

A Design Space for Animated Textile-forms through Shuttle Weaving: A Case of 3D Woven Trousers

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DOI

[10.1145/3715336.3735741](https://doi.org/10.1145/3715336.3735741)

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Publication date

2025

Document Version

Final published version

Published in

DIS 2025 - Proceedings of the 2025 ACM Designing Interactive Systems Conference

Citation (APA)

Voorwinden, M., Buso, A., Karana, E., & McQuillan, H. (2025). A Design Space for Animated Textile-forms through Shuttle Weaving: A Case of 3D Woven Trousers. In N. Jardim Nunes, V. Nisi, I. Oakley, Q. Yang, & C. Zheng (Eds.), *DIS 2025 - Proceedings of the 2025 ACM Designing Interactive Systems Conference* (pp. 2465-2484). (DIS 2025 - Proceedings of the 2025 ACM Designing Interactive Systems Conference). ACM. <https://doi.org/10.1145/3715336.3735741>

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A Design Space for Animated Textile-forms through Shuttle Weaving: A Case of 3D Woven Trousers

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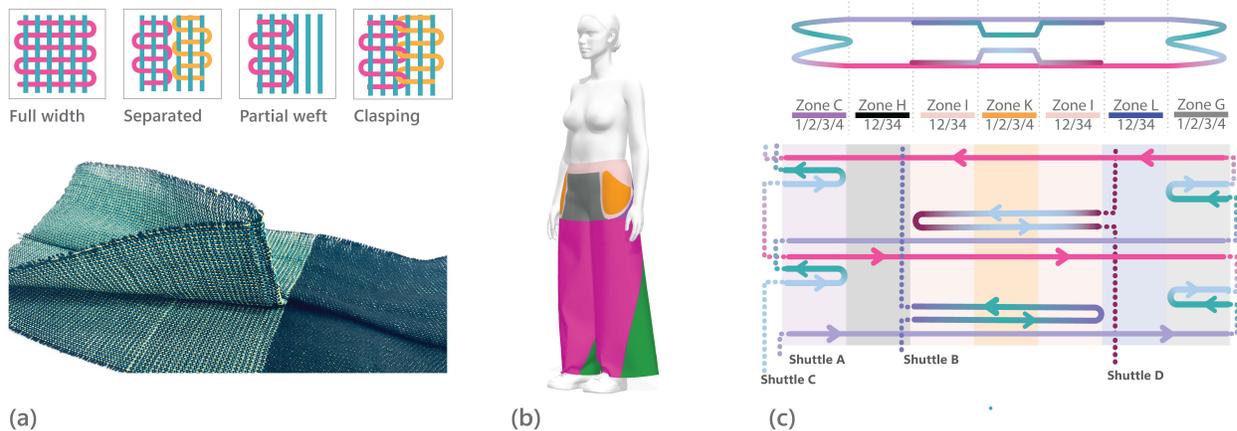


Figure 1: (a) Weft insertion variables for shuttle weaving, exemplified by one of the samples presented in our design case. (b) The digital design made in CLO3D for the animated shuttle woven textile-form trousers. (c) Cross-section of trouser layers (above) and shuttle movements (below).

Abstract

Animated textile-forms hold great potential to seamlessly embed interaction in textile-based artefacts. This paper presents a comprehensive design space for animated woven textile-forms, explored via shuttle weaving. HCI designers have explored the potential of shuttle weaving for local material placement via partial weft insertions and continuous yarn paths to create flexible circuits, sensors in textiles, and, more recently, for animated textile-forms. While these examples indicate early steps towards animated woven textiles, further articulation of the many processes, ingredients, structure, and form variables available to designers is required to realize the full potential of this weaving technique. Addressing this

gap, we developed a design space through a combination of literature review and practice-led exploration undertaken for a specific design case - animated 3D shuttle-woven trousers. Our work aims to inspire HCI designers to explore and expand the use of shuttle weaving as an accessible and versatile technique for textile-forms with rich interaction possibilities.

CCS Concepts

• **Human-centered computing** → **Human computer interaction (HCI)**;

Keywords

Textile-form Interfaces, Weaving, HCI Textiles, Prototyping, Design Tool, Material Driven Design

ACM Reference Format:

Milou Voorwinden, Alice Buso, Elvin Karana, and Holly McQuillan. 2025. A Design Space for Animated Textile-forms through Shuttle Weaving: A Case of 3D Woven Trousers. In *Designing Interactive Systems Conference (DIS '25)*,



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ACM ISBN 979-8-4007-1485-6/25/07
<https://doi.org/10.1145/3715336.3735741>

July 05–09, 2025, Funchal, Portugal. ACM, New York, NY, USA, 20 pages.
<https://doi.org/10.1145/3715336.3735741>

1 Introduction

Animated textiles can be adaptive, active, or autonomous during their use time through physical, digital, or biological means [13]. The concept expands existing understanding of smart and e-textiles by emphasizing the importance of both computational and biological components, as well as the inherent qualities of the textiles themselves in shaping their ultimate expression and functionality.

Research in HCI textiles has previously explored animated textiles by integrating animate [107] or smart materials at a surface level, for example, through 3D printing [126], embroidery [43, 45], screen-printing [113], and coating [36]. HCI designers have utilized textile structures for animated textiles via knitting [1, 67, 68, 101], felting [62], crocheting [38], and weaving [8, 57, 59, 91]. More recently, animated textiles have been explored through woven textile-forms [13, 14, 16]. In woven textile-forms, the textile and form are produced simultaneously [69], allowing seamless, sustainable, and conformal production of textile-based products [71]. We contribute to this body of work and focus on shuttle weaving.

Traditionally, shuttles are used to carry the weft yarn across the full width of the loom, making fabrics with selvages at the cloth edges. However, for some decorative fabrics, shuttles are also used to carry the weft yarn to specific sections of the fabric (partial weft) to make localized motifs on the surface of textiles. Shuttle weaving is widely used on hand-operated looms and holds great potential for animated textile forms. In HCI, design, and technical textile literature, this partial-width weft insertion is referred to as discontinuous weft [64], supplementary weft [92], tapestry weaving [59, 76, 109], partial weft [18, 24], and inlay [25]. In this paper, to simplify the language and highlight the tool and process rather than the result, we use the term ‘shuttle weaving’ to encompass the process that allows full-width and partial-width weft insertions.

In HCI, shuttles can tune material placement, enabling the fabrication of complex multi-material woven textiles that are seamless and conformal. The technique has previously been used for sensors and circuits in e-textiles [91], to control the placement of animate materials [25, 117], the fabrication of non-rectangular textiles [41, 109, 125, 128], and, more recently, for animated textile-forms [74].

HCI has adopted shuttle weaving in part because it is relatively accessible. At its simplest, shuttle weaving requires a simple frame loom and an assortment of appropriate materials on shuttles. Increasingly, a wider range of looms are present in HCI labs, further expanding the use of shuttle weaving. Scholars have supported the uptake of these tools by providing background knowledge relating to broader weaving skills [23, 85, 92] by adding shuttle weaving-specific functions to weave design tools [26]. However, despite the relative accessibility of the technology and the increasing provision of tools that support its exploration, understanding the design and fabrication process of complex shuttle-woven textile-forms in HCI remains a challenge.

This paper expands knowledge of the material, process, structure, and form variables available to HCI designers and contributes a comprehensive design space for shuttle-woven textile-forms. We

present examples of how this design space can unlock the potential of woven textiles’ inherent material qualities and structures to generate novel responsive behavior and interactions for animated and seamless textile-forms.

2 Related Works

2.1 Animated Woven Textiles in HCI

Weaving is one of the most common textile production techniques and possesses the potential to create a wide diversity of material structures, aesthetics, and forms. Researchers have explored the potential of weaving in HCI through integrating animate materials such as e-threads [91], for example, to develop patches for on-body actuation [59] and textiles that can detect movement [57]. While many of these examples utilize flat weaving techniques and simple weave structures, others have explored the use of complex multi-layered weaving for smart textiles [92], including textile circuits [78], touch sensors in clothing [89], sensors in pajamas [53], and sanitary napkins [81].

HCI Researchers have used shuttle weaving to control the local placement of conductive threads [8, 84, 98] and biodegradable conductive threads [129] in multilayered textiles to create flexible circuits and sensors for e-textiles. Other scholars have integrated materials, such as SMA [59], shrinking yarns [76], and over-twisted linen yarn [117], with a partial weft to allow a local and controlled shape change in textiles. Another application HCI researchers have found for shuttle weaving is in the development of augmented and extended reality, tracking, and computer vision systems to fine-tune the placement of colored threads for AR markers [77], QR codes [80], and optical fibers [57]. HCI researchers have also explored shuttle weaving to expand beyond the rectangular grid of warp and weft yarns. For example, by combining the placement of multiple materials with partial-width shuttle weaving, researchers have developed skin-woven sensors [41, 128] that conform to the shape of the body part on which they are applied and shaped textiles designed for disassembly [125].

Researchers working with textiles identify the inherent complexity of woven textile design, particularly in HCI textiles [23]. As many of these projects are material-driven and rely on knowledge sharing and collaborations [16, 73], documenting the situated knowledge [6, 74] can be challenging. Some textile scholars have provided frameworks for understanding textiles as a material hierarchy [36, 95, 110]. Growing interest in textiles in HCI also led to the provision of accessible and affordable looms [3] and tools that facilitate off-loom weaving [22]. Today, many labs exploring textiles in HCI have access to shaft and jacquard looms such as the TC2 loom [82]. Some software tools have been developed to support the drafting of complex weaving structures on shaft and jacquard looms [26, 35], and scholars have developed hardware/software interfaces [3, 124] and generative systems [2] that enable creative and improvisational jacquard weaving.

Although HCI’s interest in weaving is demonstrated by the tools developed, and in shuttle weaving specifically by the many examples outlined, both tools and examples are primarily for and of 2D textiles.

2.2 Shuttle Weaving for 3D Form

In addition to material placement for aesthetic and functional purposes and the generation of fabric selvages, shuttle weaving can also be used in a similar manner to short-row knitting, which can be used to create 3D geometry in knitted textiles [65]. In technical textiles and engineering, shuttle weaving is also of interest and is commonly used to create both the textile and form simultaneously, for example, for bifurcated tubular textiles for medical uses [7] and protective clothing [103]. Additionally, many near-net-shape preforms [28] are produced using 3D weaving techniques, such as carbon fiber reinforced plastics [99] for lightweight applications [55], and seamless nodular connection components [29].

2.3 Woven Textile-forms

In textile and fashion design, the simultaneous construction of form and textile has been increasingly explored with jacquard looms (such as the TC2). Also referred to as 3D weaving [20, 21], Whole-garment Weaving [63], and/or Composite Garment Weaving [87], woven textile-forms [69] utilize multi-layered weaving on jacquard looms to create textile-based objects. While some researchers have explored shuttle weaving to create seamless textile-form garments on hand-operated looms [27, 79, 87], or on proprietary circular looms in the case of Unspun [112], the majority of these projects utilize a conventional loom offered by industry such as a jacquard rapier loom [63, 72, 73], as they seek to simplify supply chains and reduce over-production, waste and reliance on manual labor in the textile industry [21, 69, 104]. In the context of HCI, the unique, performative potential of textile-forms as multi-situated materials [14, 50], capable of adapting seamlessly to various environments and contexts, is of interest. For example, animated textile-forms combine animate materials with textile-form approaches to develop garments that can be easily modified during production or at home according to changing needs [16]. Shuttle weaving has also been explored to seamlessly embed form and interaction in textile-forms using magnetic reverberations [74], in auxetic-inspired textile-forms activated by shape-memory alloy [83], and wearable sweat sensors [128]. These examples highlight shuttle-woven textile-forms as ideal candidates for creating interactive objects that blend naturally into daily life, offering intuitive and embedded interaction.

As interest, knowledge, and experience with weaving increases in HCI, the design potentials and challenges of combining individual warp control (jacquard shedding) with shuttle weaving and/or animate materials for woven textile-forms are beginning to be understood. In support, researchers have explored the visualization of animate behavior in woven textiles [75] and provided hands-on learning and prototyping tools for textile-forms [16, 23, 27, 116, 123]. Recent examples demonstrate the potential of combining form [40] and animate materials [18] through short-row shuttle weaving. However, these were created using specialized machinery that was not widely accessible to the HCI community. Therefore, it is essential that HCI designers can create intricate, animated 3D woven forms with shuttle weaving within textile-lab settings. For shuttle weaving of textile-form specifically, the timing and sequencing involved are important and complex, requiring additional documentation and knowledge [74]. Therefore, despite the relative accessibility of the technology and the increasing provision of tools that

support its exploration, understanding the design and fabrication process of complex shuttle-woven textile-forms in HCI remains a challenge.

3 Our Approach

This paper presents a comprehensive design space for shuttle-woven animated textile forms, grounded in design engineering literature on woven textile manufacturing, HCI animated textiles literature, and three of the Authors' (Voorwinden, Buso, and McQuillan) extensive experience with industrial and hand-weaving practices. Through a design case - an animated 3D woven trouser - we examine how this design space can be explored to unlock the potential of textiles' inherent material qualities and structures to generate novel responsive behavior and interactions for animated textile-forms. The design space, samples, and case offer a foundation for designers exploring shuttle weaving's affordances for animated woven textile-forms.

3.1 Methodology

We adopted a material-driven approach, focusing on the unique characteristics and advantages of shuttle weaving techniques, particularly aimed at developing new material qualities. We started this research by carefully considering the variables involved in the woven textile-design process through reviewing sources from technical 3D weaving, textile design (including exhibits etc), and the HCI community (e.g., ACM digital library), with attention paid to cases where textiles and form were developed simultaneously and/or where interactive or animate qualities are present. We organized our findings from the literature based on the techniques and tools provided by the Material Driven Design (MDD) method [48]. For example, we employed the material taxonomy template [49] (Fig. 2) to cluster essential weaving elements related to process, ingredients, structure, and form. The Material Process refers to all the motions on the loom, indicating the different configurations possible for weaving. Material Ingredients encompass the origins and composition of the threads used in the weaving process. Material Structure describes materials' arrangement, placement, and organization during weaving. Finally, Material Form pertains to the translation of form to a weavable form and the zones and surfaces the designer can utilize.

This process underwent multiple iterations within the research team, where differences in underlying knowledge (experts and novices in weaving and interaction design) were utilized to iteratively provide technical background, challenge norms, critically reflect on complex jargon, and question categorization decisions. To facilitate the visual and conceptual understanding and, thus, designer engagement with the outcomes of our findings, we created graphic representations that encapsulate the key elements from this process. These graphic representations are brought together in a poster and are available as supplemental material for designers to use as inspiration and as a reflection and discussion tool.

Next, we identified key variables related to shuttle weaving insertions and initiated an exploration of the design space specific to an animated woven textile-form application: a woven trouser. Drawing from previous research conducted on shuttle-less industrial jacquard looms, we conceptualized an animated woven textile-form

trouser using shuttle weaving, building on existing woven textile-form examples [69, 70, 72], enabling targeted exploration of shuttle weaving techniques in a selection of samples, and their potential to create animated textile-forms.

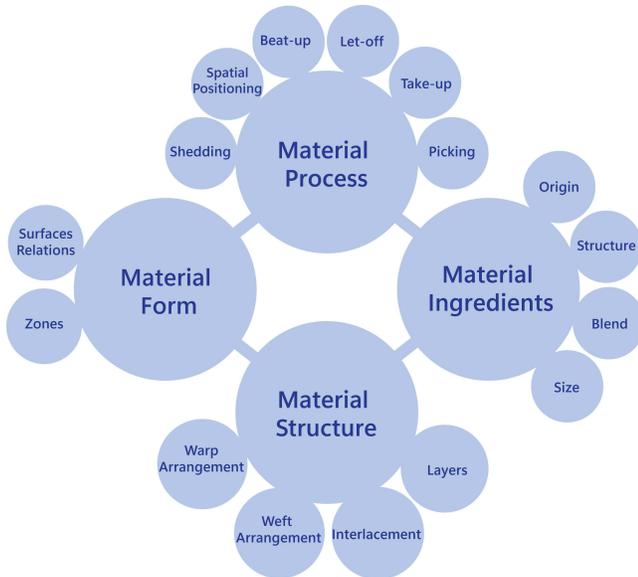


Figure 2: The material taxonomy developed in the first phase of this study. It clusters elements of Material Process, Material Ingredients, Material Structure, and Material Form.

4 Design Space for Animated Woven Textile-forms

This design space is meant to illustrate the options available to designers. It is neither intended as an exhaustive list of variables nor a decision tree but as a resource for selecting elements for further exploration. Therefore, this design space will never be ‘finished’ and is a living document that evolves as new technology, software, and materials are invented.

4.1 Material Process

The Material Process refers to all the motions on the loom, indicating the different configurations possible for weaving (Fig. 3). While in many cases these variables are not easily modifiable by the designer or weaver, (beyond choosing which loom to use), knowledge of these variables can enable better decision making for experimentation, and facilitate in the development of new tools and modifications.

4.1.1 Shedding. Shedding refers to creating a temporary opening, or shed, between the warp threads on a loom. This opening allows the weft thread to pass through and form the woven fabric. Most hand-operated looms are equipped with shafts, creating a repeating shed. While many shafts can be installed on the loom, allowing for the creation of complex structures, shafts will have limited options compared to jacquard shedding [120]. Jacquard shedding allows the threads to be lifted individually, with or without a repeat [32]. Some

manual and semi-automatic looms are equipped with a jacquard system, such as the TC2 loom [82], and a wide variety of jacquard systems are available for fully-automatic looms. A compound harness often equips a combination of shafts and individual lifting of threads, and is often found in drawlooms and early jacquard looms [11]. In these compound harnesses, shafts are used to weave the base fabric, and the jacquard heddles can weave a figurative image [39]. Other historical or primitive looms include various tablet and backstrap looms [11].

Special shedding systems have been developed to create 2.5D or 3D fabrics. For example, pile fabrics such as velvet are often created by weaving two layers with a floating thread simultaneously and then cutting them apart to make a pile (face to face) [42]. Creating these two fabrics simultaneously requires the heddles to go up or down and have three positions [111]. However, velvet fabrics are created on hand-operated looms by inserting a pile-rod [60]. Furthermore, researchers have designed non-interlaced 3D fabrics and fully interlaced 3D woven, 3D fabrics [52], where the shedding is duo-directional.

4.1.2 Spatial Positioning. Spatial positioning refers to how warp threads are positioned in space on the loom. This positioning is relatively fixed, depending on the loom type. The most common warp spatial positioning on looms is side by side [52], where the warp threads are divided horizontally, as seen on most fully automatic and manual looms, including vertical tapestry looms [11]. In some cases, the warp has a variable spatial positioning, for example, with a multilayer warp [52]. On 3D weaving looms, warp threads can also be positioned grid-like [51]. On circular weaving looms, the warp threads are positioned in a circle, and a shuttle continuously circles through the shed to form the fabric. Fabrics made by circular weaving looms are generally employed in high-volume industrial production (e.g., for products such as rice, flour, and cement); however, they have also been investigated for their application in circular weaving for 3D woven preforms [10]. The company Unspun recently initiated explorations into utilizing circular weaving for garment production [112]. In addition to these fully automated looms, designers have explored alternative loom setups such as four looms connected [46] to create 3D woven objects.

4.1.3 Picking. Weft threads can be inserted in various ways. The most common method used in fully automated looms is shuttle-less weaving, including rapier, air- or water-jet, and projectile weaving. In shuttle-less picking, the weft thread is cut with each insertion and positioned across the full width of the warp. As a result, the edges of these shuttleless woven fabrics often exhibit a fringe or can be finished as a ‘tucked-edge’ or with a leno edge. In contrast, shuttle weaving is typically employed in hand-operated manual and specialized semi- and fully automatic looms. This method throws the shuttle back and forth across the loom’s width, resulting in a continuous weft thread. The edges of these fabrics are called selvages, meaning that the edge is self-finished and does not unravel.

Additionally, shuttles with partial weft placement enable localized material placement, such as machines for bifurcated medical textiles [93]. For a precise weft length insertion [18], some looms have installed two robot arms with vision feedback to pull the weft back to its turning point. The possibilities of shuttle weaving are particularly beneficial for animated textiles, allowing for local and

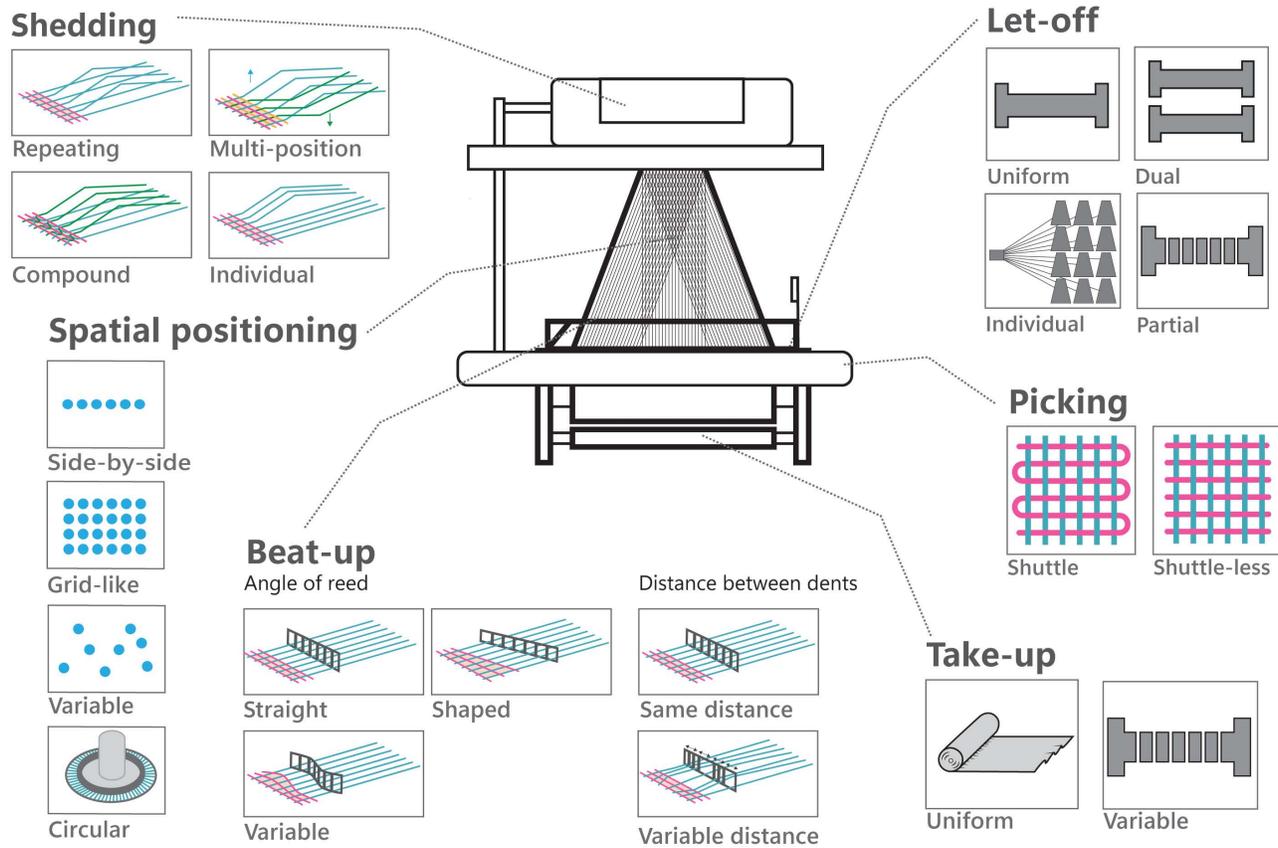


Figure 3: Material Process variables: Shedding, Spatial positioning, Picking, Beat up, Let off and Take up, are primarily a result of the loom set up.

continuous integration of conductive threads or actuators [34, 119]. Other approaches researchers have used in weaving to place materials in specific fabric zones through shuttle-less weaving are fil coupe weaving, where some threads are removed [90], and inserting supplementary wefts with a crochet hook [24].

4.1.4 Beat-up. The weaving cycle concludes with the beat-up of the weft thread to the fell (the edge of the fabric in a weaving loom formed by the last weft thread), typically facilitated by a reed. The number of openings in the reed (dents) dictates the density of the warp. While most reeds have consistent spacing between dents, certain exceptions produce textiles with varying warp densities or shapes. For instance, in a fan reed (also known as an ondulé reed [106]), the dents are arranged at an angle, creating textiles with multiple warp densities through the adjustment of the reed’s vertical position during the weaving process [12]. Other examples are the rail reed, which changes the dent spacing while weaving on a manual loom [94], and the open reed, designed for net-shape weaving of reinforced composites [115], where supplementary warp threads are woven on a base fabric, creating a shaped edge. The angle at which the reed is positioned can also be varied; for example, a bent reed can create non-cylindrical tubes [31]. More recently,

researchers explored a variable reed [20] and partial weft insertion to manipulate vertical placement of picks, and a reed with a clamp combined with partial weaving and variable warp and weft tensions [18], both to allow 3D geometry to emerge.

4.1.5 Let-off and Take-up. The warp let-off and the fabric take-up are considered secondary loom motions, allowing for the continuous weaving of the desired fabric length [120]. The release of warp yarns is typically done with a warp beam. The let-off and take-up are connected on semi- and fully automated looms, thus controlling the tension automatically. On manual looms, this process involves releasing the warp beam and then re-tensioning the warp yarns via the fabric beam. Multiple warp beams provide many opportunities; in flat weaving, seersucker fabrics are created by using a different tension on two warp beams; the highly tensioned stripes will remain flat, while the lightly tensioned ones will take up more yarn, creating a wrinkled stripe [96].

In 3D weaving, multiple warp beams can allow for different warp consumptions [66]. In 2.5D weaving, terry and warp-pleated woven structures commonly utilize two or more warp beams. The base fabric is woven on one beam, while the pile or pleat is created on a separate warp beam. A specialized mechanism, either in the reed

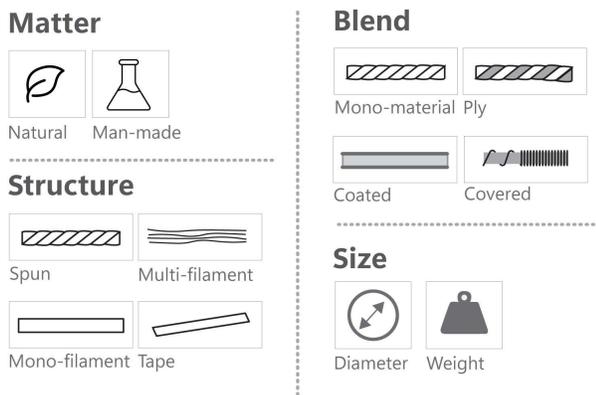


Figure 4: Material Ingredients variables, encompassing Matter, Structure, and Blend, help to determine the material's behavior when combined with Material Structure and Material Form.

that moves back and forth [9] or one where the fell of the cloth itself recedes from the reed [121], is used. Additionally, an individual let-off, typically in the form of a creel system, is extensively used for 2.5D textiles (such as terry and velvet pile fabrics) and 3D woven textiles.

The take-up of the woven fabric is typically done with one fabric beam, resulting in a uniform take-up of the fabric. However, when a loom is equipped with multiple or individual let-off of warp threads, the take-up of threads can also be altered. Researchers have explored the creation of shell-woven fabrics by creating a non-cylindrical breast beam or segmented take-up [12, 56].

4.2 Material Ingredients

Material Ingredients encompass the origins and composition of the yarns and other materials used in the weaving process (Fig. 4).

While it is possible to weave with many different materials, most fabrics are woven with yarns that are spun or extruded out of natural or man-made fibers [122]. Natural fibers can be vegetable or animal. Vegetable fibers are further divided into bast fibers (e.g., flax, hemp, jute), Leaf fibers (e.g., abaca, sisal, banana), seed or fruit fiber (e.g., Cotton, kapok, coir), and grass (e.g., bamboo). Animal fibers can be either wool or hair (e.g., sheep, alpaca, goat), or silk (natural or spider) [58]. Synthetic or man-made fibers can be regenerated (e.g., rayon), synthetic polymer (e.g. Polyester, polyamide, acrylic, aramid), and inorganic (e.g. carbon, glass, ceramic, metallic) [105]. The fibers are processed into yarn through either spinning or extruding. Most natural fibers are spun, but there are various methods for doing so. The type of spinning process (such as ring, air-jet, or compact spinning), the number of plies in the yarn, and the degree of twist applied during spinning all affect the outcome of the yarn. While man-made fibers can also be spun, they are often extruded, resulting in mono- or multi-filament yarns. Another method of yarn processing is tape yarn, such as paper tape yarns. Subsequently, the threads created through these processes can be combined with other materials, allowing new properties to emerge. Some yarns are coated, for example, with thermoplastic polymers,

a core fiber can be covered with other fibers, or two (or more) yarns can be plied together [44].

There is a wide range of material possibilities for animated textiles. Researchers have developed actuated fibers such as thermally-actuated liquid crystal elastomer [33], fluidic fibers [54], coiled nylon actuators [34], or ply multiple animated materials together, such as heating thermochromic yarns [24]. Even more traditional materials can be animated by changing the way they are processed, for example, by over-twisting materials such as linen [100, 117], silk [17], and wool [101].

4.3 Material structure

Material Structure describes the arrangement, placement, and organization of materials during weaving (Fig. 5).

4.3.1 Warp arrangement. On all looms, the warp arrangement significantly impacts the final textile's visual and structural properties. Changing the warp arrangement in weaving is one of the process's most time-consuming and expensive steps. Therefore, in most weaving workshops and mills, a standardized warp will be equipped with one type of yarn (material choice), with uniform order and density. However, exploring different warp arrangements can be interesting for animated textile-forms. Changing the warp to multiple materials can result in different behaviors, such as alternating active and passive materials [76]. Furthermore, alternating the warp yarns' density and/or order can affect the overall behavior (e.g., seersucker fabric).

The warp consumption can vary when using multiple warp beams or individual let-off. Pile fabrics, such as velvet and terry towel [86] and weaving pleats [9], require variable warp consumption. While the warp yarn position is constant relative to its neighbors in most fabrics, some techniques allow it to move, varying the warp consumption. Leno weaving (or gauze or cross-weave) is a technique where warp yarns are paired and twisted around the weft yarns, allowing for gaps to emerge in the final fabric [37]. Other textile techniques where the warp is fully interlaced include 3D weaving, where the heddle can be moved up and down and left and right [52], and special insertion devices such as those used with open-reed weaving [115].

4.3.2 Weft arrangement. The weft arrangement is a variable that designers frequently adjust in the weaving process. This can involve using different yarn types (multi-material), altering the insertion order of the threads [76], or modifying the density of the inserted threads. The weft can be applied across the full width of the loom or only partially, depending on the type of weft insertion (shuttle or shuttleless). In tapestry weaving, partial weft placements are standard, as multiple colors are placed only where necessary to form the fabric motif. To ensure a continuous fabric, adjacent weft threads are clasped together. Designers and researchers have also investigated the potential of partial wefts combined with a separated weft movement to create a finished selvedge opening in the textile that eliminates the need for post-weaving cutting, or for tubular bifurcated textiles for medical applications [64]. Other methods for creating edges in weaving include fringes (loose threads), achieved through cutting the weft insertion with every pick and using a specialized device to tuck in the fringe created.

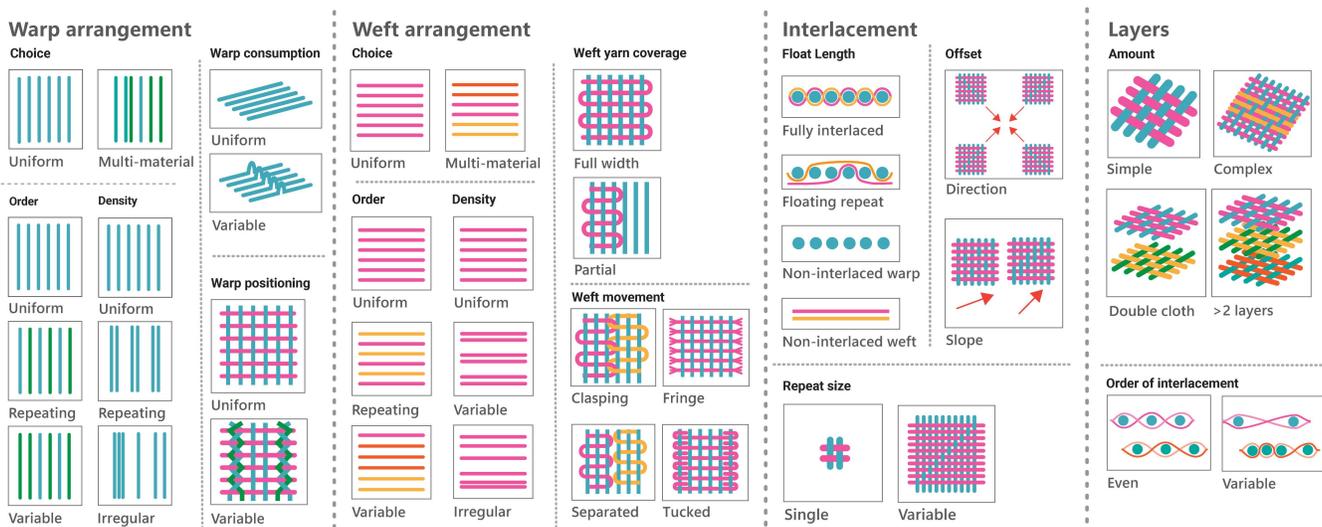


Figure 5: Material Structure variables such as Warp arrangement, consumption, and positioning are established when the loom is set up and are usually difficult to change once weaving. Weft arrangement can be modified while weaving, or programmed when designed similarly to Interlacement and Layer variables.

4.3.3 Interlacement. Different types of interlacement between the warp and weft threads are known as weave structures or bindings. There are several fundamental weaves (e.g., plain, twill, and satin) from which most others are derived (see [23] for fundamental knowledge on these structures). In animated textile-form weaving, this generic classification is less relevant than the elements of a weave structure that contribute to a particular arrangement and behavior. For example, the behavior of animate materials in a multi-layer structure depends on its float length, rather than whether it is a twill or satin. Interlacement types can be varied by changing the repeat size, slope, and offset [102]. Sometimes, warp and/or weft can also intentionally not be interlaced (floating) to create visual effects, such as grouped warp and weft distortions [102], to insert objects such as solar cells [114], to create shaped textiles [61], or to create expanding textiles [13, 15]. Additionally, researchers have used different interlacements to varying degrees of shrinkage in adjacent zones to create domed textiles [19].

4.3.4 Layers. The resulting interlacement is called a ‘simple’ weave when weaving involves a single warp and weft system. In contrast, when multiple warp and weft systems are employed, these techniques are classified as ‘complex weaves’. Complex weaves can produce one-layered fabrics, known as compound weaves [97, 120] or double cloth [91], where various structures are incorporated on both the front and back of the material. For instance, creating figurative images on a jacquard loom requires using multiple colored weft yarns that remain concealed on the fabric’s reverse side. Consequently, the two sides of the fabric are constructed with distinct weave interlacements. These variations can be leveraged to develop textile-form interfaces, such as manipulating tension differences to create a rollable textile interface [15]. In double weave or multilayer textiles, the layers can be linked together or separated [92]. In the

case of complex weaves, the number of threads used in the layers (order of interlacement) can also vary by dividing the warp threads unevenly over the layers, which can be used to manipulate the density and behavior of the different layers.

4.4 Material Form

Material Form pertains to the translation of form to a weavable form and the zones and surfaces the designer can utilize (Fig. 6). Material Form encompasses the fabric and form state of the artefact, and while shuttle weaving holds potential for 2D textiles - there is enormous under-explored potential in its combination with multilayer textile-form weaving.

4.4.1 Surfaces. In textile-forms, surfaces can begin as 2D (developable) or be generated by flattening a 3D (non-developable) form [127]. When flattening a 3D form for weaving, it may be possible to flatten the form whole [30], while in other cases, segmentation [72] and/or unwrapping [41, 125] the form is required. The axis of flattening can be tuned for feasibility, aesthetic, or functional reasons. For example, a form could be flattened on an axis, resulting in too many layers to feasibly weave, while another minimizes post-loom fabrication processes [69]. The goal is to make 2D surfaces that can be woven, in single or multiple-layer stacks, and achieve the desired form once removed from the loom. The number of surfaces in a stack does not necessarily correlate to the layers in the final weave structure (see material structure layers section), as the surfaces that make up two parts of a form may be combined in a design.

4.4.2 Zones. Zones are 2D areas of solid color indicating a specific weave structure determined by the form’s stack of surfaces. Each zone can have a variable size and shape aligned with the warp and/or weft, or curved on certain looms. Each zone has a placement relative to adjacent zones, resulting in a Map of Bindings (MoB),

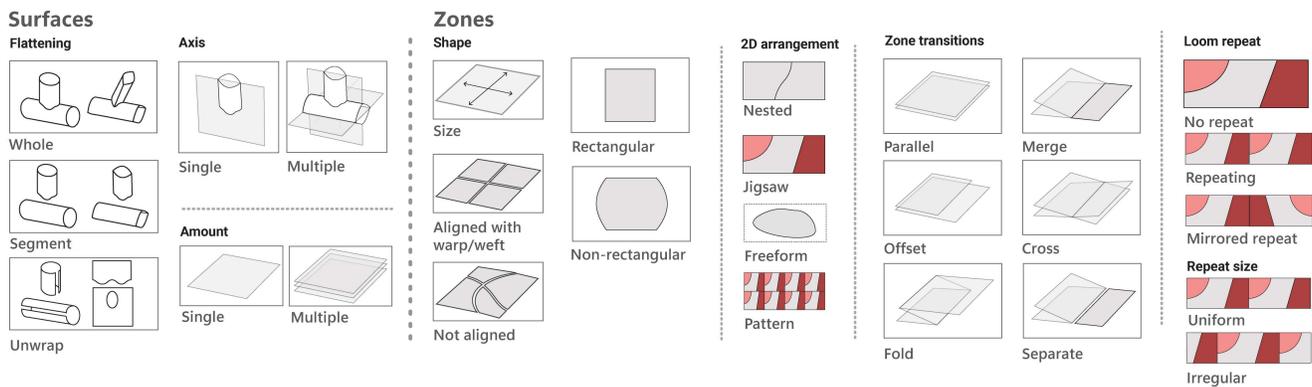


Figure 6: Material Form variables are grouped into Surfaces and Zones. They combine elements determined by the design process (flattening and zone transitions, for example), with some specific limitations set by the loom (such as loom repeat). These interact with Material Process, Material Structure, and Material Ingredients to realize a complex woven textile-form.

sometimes known as the ‘Artwork’; design goals determine this 2D arrangement and can be nested, jigsaw, patterned, or freeform. The boundary between two zones can result in various layer transitions that profoundly impact the resulting form and, therefore, its interactivity or performativity. For example, a woven hinge transition can be freely opened and closed [118], while merging transitions tend to ‘spring back’ to the state in which it was woven [16]. Furthermore, the loom itself can have an essential role in the design of zones and the MoB by constraining the maximum MoB dimensions due to the loom repeat size, as well as repeat arrangement (no repeat, number of repeats, mirrored) and uniformity. While most woven textiles have a rectangular form on the loom due to the warp and weft grid, shuttles can enable non-rectangular woven shapes by skipping warp yarns at the perimeter, and multi-layer weaving can generate non-rectangular surfaces once unfolded.

Form plays a key role in any textile artefact’s interactive and performative potential. In woven textile-forms, form is developed alongside material structure and ingredients within the material process of weaving. Consequently, the expanded palette of variables available to designers can result in outcomes that are difficult or impossible to replicate with conventional textile-based fabrication methods, often resulting in surprising material experiences.

5 The Potential of Shuttle Weaving for Animated Woven Textile-forms

The design space reveals many variables designers can explore to develop animated woven textile forms. Although many of these variables also apply to shuttleless weaving, some offer unique opportunities that cannot be exploited with shuttleless techniques (Fig. 7). Perhaps most interesting is how it allows for a partial weft. The partial weft creates the ability to tune the placement of materials, enabling the fabrication of complex multimaterial woven textiles. Moreover, weavers can manipulate the sequencing of shuttles, thereby determining whether the materials will clasp, producing a seamless textile, or separate, resulting in an opening between two distinct zones within the fabric. Furthermore, most weavers take advantage of shuttle weaving to create a selvedge, meaning

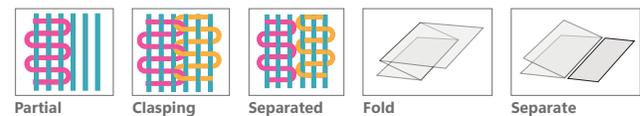


Figure 7: Some variables from the design space are only accessible through shuttle weaving: Weft insertion can be partial, clasp, and separated, while multilayer transitions can have seamless folds and separations.

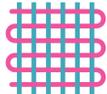
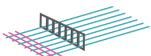
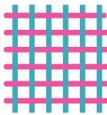
that the weft yarn wraps around the last warp yarn, and thus cannot unravel from the fabric. When a partial weft is combined with multiple layers, weavers can move the shuttles between layers to create seamless folds, increasing the volume to extend many times its original size, or enabling novel interactive experiences.

Since every variable in this design space can be modified and mixed to achieve specific design goals, we realized that multiple combinations are possible with these variables. Given the scarcity of examples of shuttle-woven animated textile-forms in HCI, we chose to begin experimenting with the design space using a conventional machine setup that would be accessible to many HCI researchers (TC2, and see Table 1). Next, we map the design space variables to a collection of samples to illustrate some possibilities within this design space, and through a design case, emphasize the potential of shuttle weaving for animated textile forms.

5.1 Design Case: Animated Woven Textile-form Trouser

Building on projects exploring animated textiles and woven textile-forms, such as morphic (rapier) woven trousers [13, 73] and animated textile-forms [15], we selected trousers as a design case for this research due to its potential to explore both complexities in form, and change in the use time. Recognizing that each human body is unique and inevitably changes over time, we aimed to develop a garment capable of changing with the wearer. Such adaptations may manifest through size or fit modifications and alterations in the garment’s aesthetic characteristics. This approach

Table 1: Material Process and Material Structure variables utilized for all samples. This is a common setup for many TC2 looms in HCI textile labs

Material Process		
Shedding  Individual	Picking  Shuttle	Spatial Position  Side by Side
Beat-up  Straight	Let-off  Uniform	Take-up  Uniform
Material Structure		
Material Choice  Uniform	Warp Position  Uniform	Warp Consumption  Uniform

seeks to enhance the garment’s functionality and longevity, extending its usability across various contexts and stages of life.

Inspired by Anni Albers’ essay ‘A structural process in weaving’, which describes shuttle-woven textiles that can expand up to six times their size [4], Voorwinden developed a sample (sample 0) exploring a partial shuttle weaving for a seamless textile structure. This sample, shown in Figure 8, features a continuous but partial weft that allows the fabric to expand up to three times its flattened woven dimensions without seams. The method used a continuous and partial weft yarn that moves horizontally and vertically between layers.

To reduce the number of variables to explore in this study and make the techniques accessible to HCI designers, all samples presented in this paper were produced using a conventional loom setup. This setup features individual jacquard shedding (TC2 loom), shuttles for picking the weft yarn, a straight reed with consistent spacing for the beat-up, and uniform let-off and take-up mechanisms. For the warp arrangement, we also chose a conventional set-up; uniform material selection (the loom was equipped with 2,640 mercerized cotton 44/2 warp yarns), order, density, and consistent positioning and consumption of the warp. Thus, these experiments mainly focused on combining weft arrangement, textile interlacements, and form variables. Design files were generated using Nedgraphics software to produce 7 samples.

We began by focusing on variables that enable the exploration of how partial weft can allow designers to tune material placement

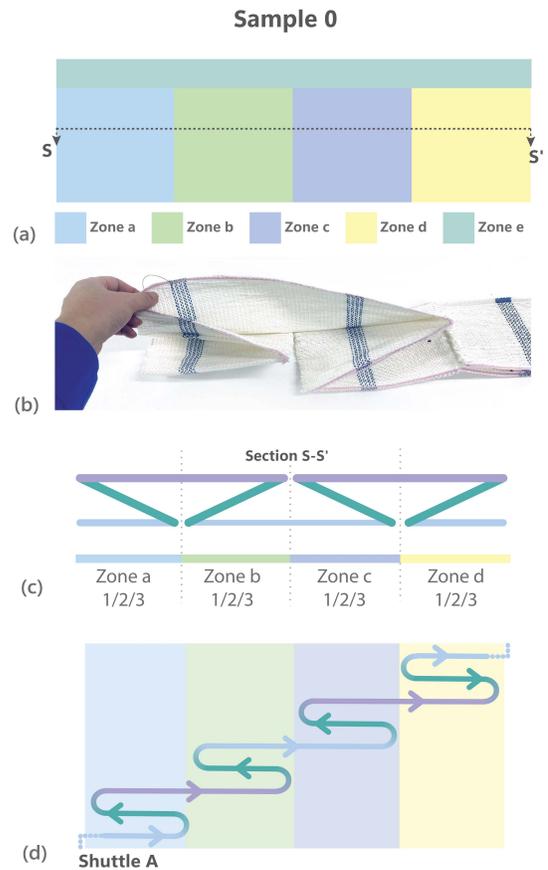


Figure 8: Sample 0. (a) The Map of Bindings (or artwork), indicating the zones. (b) Picture of Sample 0, woven in three layers. (c) Cross section of Sample 0, where the separated layers are indicated by the notation 1/2/3. Each layer has a corresponding color - lilac for layer 1, green for layer 2, and light blue for layer 3. In each zone, the same layer notation applies. However, because of the shuttle paths, the textile can expand by unfolding. (d) Shuttle path of zones a, b, c, and d. Sample 0 is woven with one shuttle that travels, with partial wefts, through the layers.

(Samples 1.1-1.3). Then, we created samples that explore textile-form creation with shuttles (Samples 2.1-2.3). Lastly, we combined these insights into one animated woven textile-form trouser.

5.2 Experiments with Shuttle weaving for local material placement and multiple layers

In the context of our design case, each sample was designed to understand how material placement could be controlled in multi-layered structures for textile-forms. These techniques can be employed to place animate materials in the zones that require animate behavior. However, even without embedding animate materials, a partial weft can change the material properties of a textile or create new form potentials. These samples use both animate and passive materials in their composition. Sample 1.1 (Fig. 9) was developed

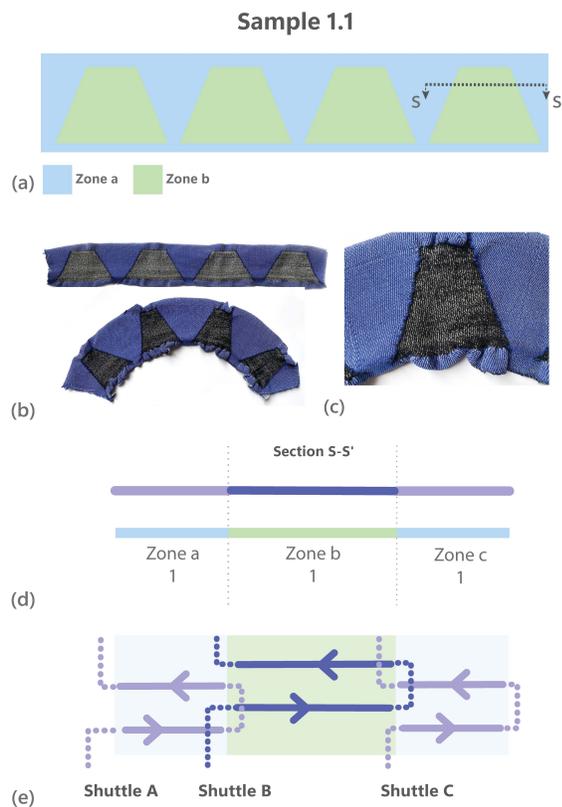


Figure 9: Sample 1.1 utilizes multiple partial wefts clasped together to create a textile that can be shaped according to the placement of the zones. (a) The Map of Bindings showcases the different zones. Zone b is cone-shaped, and the heat-shrinking yarns are only placed in these zones (b) Sample 4, showcasing the flat surface after weaving, and below the curved shape after shrinking (c) Detail of dart. (d) The cross-section of zones a and b, together with layer instructions. (e) Shuttle path for zones a, b, and c. Each shuttle weaves partial, and, in total, there are 9 shuttles used to create this textile, alternating a cotton yarn (shuttle A and C) and a heat-shrinking yarn (shuttle B).

to place multiple materials in a continuous and seamless textile, exploring how heat-shrinking yarn can be placed to enable localized shape-change. Sample 1.2 (Fig. 10) uses a single-layer base fabric with zones of supplementary material placed in an additional separate layer with partial weft shuttle weaving to make belt loops. Sample 1.3 (Fig. 11) explores how partial weft can create a curved selvedge and is woven similarly to 1.2. However, the zones are not aligned in the vertical (warp) direction, as you may find at the opening of a pocket.

5.2.1 Sample 1.1. Sample 1.1 shows a continuous, seamless textile with multiple materials placed in neighboring zones. Zone A is woven with cotton yarn, and Zone B is woven with a heat-shrinking yarn. Each transition between zones involves a new shuttle; nine

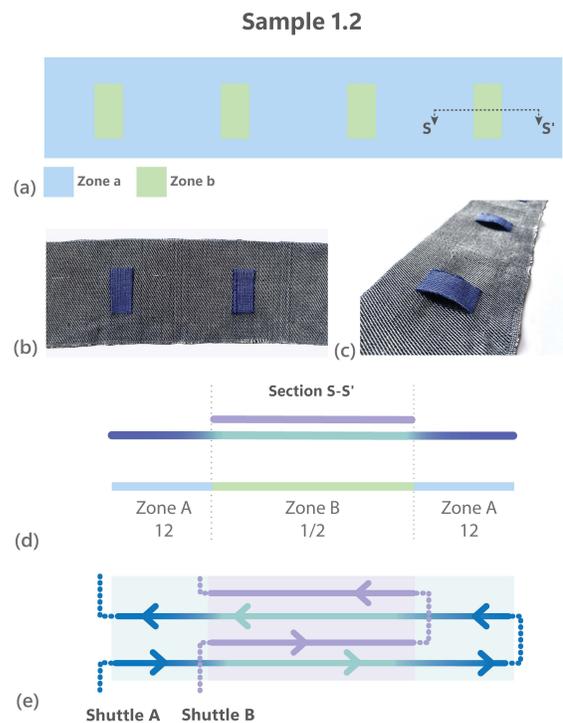


Figure 10: Sample 1.2 combines a partially separated weft parallel to the warp direction, and a full-width weft. (a) The Map of Bindings showcases the different zones. (b) Sample 1.2 from a top view (c) The double-layered weave creates belt loops (d) The cross-section of zones a and b, together with layer instructions. (e) Shuttle path for zones a and b. Shuttle A is weaving both zones, full width. Shuttle B is weaving a partial weft on the top layer.

shuttles are used. Zones A and B are woven alternately to ensure the wefts interlock. After the textile was removed from the loom and steamed, the sample transformed from a straight rectangle into a curved shape.

5.2.2 Sample 1.2. Sample 1.2 shows a base fabric (Zone A), which is supplemented with loops (Zone B) that emerge from this base fabric and are woven in a different yarn. The separated layer is attached to the base fabric in the horizontal direction but is separate from the base fabric in the vertical direction. The belt loop is fully finished with a selvedge. However, this is only possible if the zones are aligned with the warp direction.

5.2.3 Sample 1.3. Sample 1.3 has three double-layered curved zones woven with a partial weft placement, creating an unaligned zone (because it does not align vertically with the warp direction). Each half-circle in this sample is double-layered, and these curved zones can be separated from the base fabric (zone A) by cutting warp yarns in zone D. Zone B attaches the separated layers to the base fabric. The edges in zone D feature a tighter weave structure designed to prevent fraying by forming a selvedge.

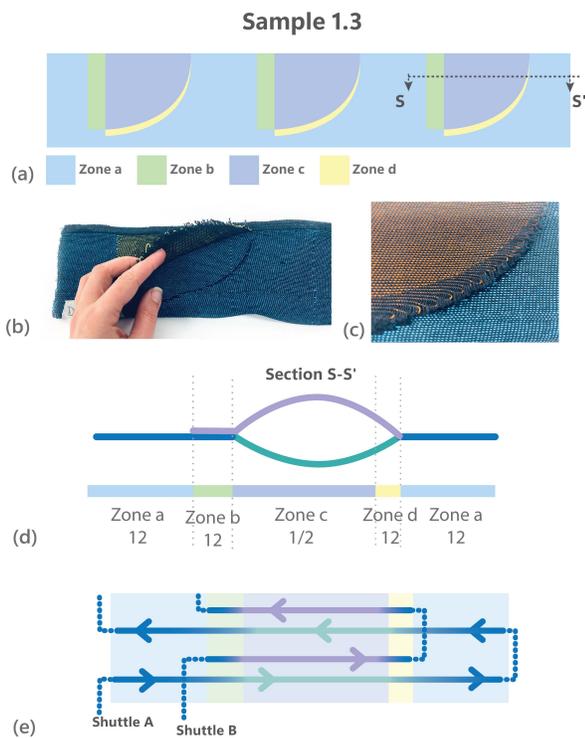


Figure 11: Sample 1.3 utilizes a partial weft to create selvages in the middle of the fabric. (a) The Map of Bindings showcases the different zones. (b) Picture of Sample 1.3, showcasing the curved two-layered zone c. (c) Detailed picture of zone c and d, where zone d is woven with a different weave interlacement, to create the selvage. (d) The cross-section of zones a,b,c and d, together with layer instructions. (e) Shuttle path for zones a, b, c and d. Shuttle A travels full width, to create the base fabric, and shuttle B weaves partial width to create the two-layered zone.

5.2.4 Samples Findings. In samples 1.1-1.3 we have utilized shuttle weaving for two purposes. First, it is a method that could mitigate some issues that emerge with shuttleless textile-form weaving (e.g., fraying, cut edges, and fractional density). Additionally, we were interested in the opportunities that shuttle weaving could offer to facilitate localized animate material placement and seamless transitions between layers and form elements for animated woven textile-forms.

The layers of developable surfaces that make woven textile-forms are 2D unless elastic or shape-changing yarns are used. In shuttleless weaving, these can be used but must be inserted across the entire textile width, which isn't always desirable [13]. In Sample 1.1 (Fig. 9), the zones are shaped as darts and woven with a heat-shrinking yarn inserted only in those areas. These darts ensure an uneven shrinkage and thus shape the waistband of a garment towards the desired size, which the user can activate to personalize the fit. In Sample 1.2 (Fig. 10), we created belt loops seamlessly integrated with the base fabric. To highlight the various layers, we

chose a different yarn color; however, the material itself can remain constant to blend the form element into the base fabric seamlessly, or yarn variables can be selected for specific properties (such as increased durability). The partial weft creates a seamless second layer without loss of density, reducing the production steps needed in the construction of the garment, and may improve durability through a reduction in cutting and stitching. Sample 1.3 (Fig. 11) shows how a selvage can be utilized in a curved section to create, for example, a pocket. The curved zones are not aligned with the warp yarns; therefore, some warp yarns must be cut to release the pocket from the base layer. To further reduce post-production, an edge is woven in a dense weave structure (tabby weave), creating an internal curved selvage.

While all of these samples were developed to support the design of shuttle-woven textile-form trousers, these techniques have also been used for other applications in HCI textiles [24, 59, 92]. Sample 1.1 can use any shrinking or contracting material, such as heat-shrinking polyester yarns, wool, linen, or silk, or conductive/resistive materials. When incorporating E-yarns in a textile, they are often interwoven with a base (passive) yarn, which can impact the effectiveness of the sensor. Using the methods described in these samples enables the addition of conductive or resistive materials without blending and with greater control of their placement. Furthermore, many variations can be explored of the separated second layer as shown in samples 1.2 and 1.3, for example it can allow for the seamless integration of (shaped) pockets to hold electronic components, animated materials like veneer [100], solar cells [114], or to separate elements in a circuit [92]. Building on the use of shuttles in HCI textiles, we see the potential for combining it with woven textile-form methods toward new classes of seamless interactive textile-form artefacts.

5.3 Experiments with Shuttles for Multilayer Zone Transitions for Form

The second set of samples sought to understand the form construction of the trousers. We utilized partial wefts, much like short row knitting, to mitigate the fractional density in multilayer structures and create a seamless textile-form. Sample 2.1 (Fig. 12) explores the use of tubular woven zones in combination with separated wefts. Sample 2.2 (Fig. 13) explores the use of partial wefts creating folds in zones, allowing for extra surfaces to emerge in these zones. Sample 2.3 (Fig. 14) combines these insights, but adds an additional shuttle that clasps the separated folds.

5.3.1 Sample 2.1. Sample 2.1 explores how a partial weft can mitigate fractional density [69] in multi-layered zones. Zone A, C and E are woven in one layer, and B and D are woven in two layers. In the two-layered zones, two picks of weft yarns are woven with a partial weft to compensate for the fractional density. Shuttle A weaves full-width coverage (Fig. 12 g), while shuttle B is used only for partial weft coverage. Furthermore, between zones C, D, and E, the zone transition is separated, resulting in an opening that emerges between the zones in the textile (Fig. 12.c), and creating a seamless tubular fabric in zone D.

5.3.2 Sample 2.2. Sample 2.2 shows three neighboring zones, which are all aligned with the warp/weft direction. Zone a is a one-layered

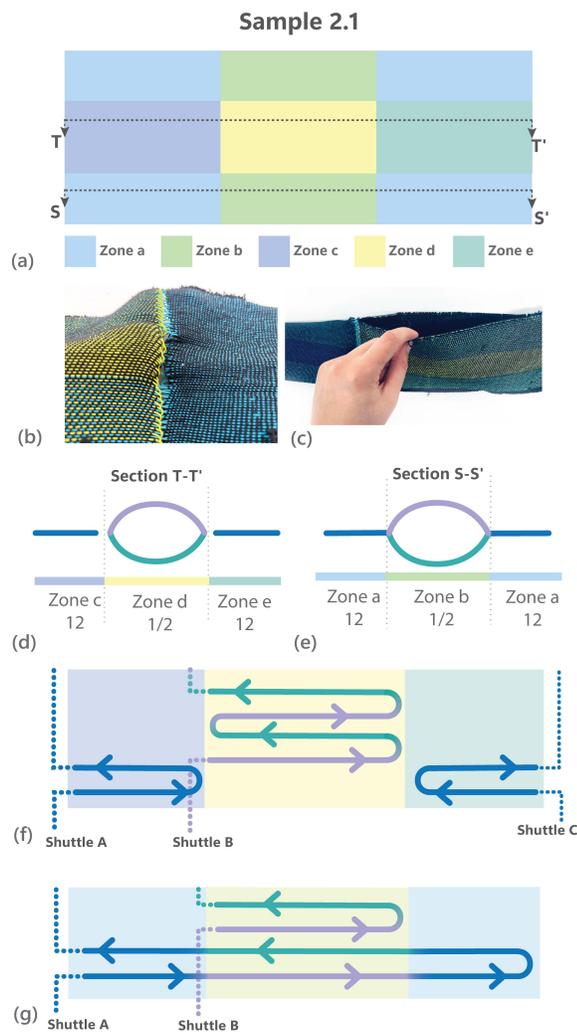


Figure 12: Sample 2.1 combines partial weft with a separated weft movement (a) The Map of bindings showcasing the different zones. (b) Picture of Sample 2.1. The two-layered zone in the center (zone b,d) has double weft insertions compared to the single-layered sides (zones a, c, e). (c) Detailed pictures of the zone transition where the bottom and top zones merge, and the middle zone is separated. (d) Cross section zone c, d, and e. (e) The cross-section of zones a and b, together with layer instructions. (f) Shuttle path of zone c, d, and e. (g) Shuttle path of the cross-section zone a and b.

zone that holds the textile together. Zone b is constructed out of four layers, where the shuttles move between layers, creating folds at the edges of zones. Zone C is woven in two layers. It took the insights gained from Sample 2.1, and thus, to compensate for the fractional density in the four-layered section, the shuttle movements were doubled in the multilayered sections, simultaneously creating the folded zone transition in zone B. Both on the outer edges and on the edge between zones B and C.

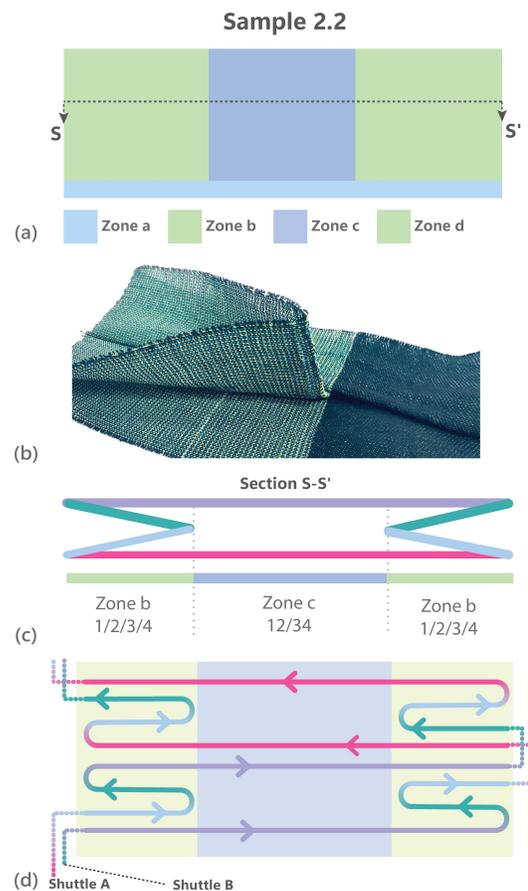


Figure 13: Sample 2.2 combines a partial weft with a fold in the zone transition (a) The Map of bindings showcasing the different zones. (b) Picture of Sample 2.2 when folded out, showing the folding zone transition between zones b and c (c) The cross-section of zones b and c, together with layer instructions. Zone a is omitted as it is a one-layered section. (d) Shuttle path for zones b and c. Both shuttles travel full width and partial width. The partial wefts create the folding zone transition where the weft yarn travels from layer two (green) to three (light blue) or the other way around, in zone b.

5.3.3 Sample 2.3. Sample 2.3 explores how a non-interlacing clasping weft can create a fabric designed for separation. This weft yarn can be easily pulled out, much like a ravel cord in knitting, to divide the fabric as needed. Shuttle B does not interlace with any warp threads; it only clasps with the folding edges created by shuttle A. The correct insertion sequence is essential to make sure the wefts are clasping. While we used a weft thread for this feature, another strategy with a similar result is to utilize a warp thread as the ravel cord, where both sides of the folding edges are clasping around the warp thread. When this warp thread is pulled out, the fabric can unfold to 3 times the width of the initial fabric.

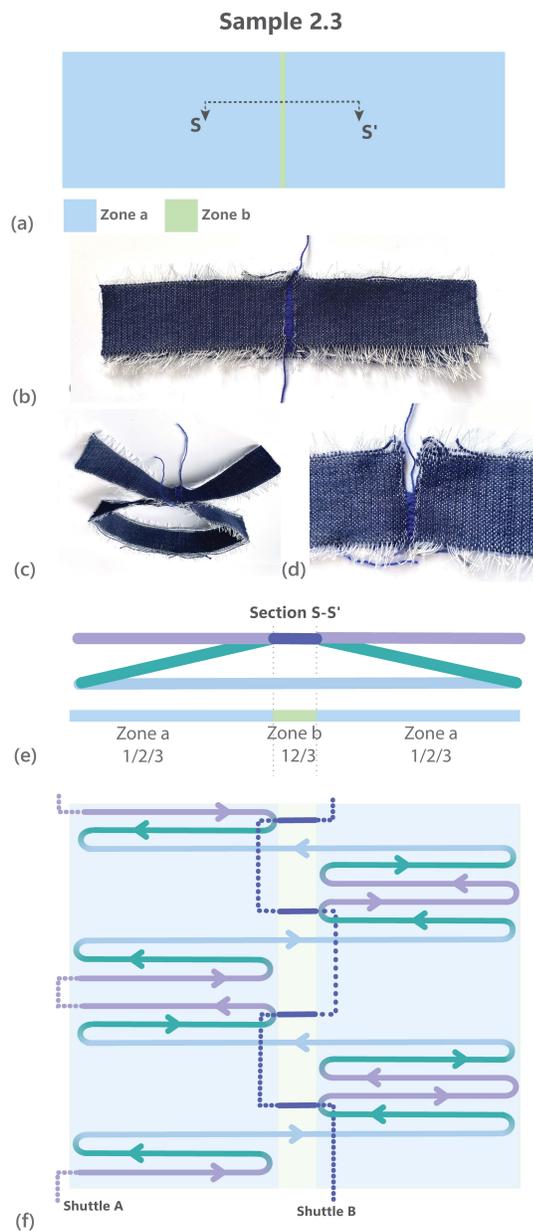


Figure 14: Sample 2.3 combines a partial weft with folding zone transitions in multiple layers, connected through a clasping weft. (a) The Map of Bindings showcases the different zones. (b-c) Pictures of Sample 2.3, showcasing the flat textile-form, and the design unfolded. (d) Picture of Sample 2.3 showing how the clasping weft can be removed from the folding zone transitions. (e) The cross-section of zones a and b, together with layer instructions. (f) Shuttle path for zones a and b. Shuttle a is weaving both full and partial widths. In zone b, Shuttle B is not interlacing, but only clasp alternating the left and right selvages of shuttle A.

5.3.4 Sample Findings. The second set of samples took insights from the first set of samples, such as inserting more wefts in multiple layers to mitigate the fractional density, using clasping wefts to connect two yarns, or separating wefts to create a gap or separate layer with selvages, to create a more complex form.

The planar insertion methods required on (most) looms, require weavers to create extra surfaces through weaving multiple layers connected by a woven ‘seam’, in shuttle weaving, these layers are connected through the continuous weft yarn, creating a ‘fold’. In the context of 3D woven garment design, these seamless edges are beneficial, as they do not unravel and thus need little or no post-weaving construction such as sewing.

Sample 2.1 illustrates how different weft densities can be achieved in neighboring zones. One of the main challenges in fabricating woven textile-forms is that the multilayer zones are too thin, due to the fractional density, or the zones where layers merge are very dense and therefore use more material than needed. Utilizing these different densities prevents the use of too much material, because the yarns are only placed where needed. Additionally, in Sample 2.1, the center forms a seamless tubular structure, which could create, for example, a trouser leg. Sample 2.2 explores how to weave the basic geometry of the trouser waistband with partial wefts, aiming to create textile-form that does not need post-weaving construction. This sample shows that internal folds can be woven, providing opportunities to create seamless woven textile-forms that do not need cutting to release the form. Sample 2.3 explored another take on creating textile-form that the user can manipulate; the clasping thread between the two multi-layer zones can be pulled out, revealing hidden material, color, or pattern. Simply pulling one thread out, users could change the whole fit or size of the garment.

Outside of the context of these trousers, HCI designers can utilize a varying material density, such as shown in Sample 2.1, by allowing the targeted placement and concentration of active yarns and materials in specific areas. These folds shown in Sample 2.2 can also be utilized with animated materials. For example, SMA wire can be woven through partial wefts in the folds, so the form can unfold autonomously [83], or yarns with varying properties can be utilized to create different folding behaviors. HCI designers can use a ravel cord not only in garments but also in designing textiles that can be disassembled easily. For example, a section of a textile containing e-threads, or other hardware such as zippers, can be removed for recycling. It also provides potential for users to change the fit, for example, if this structure is added to a waistband, a user could, if needed, pull out the ravel cord, and easily make a garment a size bigger, or change from a tapered to a straight-leg trouser. Furthermore, it could also be used for aesthetic purposes, such as revealing a color or structure underneath, allowing for extended use-time.

5.4 Trouser Prototype

In the final trouser design, we combined insights from our previous samples and developed animated textile-form trousers. The 3D digital design tool for fashion design (CLO3D) was used to simultaneously develop a MoB and 3D renders of three stages of

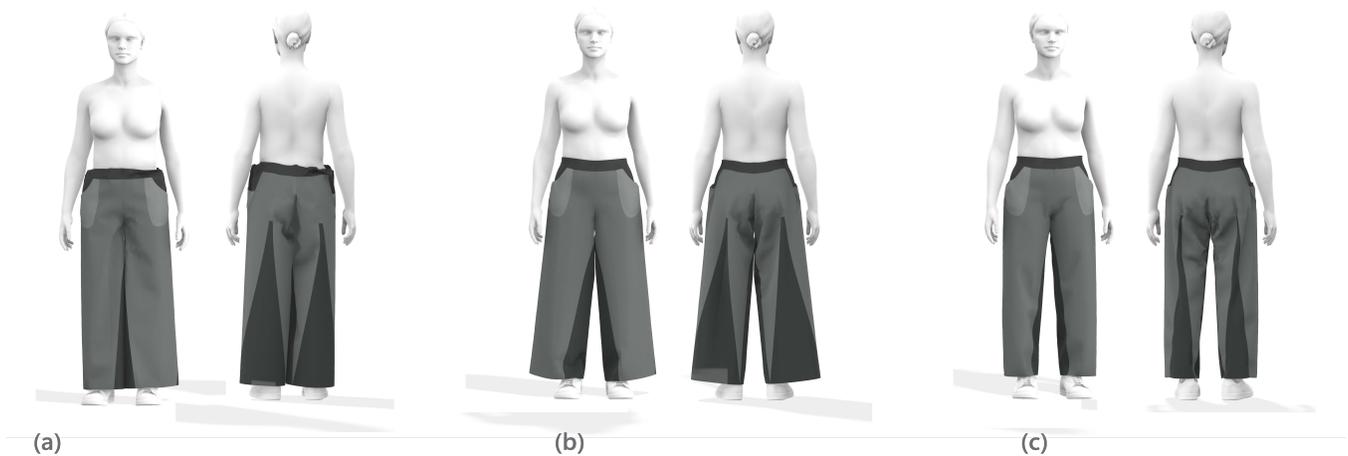


Figure 15: 3D renders of the digital design of the textile-form trouser made in CLO3D, showing the different stages the trouser can be changed into. (a) The first stage shows the form after weaving and taken off the loom (front and back view). (b) The second stage shows the trousers when it is shrunken to the size of the user. (d) The third stage shows how the user can adjust the fit of the trouser leg.



Figure 16: Sample 3.1. (a) Front view of trouser prototype (b) Back of trouser prototype (c) side view of trouser prototype before shrinking (d) Side view of trouser prototype after shrinking.

transformation (Fig. 15). Previous examples of animated textile-form trousers were produced on shuttleless looms [13]. On shuttleless looms, the animate material must travel the full width of the design, limiting possibilities and control of form. Starting with a basic design for shuttle-less woven textile-form trousers, we show how using shuttles to locally place yarn can fine-tune the shaping possibilities. The multilayered 3D form is also a significantly more complex form than the samples, and we anticipated that this would challenge the methods explored so far and highlight gaps in our understanding.

Initial sampling for Sample 3.1 (Fig. 16) focused on understanding the sequence and timing within the weaving process to ensure the shuttles were clasp and separating where needed. We explored this at the trousers' most complex section, where the trouser legs and pocket bag intersect, requiring the careful control of multiple shuttles (Fig. 18). In combination with the complex curvilinear form of the trousers, sequence and timing issues led to accidental clasp that prevented the form from unfolding, and at other times caused gaps in the textile structure when wefts were separated instead of clasp as intended.

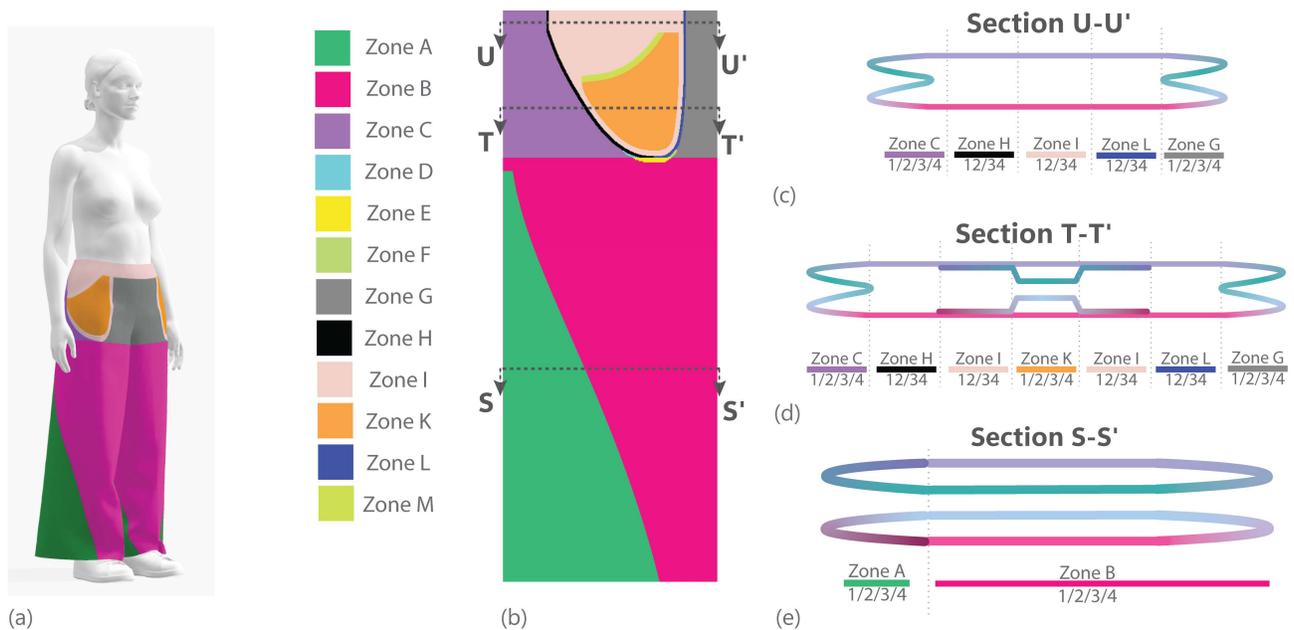


Figure 17: Design of the animated shuttle-woven textile-form trouser. (a) Digital design in CLO3D. (b) Map of Bindings, with sections indicated. (c) Cross-sections of waistband (section U-U'), hips (section T-T'), and legs (section S-S').

In the final iteration of Sample 3.1 (Fig. 16), we added zones to embed animated materials. In Figure 18, we show three cross-sections of the garment. The waistband (section U-U') is woven with heat-shrinking yarn, allowing the user to shrink the waistband to the desired size. Section 2 shows a cross-section of the zone where the pockets (section T-T') are located. Section 3 shows the trouser legs (section S-S'), with zone A woven with a heat-shrinking yarn carried in a different shuttle. Figure 18b and c show the complexity of the shuttle movements, once multiple shuttles are utilized for multi-layered structures. The correct sequence is essential to ensure the heat-shrinking and cotton yarns clasp, highlighting the weaving process's temporal nature.

6 Discussion

This paper expands on the notion of shuttle weaving for animated textile-forms, providing HCI designers with a design space that explores Material Process, Material Ingredients, Material Structure, and Material Form variables of shuttle weaving, supported by a design case. The design case illustrates that shuttle weaving holds potential for creating multi-material woven textile forms, allowing users to alter the size, structure, or aesthetic expressions of products. In this section, we reflect on the complexities and opportunities arising from this research, explore the broader implications of shuttle weaving and the design of animated textile forms for HCI, and discuss the limitations of our study and future works.

6.1 Enabling collaborations through shared language

The design and development of animated woven textile-forms utilizes skills and thinking beyond existing textile- and form-design silos, highlighting the need for interdisciplinary collaboration. However, the terminology, techniques, and equipment utilized by textile designers, HCI designers, and those working with technical textiles vary considerably between and within these fields. Furthermore, the division between craft, design, and industrial production leads to each field having different knowledge and skills. To advance the development of animated woven textile-forms in the future, the diverse skills and knowledge present in these different fields need to be brought together. Yet, this is not straightforward. The long history of woven textiles has resulted in many different concepts, techniques, and terminologies within and between these fields. For example, we have observed that terminology used to describe a partial weft varies greatly (e.g., inlay, discontinuous weft, supplementary weft, tapestry), and therefore it can be difficult to communicate these techniques across and within disciplines. Furthermore, we have observed that many terms describing specific techniques highlight the textile results instead of the techniques themselves. This emphasis fails to improve understanding of these methods and hinders effective communication. Therefore, we have aimed to adopt terminology and descriptions in the design space that concentrate on processes rather than outcomes. We hope this supports collaborations and opens up space for the exploration of weaving techniques beyond predefined results, enabling designers to explore the full potential of these methods.

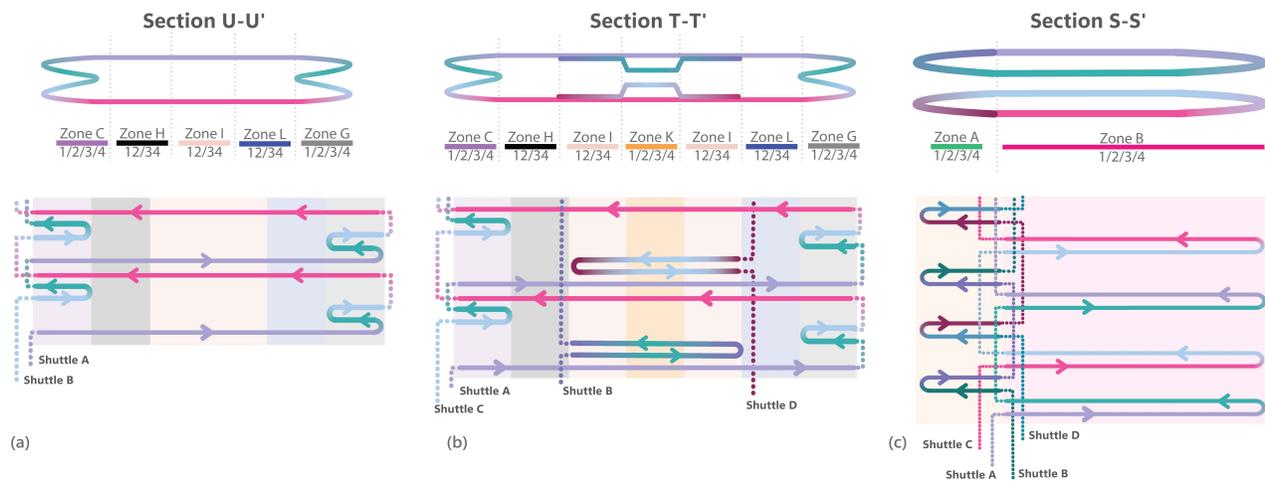


Figure 18: Cross sections and shuttle paths for the trouser. (a) The waistband, (b) the hips, and with integrated pockets. (c) The legs. The darker colored shuttles (B, D) are woven with heat-shrinking yarns.

6.2 Unlocking the potentials of looms in HCI and Industry

HCI Textile communities are grounded in a rich tradition of craft and DIY, and these approaches have brought considerable value to the domain. While hand-operated looms allow designers to engage in open-ended processes and direct interactions with the materials, it should be acknowledged that even hand-operated looms bring certain limitations. Many hand-operated looms impose conventions, which influence how crafters craft. This paper aims to show that if weavers dare to break with some weaving rules that have gradually emerged in weaving traditions, there is a lot of untapped potential to be found that may cater to changing priorities and emerging needs in the design and production of textile-based products.

When we aim to design textile products that are produced with sustainability in mind, for example, through designing for disassembly, zero-waste production, and local and on-demand manufacturing, we should also question the machines and tools we use to make these products. Crafters have the unique ability to explore these new and existing processes, inspiring and collaborating with the industry to change future textile production. In addition to this, historical methods could also offer valuable insights. Some researchers have started to push back on contemporary limitations by re-examining the potential of historical textile samples [5, 37], revisiting patents [88] and looms [27, 108, 124] that have long been forgotten by industry.

In our experience as HCI and textile designers working with industry, designers can use the design space in two ways. First, to explore variables within the context of industrial production using the tools they already have in their labs. This may include the modification of looms, but there is much to be explored within the bounds of existing tools, including frame and floor looms. HCI researchers could also use this design space while experimenting with a broader range of loom types available in industry. Secondly, designers can propose novel configurations and use cases that inspire and inform future developments in industry. The design space

could enable HCI textiles to step outside of the lab, facilitate collaboration between HCI and industry, and together utilize the full potential of fully automated industrial looms that can produce these complex shuttle-woven textile-forms.

Translating experimental HCI woven textile research into industrial contexts can be challenging. First, while automated and industrial looms with the capability of complex shuttle-weaving exist, they are not often presented in this way or developed for HCI contexts. It can be difficult for an HCI researcher to identify the potential of industrial machines developed for a specific purpose. Secondly, communicating convincingly with industry partners about the potential applications of these looms requires a shared language and ideally, the right 'proofs' to challenge assumptions about what industrial tools can or could do. We have found that samples woven on non-industrial looms, such as the TC2, but also frame looms or floor looms, if developed through a lens of industrial application informed by this design space, can make for tangible demonstrators of possibility and impactful tools for productive discussion with industry. We hope this design space inspires and supports explorations across craft-industry, historical-contemporary, and engineering-design divisions.

6.3 Limitations and future work

This paper identifies many variables available for exploration, yet we have only investigated a small subset of them in our design case. As the Material Process section of our design space outlines, many machine configurations can facilitate the manufacture of animated woven textile-forms. However, accessing suitable hardware remains a significant barrier for many HCI researchers and textile designers. The semi-automatic TC2 loom employed in this study was chosen because of its accessibility to HCI designers, but it also limits the possibilities we could explore. For example, interlocking warp and weft yarns in leno weaving could provide opportunities due to small-scale yarn movement variables. Therefore, future work may

include other machine configurations to examine different subsets of the variables presented in the design space.

While the actuation of materials and their inherent properties, as outlined in Material Ingredients, is important for animated textiles, we focused mainly on variables concerning weaving processes in this paper. Additionally, in our design case, the exploration of materials and actuation methods was limited, restricting the ability to thoroughly investigate the range of materials employed in animated textiles. Therefore, we recommend HCI designers explore a wider range of existing and novel animate materials across different levels of the textile hierarchy [36, 47]. For example, designers could explore how yarns with variable properties across their length could be combined with shuttle weaving for localized animated behavior in woven textile-forms.

Exploring Material Structure in woven textiles is tied to the machines and software available. However, the machine and software we utilized are not developed for shuttle weaving of animated textile-forms. Therefore, the complexity that emerges from this appropriation of tools limits the depth of exploration. Furthermore, as we aimed to focus on separating the concepts from the outcomes of weaving variables, some subsections, such as interlacement, are very detailed. We recognize that many weavers may not select variables as detailed as we show them in the design space, but instead refer to a weave structure as ‘twill’ or ‘tabby’. However, we hope this unfamiliarity is counterbalanced by providing an in-depth understanding of the building blocks of a weave structure.

While Material Form is an essential factor in the design and fabrication of woven textile-forms, few papers outline methods to create woven textile-forms, or digital design tools that would support this (so far manual) design process. This section of the design space is therefore based on a relatively narrow set of references from design, HCI, and engineering, and is supplemented by our own extensive experiences in designing woven textile-form. This is particularly true of animated textile-form, where change over time at a form level, as connected to textile structure, is underexplored and lacks supportive design tools. We hope this initial exploration inspires future research to detail and operationalize form-driven methods for animated woven textile-form, which could then support the development of digital design tools.

Lastly, this study did not conduct any user-centered evaluation, an area of interest, especially for wearability and movement principles relevant garments like the trouser case study. Additionally, this approach has potential for other real-world applications and interaction experiences. We recommend future investigations of user experience and novel interactions with animated shuttle-woven textile-forms in various contexts.

6.4 Final Reflections and Conclusion

Shuttle weaving of animated woven textile-forms introduces challenging complexities, even for experienced textile designers. To support the understanding of these techniques for novice designers, we, and other researchers before us [74] have explored documenting and visualizing the precise knowledge of sequence and timing to clasp and separate weft threads. Most digital tools for weaving lack critical features that would ease some of these complexities, such as cross-section visualizations for partial weft insertions or

visualizing shape-changing properties of the animated textile. Our many years of experience working with woven textile-forms allowed us to appropriate machines and software to explore these techniques without such tools. However, we recognize that novice designers may struggle to experiment deeply with these techniques. By mapping out the possibilities shuttle weaving offers, this design space can serve as an initial set of resources for future research seeking to develop design tools and digital workflows. Such tools could help reduce skill barriers that often hinder novice designers in exploring alternative or complex weaving techniques, while streamlining the workflows of expert designers.

Lastly, while the design space has been iteratively refined within the research team and students, who represent diverse skill levels and experiences, from novice to highly experienced industry professionals, it has not yet been subjected to broader evaluation. We anticipate this could uncover variables specific to contexts and application domains, such as variables provided by alternative loom configurations or when weaving embedded and unobtrusive textile sensors. Therefore, future studies should be conducted with other designers, both experts and novices, working within a range of contexts and application domains to continue to detail and refine the interconnected variables presented here. In time, we aim to contribute to deepening the understanding of the opportunities that shuttle weaving textile-forms provide to textile research in industry, design, and HCI.

Acknowledgments

Thank you to our colleagues and students at Industrial Design Engineering, TU Delft, particularly members of Centre of Design Research for Regenerative Material Ecologies, and the Materials Experience Lab for providing feedback and assistance at critical stages of the development of this work.

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