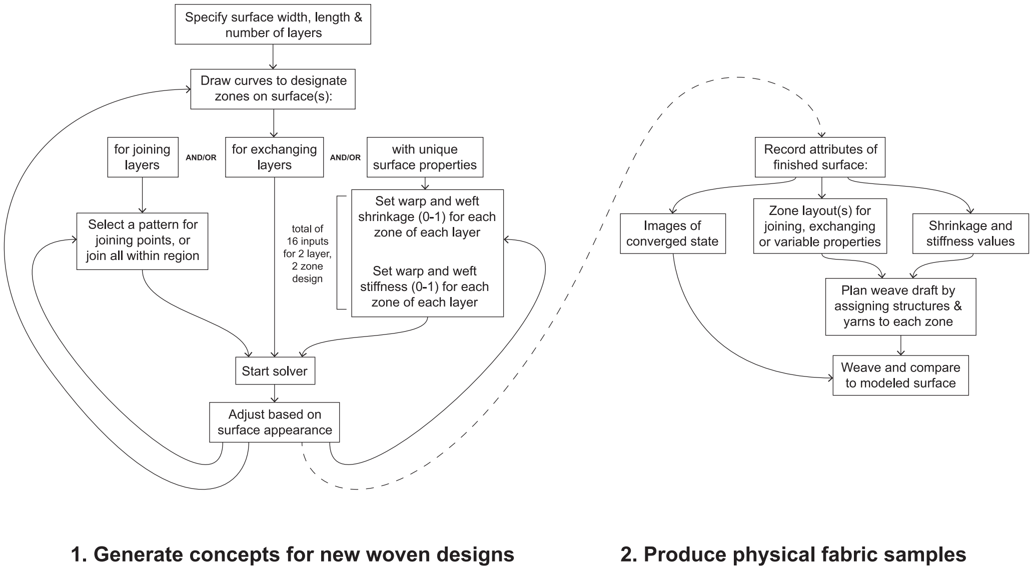


Fig. 4. Diagram of design and physical sampling workflows.

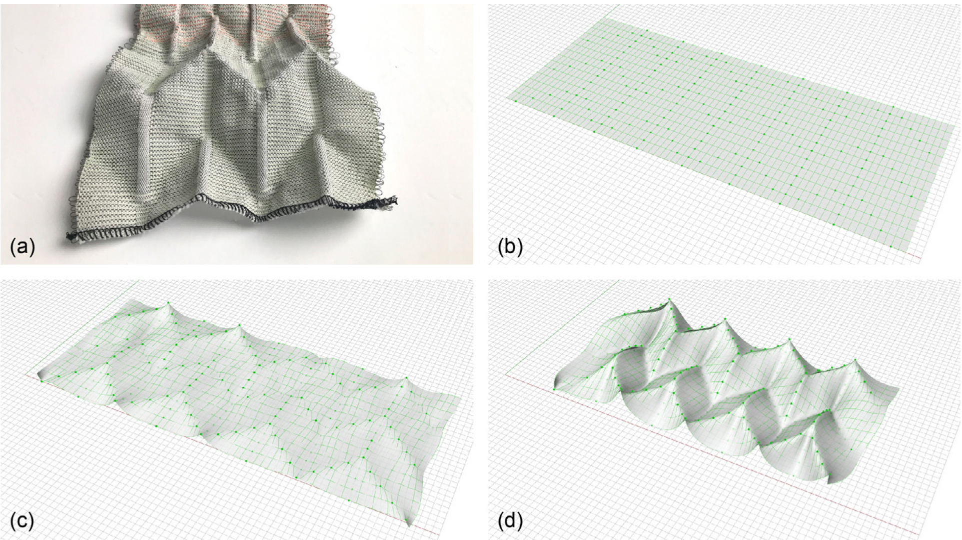


Fig. 5. A self-folding woven fabric used during the calibration process (a), and a surface model with similar properties as the fabric, shown relaxing into shape (b, c, d).

that region will resist bending when other forces (such as the shrinkage of nearby regions) are applied. Because stiffness is described qualitatively in this system, with 1 as the maximum value, adjusting the strength of the *ClampAngle* goal during the calibration phase was essential for setting an upper limit that resulted in behavior comparable to the stiffest yarn typically used to weave such fabrics. These properties are frequently used, especially in opposition to each other, in weaving dimensional textiles but are by no means responsible for all textile behaviors. Shear, drape, the effects of yarn twist direction and yarn size (bulk) are among the other properties critical to the accurate simulation of fabric behavior. Shrinkage and stiffness were chosen as variables because of their direct conceptual connection to particle spring-based simulation, the large-scale deformations they can produce at relatively low resolution, and the broad range of visual effects that can be achieved by manipulating them. In fabrics, shrinkage and stiffness are generally caused by the interaction of yarn behavior and weave structure, which can be fine-tuned to produce a specific degree of either behavior.

3.2. Connecting properties to user-generated designs

To use the components of shrinkage and stiffness more effectively for design and iteration, the Grasshopper definition was then modified to allow assigning unique values for each parameter, in both warp and weft directions, to each region of the surface. This was initially done by allowing the user to address rectangular regions of the grid; later, the ability to define a region bounded by curves drawn in Rhinoceros was added. Users familiar with these drawing tools can quickly generate their own compositions; for others, moving and scaling existing curves (such as the set of sample files) may be faster. The simplest approach, used here, designates "Zone A" as the area inside the curve(s) and everything outside as "Zone B", but any number of additional zones could be defined, each with its own set of warp and weft shrinkage and stiffness values.

As in the physical weaving process, an additional surface can be stacked above the original surface in the Grasshopper definition, representing an additional layer of woven fabric. In addition

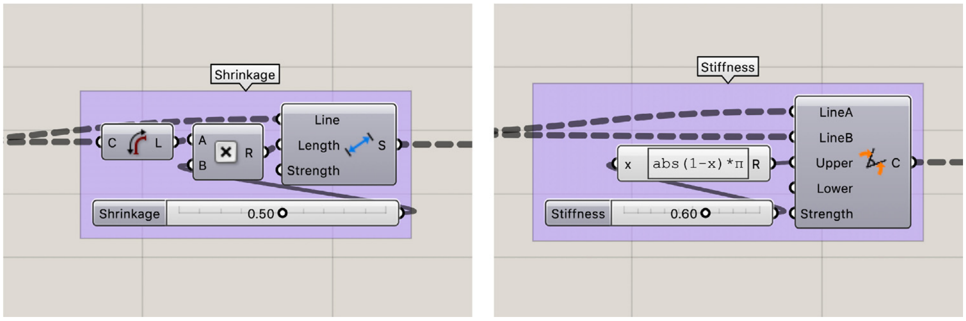


Fig. 6. Use of *Length* and *ClampAngle* components in Kangaroo to control shrinkage and stiffness.

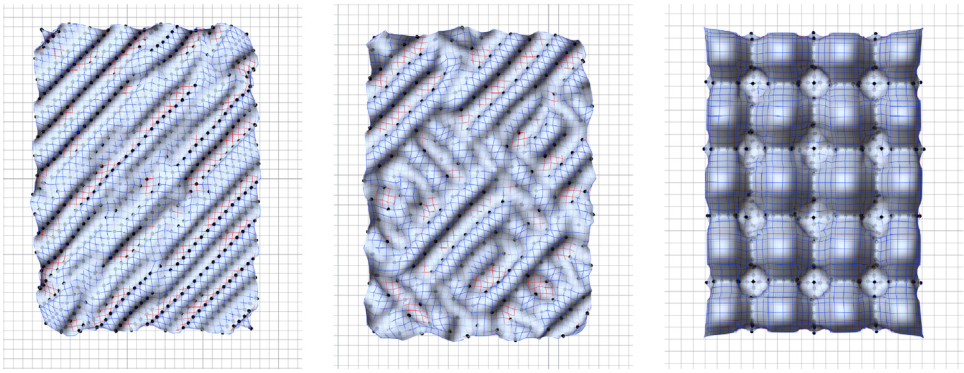


Fig. 7. Layer-joining patterns including (from left to right) diagonals, staggered points, and a square grid produce distinct textures in the same model. Black dots indicate tie-downs.

to specifying warp and weft shrinkage and stiffness in each zone of each layer, there is an opportunity to specify how adjacent layers in the stack interact. In Grasshopper, any pair of corresponding points on two layers can be specified as joined (using a *Length* goal with a very small value) or not joined; similarly, any pair can be exchanged (reversing their order on a vertically constrained polyline) or not exchanged. This simulation of fabric linkages is important in predicting the resulting physical behavior of the fabric: for example, the pattern of tie-downs between layers directly affects surface texture. A set of patterns were created for selecting point pairs to join (e.g. diagonal lines, uniformly spaced points), permitting quick testing of surface variations (see Figs. 6 and 7).

The use of curves to define join regions and exchange regions, and the opportunity to define repeating tie-down patterns, positions these attributes as analogous to the controls of woven fabric design when creating a visual layout that will eventually be translated into a weave structure.

3.3. Designing fabrics by manipulating surface properties

After establishing the ability to locally control shrinkage, stiffness, joining and exchanging of surfaces, a series of designs were developed to illustrate the range of potential surface behaviors. This taxonomic approach of generating a library of fabric behaviors has been a fruitful step towards developing designs for experimental weaving techniques in prior research [17]. Fabric behaviors were modeled including pleating, crumpling, curling, folding and complex curvature. Groupings of similar models showed subtle variations when either the shrinkage and stiffness values *or* the composition of zones A and B were adjusted. While the system was deliberately underconstrained in regard to “weavability” of modeled surfaces, many of the outputs were recognizable as fabric formations. It was also discovered that some compositions with high-shrinkage zones near edges caused significant distortion of the surface boundaries, inspiring textile applications for which non-rectilinear boundaries are desirable.

3.4. Translating surface behaviors to fabric specifications

Having iterated on the shaping and appearance of the fabric in digital space, the remaining phase involves adapting the approved design into a weave draft, then weaving and finishing the fabric. In typical textile design processes, drafting is directly followed by weaving and finishing, with evaluation only possible at the very end of the process. Refining designs prior to physical setup and fabrication raises the possibility of immediately producing fully realized and intentional designs, rather than many rounds of physical trials (see Figs. 8 and 9).

Translating the parameters dictating the surface behavior into a plan for weaving required more specialized textile design knowledge than prior steps. This methodology does not generate a weave draft or card image, but instead generates the appearance of surface behavior based on user-specified properties. Many of these surface behaviors are familiar to textile designers, as they are likely to be found in precedent cases of differential shrinkage. The designer must identify these behaviors, relate them to known fabrics or structural principles, and select weave structure and material combinations that will yield them in woven form. This process may be simplified in future versions by the designer selecting weave structure and yarn combinations with known shrinkage and stiffness values from a preset library, corresponding to physical woven samples similar to those in Table 1. This would reduce both the time and level of expertise required to close the loop on this process, from sketching to drafting, weaving and evaluation. For a few modeled surfaces, a successful weaving strategy could not be found, indicating that design guidelines such as a matrix of fabric behaviors known to be compatible in the warp and weft directions, based on the yarn types and weave structures needed to produce them, could be a useful

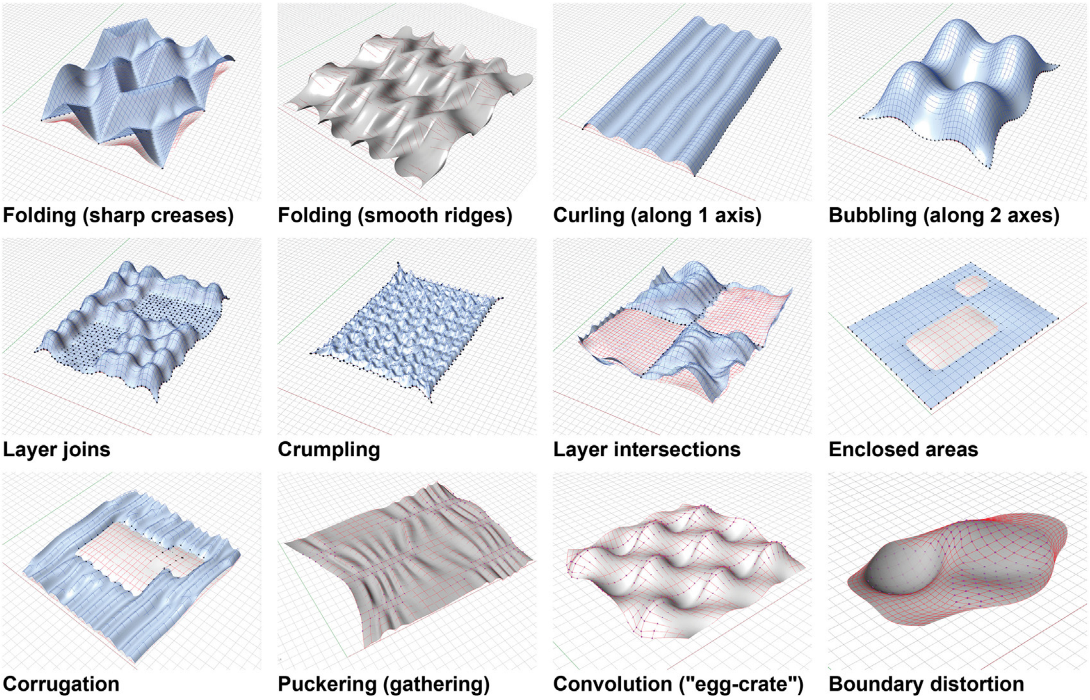


Fig. 8. Examples of behavioral qualities produced by manipulating shrinkage, stiffness and layer interaction.

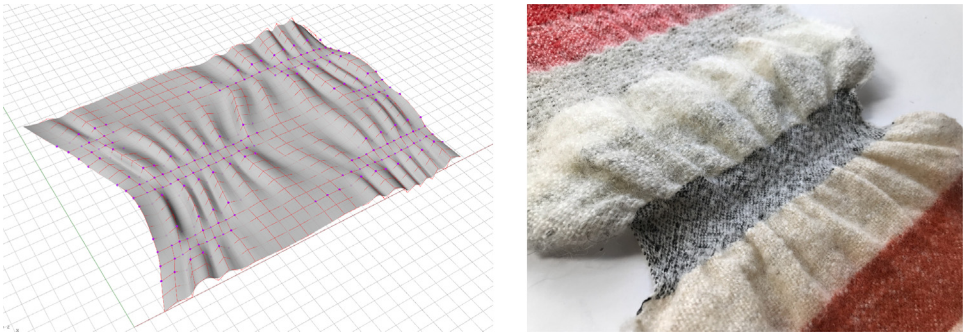


Fig. 9. A surface demonstrating puckering along partial horizontal bands, and a fabric sample with a weft stripe of shrinking yarns that create a similar effect.

addition. Further work is needed to determine if these guidelines could be incorporated as constraints in the parametric modeling environment.

4. Case study in weaving new potential fabric behaviors

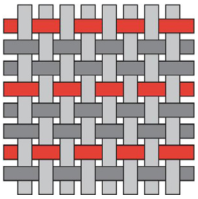
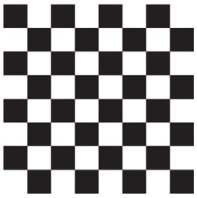
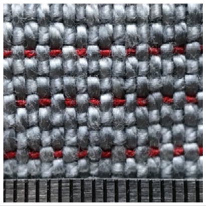
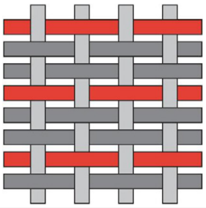
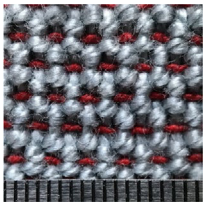
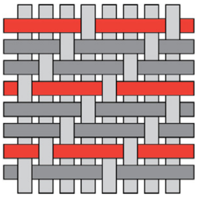
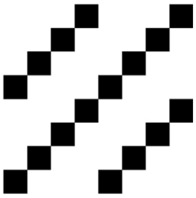
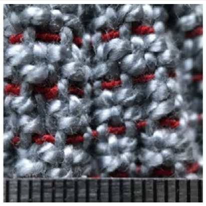
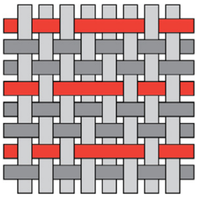
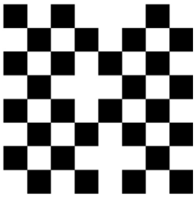
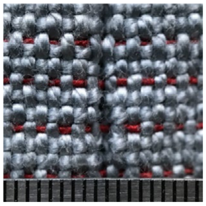
Our case study was based on the flat pattern for a long garment sleeve. Considerations for the sleeve designs included visual ornamentation, the haptic qualities of each fabric behavior when placed on specific sites of the body, and engineered panel shape as an alternative to cutting pattern pieces from fabric yardage. We developed four variations, each expressing multiple behaviors including boundary distortion and surface textures (crumpling, pleating, bubbling). While these behavioral qualities are certainly not independent of each other – surface texture from differential shrinkage will most often result in reshaping the fabric boundary – the designer has the opportunity to dictate the *type* of texture (rounded, crinkled, etc.) that excess material forms. The material palette for the fabric samples was set with consideration to the range of shrinkage and stiffness values present in each design. A thermoplastic yarn was selected for its ability to shrink up to 50% when steamed, as well as non-shrinking yarns such as merino wool, which has low stiffness, and a waxed linen yarn with high stiffness. Each surface was manipulated by adjusting the shape of high-shrinkage zones, re-starting the solver, and repeating until its boundary approximated the flat pattern. The iterative process was quick, with each model taking a minute or less to reach a converged appearance, and provided greater confidence that the first woven sample would adopt a boundary shape similar to the flat pattern outline, eliminating the need to weave and assess a series of samples.

Each design uses differential shrinkage to produce specific shape and texture. Weave structures with floats, few interlacings, and low warp/weft density tend to allow shrinkage while structures with many interlacings and high density prevent it. This structural contrast can be implemented in both single- and multi-layer fabrics.

4.1. Weaving strategy 1: Strategic placement of active yarns

A direct approach to differential shrinkage involves localized placement of yarns with specific properties. In this method, a single layer of fabric is woven with shrinking warp and weft yarns in a sparse plainweave. Between picks of shrinking wefts, which are inserted across the entire width of the fabric, a stiff, non-shrinking yarn with a large diameter is inserted as a tapestry weft,

Table 1
Weave structures and expected behaviors for a fabric containing elastomeric weft yarns (shown in red).

Weave structure	Weave draft	Description	Expected behavior	Relaxed fabric
		Plainweave with high EPI and PPI; elastomeric yarn every 3 wefts.	Very low shrinkage in weft direction	
	Same as above.	Plainweave with low EPI and high PPI; elastomeric yarn every 3 wefts.	Moderate shrinkage in weft direction	
		3 × 1 twill with elastomeric yarn every 3 wefts.	High shrinkage in weft direction; twills also have a greater degree of shear than plainweave.	
		Plainweave with elastomeric yarn every 3 wefts. Elastomeric yarns float over the 4th and 5th warp ends.	Very low shrinkage at left & right edges and high shrinkage of weft floats in center, resulting in a valley fold along vertical centerline.	

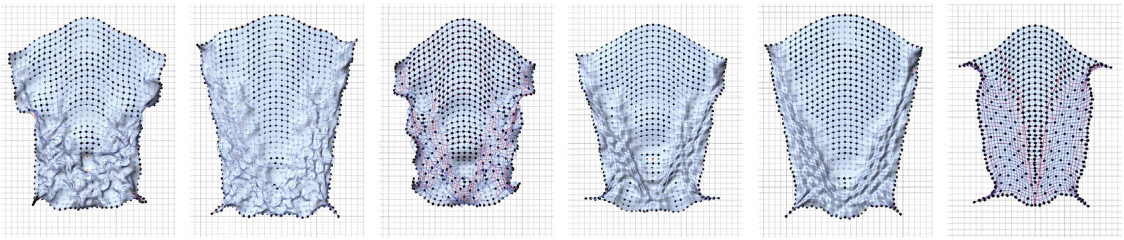


Fig. 10. Images captured during the iterative phase show the results of modifying high-shrinkage and joining zones. Sample 2A, shown in Table 2, was the final result.

weaving only in select regions. Where the tapestry weft is used, warp shrinkage is prevented by the high density of weft yarns, and weft shrinkage is prevented by the yarns' stiffness. In all other areas, both warp and weft shrinkage can occur (see Figs. 10–12).

4.2. Weaving strategy 2: Variable weave structure in two-layer fabric

With the addition of a second layer, contrasting fabric behaviors are straightforward to implement: here, layer 1 has shrinking warp and weft yarns and a sparse plainweave structure, while layer 2 has non-shrinking warp and weft yarns and a dense plainweave structure. Layer 1 will shrink in both warp and weft directions in all areas that do *not* interact with layer 2.

One variation of this technique joins the two layers with intermittent tie-downs in some regions, allowing layer 1 to shrink while layer 2 buckles. In the remaining regions, the fabric is woven as a single layer that has high warp and weft density and will not shrink.

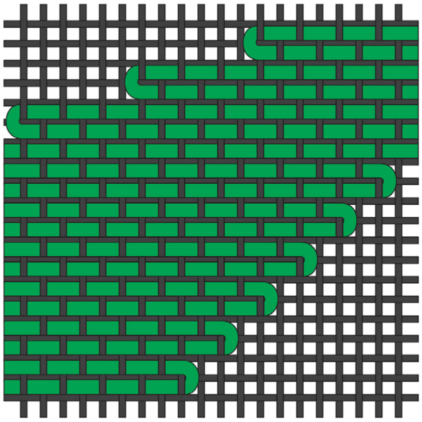


Fig. 11. A base fabric of shrinking yarns (black) is supplemented with non-shrinking tapestry wefts (green).. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

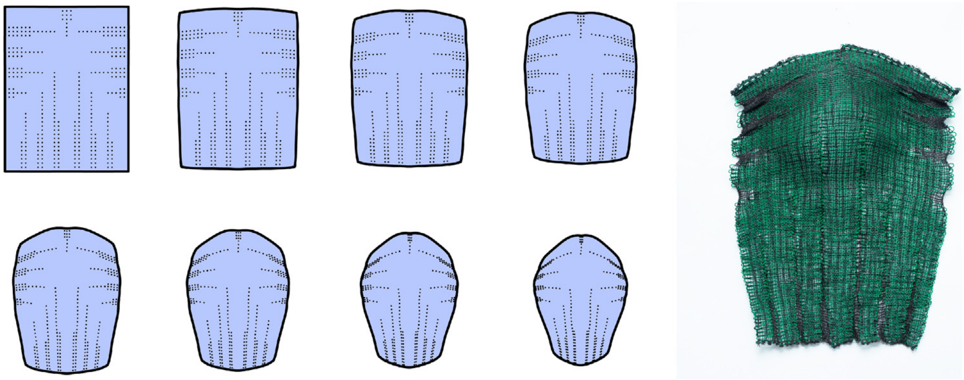


Fig. 12. Sample 1 model in a relaxed state, with shrinkage values ranging from 1 (100% of original length) to 0.33 in shaded areas. The physical fabric's relaxed appearance is reflected in this range of possible outcomes.

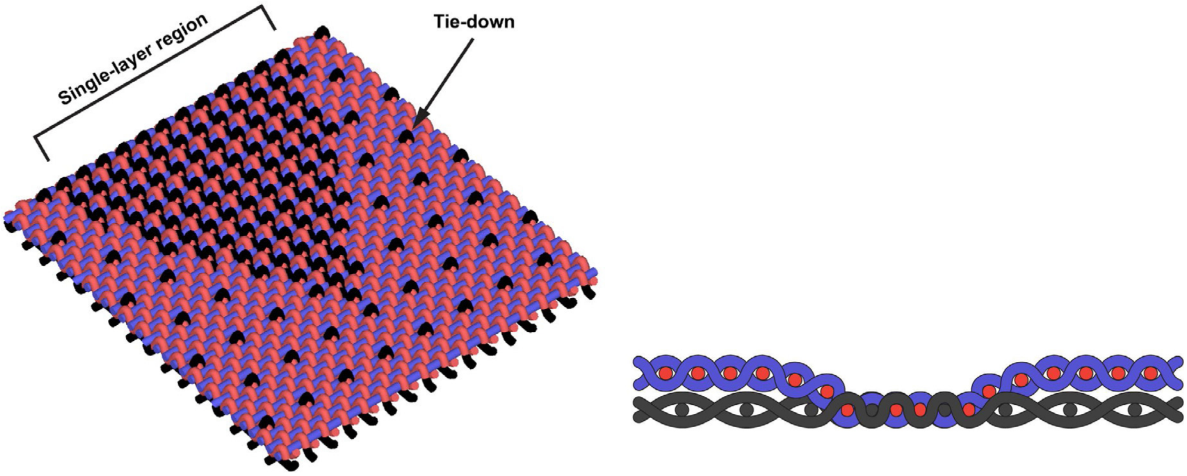


Fig. 13. Non-shrinking yarns (red and blue) weave with shrinking yarns (black) as a single layer, preventing shrinkage in the upper region of this fabric. Fig. 13a. Cross-section of the fabric structure.. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

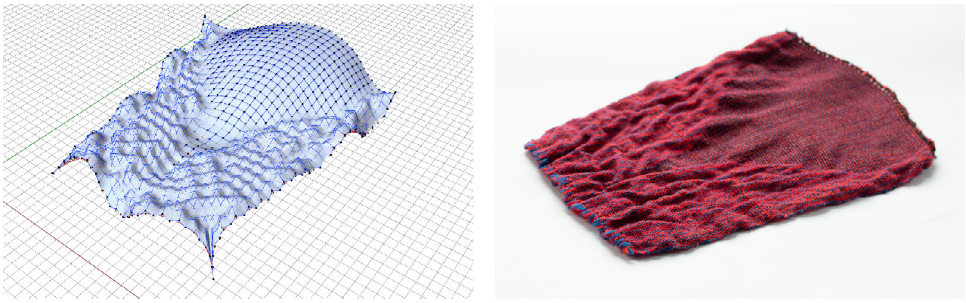


Fig. 14. Modeled surface and fabric panel woven using weaving strategy 2.

A modification of this structure joins the layers along continuous lines, without any single-layer regions. The spacing, or frequency, of these lines, and other factors including the stiffness of yarns used on layer 2, controls how much shrinkage can occur in each region (see Figs. 14 and 15).

4.3. Weaving strategy 3: Shrinkage distributed across two layers

Another possible contrast in two-layer fabric behaviors is shrinkage direction. Weftwise and warpwise shrinkage, which in strategy 2 were both present on layer 1, can instead be allocated to two separate layers. Layer 1 has shrinking warp yarns and non-shrinking weft yarns and layer 2 has non-shrinking warp yarns and shrinking weft yarns, both with a sparse plain-weave structure. The layers are joined with intermittent tie-downs throughout the fabric, *and* exchange positions in some regions. An additional set of warp and weft yarns (both non-shrinking) weave with the layer currently positioned on top, increasing that layer's density and preventing shrinkage: because of the layer exchange, this will be applied to layer 1 in some regions and layer 2 in others. Each region will have *either* weft-shrinking or warp-shrinking fabric on the lower layer and a non-shrinking fabric that forms pleats on the upper layer.

These strategies can be applied to a variety of differential-shrinkage designs and are not exhaustive. Other weave structures, such as single-layer fabrics with long floats, may yield similar

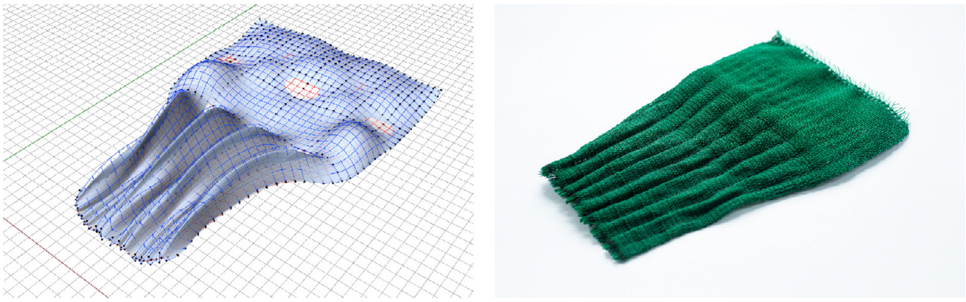


Fig. 15. Modeled surface and detail of fabric panel woven using a variation of weaving strategy 2.

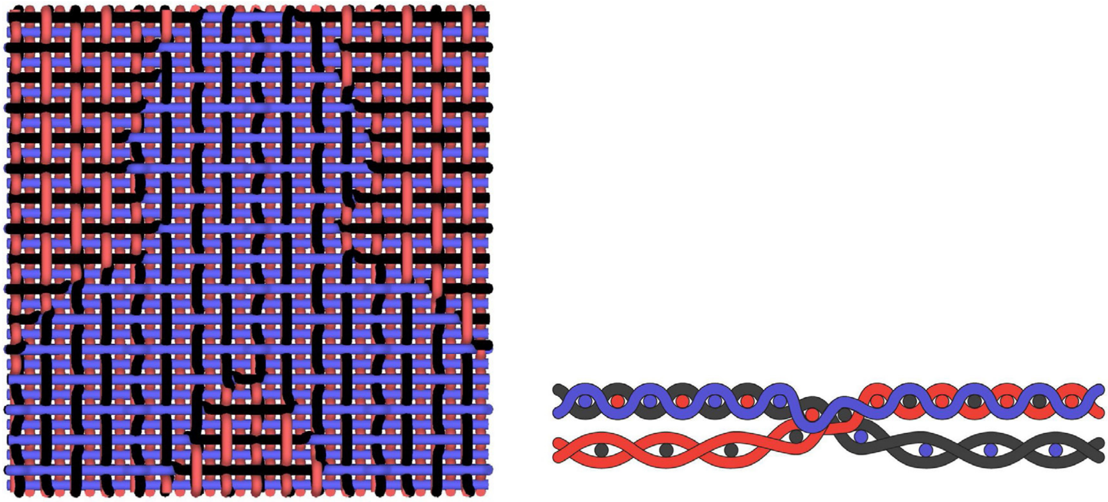


Fig. 16. Reverse side of weave structure with weft-shrinking areas (red warp and black weft) and warp-shrinking areas (black warp and blue weft). Fig. 16a. Cross-section of the fabric structure.. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

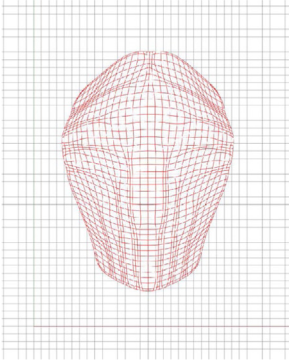
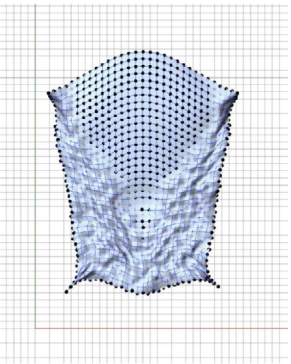
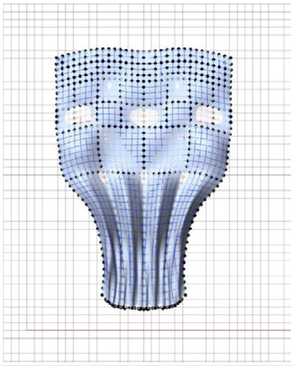
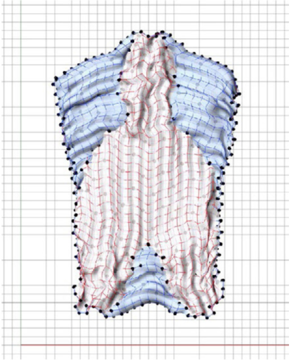
Fig. 17. Modeled surface and fabric panel woven using weaving strategy 3.

results. The appropriate weaving strategy for a surface model depends on the model's characteristics (number of layers, whether layers exchange, amount and direction of shrinkage in each region), and can potentially be indicated in Grasshopper when those criteria are met, facilitating the translation process (see Fig. 17).

4.4. Evaluating predictive capabilities by comparing models to fabrics

The woven panels, compared to their modeled counterparts, generally had a lower degree of shape change from their on-loom state to a relaxed position. In each design, shape change was dictated by the behavior of shrinking yarns, with the assumption that they would contract to 50% of their original length. Practical factors, such as warp and weft density, varied between woven samples and affected the yarns' ability to contract: sample 3 used the lowest density (8 warp yarns per inch in areas with shrinking wefts) and more closely resembled the modeled surface it was based on. The remaining three panels had the same deformation patterns as their models, although the amount of deformation was lower. Modeling these designs with more moderate shrinkage values (i.e. 75% of original length) could provide a more accurate depiction of the woven fabric's relaxation, allowing the user to modify the design layout to achieve the desired shape. Alternatively, the panels could be woven with a lower density in shrinking areas to maximize shape change. In either case, a library of expected shrinkage values and corresponding structure/material choices (including other yarns that contract, such as wool and elastic) would improve outcomes by integrating known material behavior into a digital modeling space not explicitly designed for textiles.

Table 2
Modeled surfaces compared to woven samples.

Modeled surfaces designed with this methodology.			
Sample 1	Sample 2A	Sample 2B	Sample 3
			
Fabric panels woven to the specifications of each surface.			
Sample 1	Sample 2A	Sample 2B	Sample 3
			

The issue of resolution in surface models became apparent during the weaving and finishing processes. For each design, a grid of 30 by 40 points was used to enable quick, iterative modeling that provided sufficient visual information, although some detail was lost. By representing a weft yarn, for example, as a polyline with a maximum of 30 bends, some of the smaller-scale bending and crumpling behavior of actual yarns is not reflected. As seen in sample 2B, which uses a "quilting" effect at increasingly smaller scales, short segments of a stiff yarn bend less dramatically than long segments when their endpoints are drawn together: there is a minimum size, in both woven fabrics and modeled surfaces, below which these features are not apparent. In modeled surfaces, the number of grid segments between two points is the defining factor; when weaving, the length of a yarn segment, as well as warp and weft yarn thickness and number of yarns per inch, appear to affect whether visible shape change occurs in that area.

5. Design perspectives emerging from the use of surface modeling

The experience of developing these fabric samples indicates potential for generating woven forms and behavioral effects in an approachable format for textile designers. The fact that non-rectangular boundary contours can be produced was an unexpected feature of designing with this methodology. The discovery of high-shrinkage zones that cause boundary reshaping relates to the general use of differential shrinkage in textiles but offers a high degree of specificity in end-use application. Many flat patterns for garments, such as a torso panel with a sloped shoulder, can be produced with this method, as well as ellipses, arcs and other simple shapes. Utilizing this feature effectively requires the designer to work indirectly: first sketching the desired surface boundary, then iterating on a secondary shape (the high-shrinkage region) that bears little visual resemblance to the first but causes the necessary reshaping to occur. Modifying this secondary shape towards successful outcomes introduces a design logic that underlies many existing strategies of making shape-changing textiles yet is rarely engaged with directly or visually. A designer using this methodology may observe cause and effect through shaping iterations and developing a vocabulary of geometries that produce predictable effects, subsequently combining them into more complex designs.

Several characteristics common to fabrics designed with this methodology were identified, indicating the beginnings of a visual language specific to textiles and products that make use of predictive modeling. While the features themselves, such as pleating, crinkling and other surface effects resulting from differential shrinkage, are not exclusive to this process, the level of control (through simulation and fine-tuning) over their scale, direction and placement exposes greater possibilities for their use as ornamentation. The common practice of designing a graphic image to specify local color or weave structure can be applied to the placement of surface texture, adding another element to the toolkit that textile designers use to create visual depth through interactions where patterns overlap. This approach may also be used to design fully-formed contoured panels, i.e. for garments or upholstered furniture, with behaviors such as shrinkage placed within a large-scale composition to yield precise shape.

Once a design has been developed, Weavecraft may be used as a secondary tool to generate a card image, on which yarn-level adjustments typically necessary before weaving (for example, checking for floats) can be made. The compatibility of Weavecraft's stenciling operation, in which an image is used to

Table 3
Simulation parameters for each of the four modeled surfaces.

		Warp shrinkage	Weft shrinkage	Warp stiffness	Weft stiffness
Sample 1	0-A	1.00	1.00	1.00	1.00
	0-B	0.33	0.33	1.00	1.00
	1-A	1.00	1.00	0.50	0.50
	1-B	1.00	1.00	0.50	0.50
Sample 2A	0-A	0.60	0.60	1.00	1.00
	0-B	1.00	1.00	1.00	1.00
	1-A	1.00	1.00	0.50	0.50
	1-B	1.00	1.00	0.50	0.50
Sample 2B	0-A	1.00	0.35	1.00	1.00
	0-B	0.50	0.50	1.00	1.00
	1-A	1.00	1.00	1.00	0.00
	1-B	1.00	1.00	1.00	1.00
Sample 3	0-A	1.00	1.00	0.80	0.50
	0-B	0.50	1.00	0.80	0.50
	1-A	1.00	0.50	0.50	0.80
	1-B	1.00	1.00	0.50	0.80

merge multiple weave structures in a certain pattern [9–11], with the method of assigning surface properties to regions suggests potential to further streamline the translation process.

The rapid iterations enabled by the methodology we present here, beyond saving time and material, allows for even enhanced discovery — including exploring extreme design options, sometimes even opposites of the initial design goal, leading to novel solutions. While iterative design can theoretically be exhaustive, the actual variations the designer chooses to develop are highly influenced by the design tool's controls. Just as the set of options generated in a sample blanket follows a certain format – the combinations of variables that the designer actively wishes to see, in addition to all other interactions that are inevitably produced – an environment in which a surface's appearance is controlled with numeric inputs raises curiosity about setting zero or maximum values, or even remixing values and assigned parameters, through which the designer may temporarily set aside preconceived design intentions to pursue newly improvised forms. The potential for direct experimentation with behavioral effects is now possible.

6. Conclusion

We propose that the process of designing woven fabrics, particularly those with shape-changing behaviors, can be supplemented with surface modeling for both creative and practical purposes. By leveraging widely used, although not textile-specific, software, the methods described here enable textile designers to visualize the effects of differential shrinkage and other properties on a sheet of fabric. A reasonable expectation of the finished fabric's appearance – in which boundary shape and the placement, if not exact scale or number of repeats, of surface textures are apparent – is generated with this approach. Rapid ideation, discovery of new forms and prediction of fabric behavior are core features: because weaving physical prototypes requires significant set-up time, the ability to sketch and refine in a digital space may hold value for many textile designers.

The point at which a surface model is adapted into a weave draft currently requires knowledge of weave structure and yarn properties, but there is potential to integrate this decision-making into the Grasshopper definition itself: the three weaving strategies described each align with unique surface parameter relationships that can be automatically identified. Similarly, properties of common yarns and materials could be included as components, allowing the user to specify their use in a fabric. The introduction of guardrails, such as alerts that a surface with properties past a certain threshold may not be weavable, could contribute to the overall usability of the system. We recognize that while shrinkage and stiffness can be directly described with Kangaroo goals and produce visually interesting results, additional fabric behaviors such as shear, drape and compositional variations within a single sample can increase the accuracy and potential complexity of fabrics designed and simulated with this process. The set of four fabric panels woven based on digital models are an initial indicator of the method's viability, and provide valuable information for further fine-tuning and development.

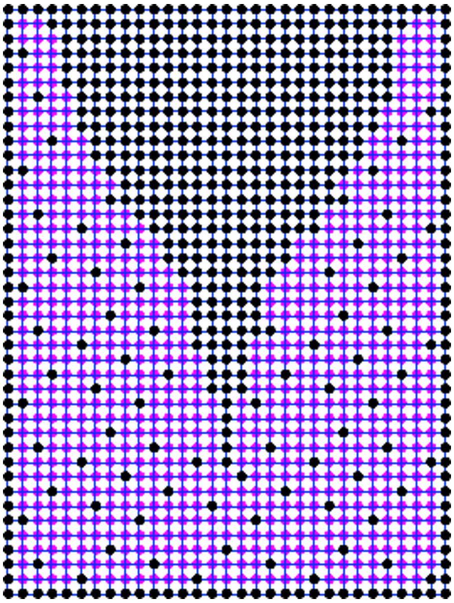


Fig. 18. Color-coded diagram of Sample 2 A. Black dots indicate joins between layers and pink dots indicate zone 0-A. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We would like to thank Rundong Wu, Joy Xiaoji Zhang and Steve Marschner for their ongoing support on Weavecraft and their continued interest in better design interfaces for textile design.

Appendix

See Fig. 18 and Table 3.

References

[1] McQuillan Holly. Digital 3D design as a tool for augmenting zero-waste fashion design practice. Int J Fash Des Technol Educ 2020;13(1):89–100.

[2] Hofmann Megan, Albaugh Lea, Sethapakadi Ticha, Hodgins Jessica, E Hudson Scott, McCann James, et al. KnitPicking textures: Programming and modifying complex knitted textures for machine and hand knitting. In: Proceedings of the 32nd annual ACM symposium on user interface software and technology. 2019, p. 5–16.

[3] Kaldor Jonathan M, James Doug L, Marschner Steve. Simulating knitted cloth at the yarn level. ACM T Graph (SIGGRAPH'08) 2008;27(3):65.

[4] Narayanan Vidya, Albaugh Lea, Hodgins Jessica, Coros Stelian, Mccann James. Automatic machine knitting of 3D meshes. ACM Trans Graph 2018;37(3):15. http://dx.doi.org/10.1145/3186265, Article35 (Aug. 2018).

[5] Narayanan Vidya, Wu Kui, Yuksel Cem, McCann James. Visual knitting machine programming. ACM Trans Graph 2019;38(4):1–13;
Nauman Saad, Cristian Irina. Geometrical modelling of orthogonal/layer-to-layer woven interlock carbon reinforcement. The Journal of The Textile Institute 2015;106:725–35.

[6] Wu Kui, Swan Hannah, Yuksel Cem. Knittable stitch meshes. ACM Trans Graph 2019;38(1):1–13.

[7] Yuksel Cem, M Kaldor Jonathan, L James Doug, Marschner Steve. Stitch meshes for modeling knitted clothing with yarn-level detail. ACM Trans Graph 2012;31(4):37.

[8] Pointcarre. Textile CAD software. 1988, www.pointcarre.com.

[9] Wu Rundong, Xiaoji Zhang Joy, Leaf Jonathan, Hua Xinru, Qu Ante, Harvey Claire, et al. Weavecraft: An interactive design and simulation tool for 3D weaving • 210:13. ACM Trans Graph 2020;39(6):14•, Article 210. Publication date: 210.

[10] Wu Rundong, Harvey Claire, Holtzman Emily, Xiaoji Zhang Joy, Leaf Jonathan, Qu Ante, et al. Weavecraft: An interactive simulation and design tool for 3D weavers. ACM Trans Graphics (TOG) 2020. Article No. 210.

[11] Wu Rundong, Harvey Claire, Xiaoji Zhang Joy, Kroszner Sean, Hagan Brooks, Marschner Steve. Automatic structure synthesis for 3D woven relief. ACM Trans Graph 2020;39(4).

[12] Anna Bauer, Philipp Längst, Riccardo La Magna, Julian Lienhard, Daniel Piker, Gregory Quinn, et al. Exploring software approaches for the design and simulation of bending active systems. In: Proceedings of the IASS Symposium. 2018.

[13] CLO3D. CLO – 3D fashion design software. 2009, https://www.clo3d.com.

[14] Ahlquist Sean. Integrating differentiated knit logics and pre-stress in textile hybrid structures. In: Modelling behaviour. Cham: Springer International Publishing; 2015, p. 101–11.

[15] Sabin Jenny E. Mythread pavilion 1. In: LabStudio. first ed.. Routledge; 2018, p. 335–60.

[16] Gengnagel Christoph, La Magna Riccardo, Ramsgaard Thomsen Mette, Tamke Martin. Shaping hybrids – form finding of new material systems. Int J Archit Comput 2018;16(2):91–103.

[17] Harvey Claire, Holtzman Emily, Ko Joy, Hagan Brooks, Wu Rundong, Marschner Steve, et al. Weaving objects: spatial design and functionality of 3D- woven textiles. Leonardo 2019;52(4):381–8.