EscapeLoom: Fabricating New Affordances for Hand Weaving

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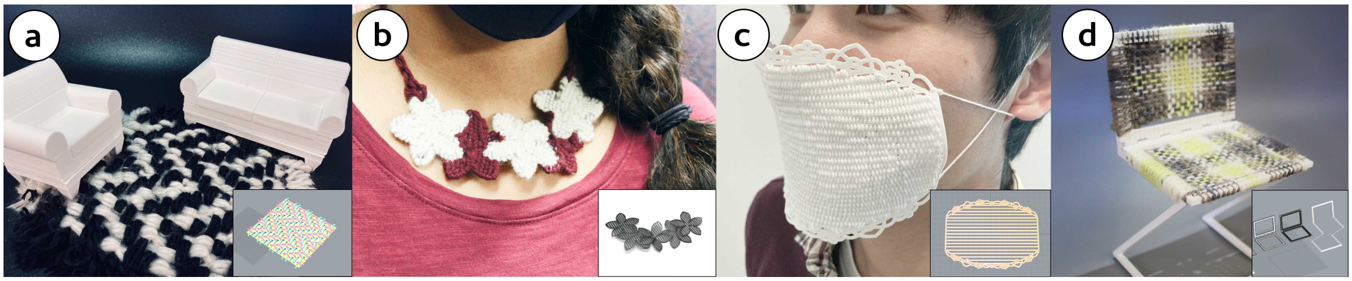

Figure 1: EscapeLoom is a computational design tool to afford new weaving workflows for novice users: Weaving a rug in complex pattern using a water-soluble guide (a), 3D printing custom shaped looms in flexible material to form a necklace and a mask (b-c), and 3D printing a rigid geometry to construct global shape with soft woven parts like a chair (d).

ABSTRACT

Hand-weaving is a beloved craft in history, holding promise for many opportunities in making from flat sheet fabrics to smart textiles. To afford new weaving experiences, we explore how 3D printed custom weaving tools interplay with different materiality, augmenting the design space of weaving. We propose novel weaving techniques enabled by 3D printed custom tools: (1) water-soluble draft to synchronize design intention and practice, (2) flexible warps to guide complex patterns and to shape resulting object, and (3) rigid global geometry for woven artifacts in 3D. EscapeLoom as a computational design tool enables users to employ various parameters in their computational design, and showcases many creative possibilities that move away from the traditional definition of a loom to dive into what more it can be.

CCS CONCEPTS

• **Human-centered computing → Interactive systems and tools**.

KEYWORDS

weaving, digital fabrication

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1 INTRODUCTION

Weaving has been a favored craft practice among a wide array of people in history. It not only allows making flat textiles with various patterns, but also proposes the potential to create soft interactive devices. While there have been great advances in industrial tools that automate weaving and other textile creations by enabling mass-production, there still exist people who enjoy craftsmanship in weaving. This is partly due to the customizability and space for creative exploration during hand-work provided by the craft of weaving, as can be seen from the growing number of tutorials online (e.g., Pinterest, YouTube and more), and partly due to the local textile communities consisting of people who enjoy participating. From hobby weaving to tangible learning experiences that help to develop fine motor skills as in a weaving class for children [19], weaving as a craft has stayed alive and keeps evolving.

Meanwhile, the rise of fabrication machines has allowed people to speed up previously labor-intensive manufacturing, including textile fabrication. Enabling mass-production of textiles with the industrial revolution, machine weaving has been slowly replacing human labor with automation in weaving. Fabrication machines, however, bring several trade-offs to craft activities. Although contributing to formerly hand-oriented activities with speed, efficiency, and cost-effectiveness, the *practicality* of these machines removes the joy and beauty from manual work, bypassing the learning experiences associated with thinking about the computational relationship between parameters and the physical phenomenon, and reduces the potential for creative exploration through traditional hand-craft [36]. Often, craft weaving teaches eye-hand coordination, problem-solving skills, interpretation of patterns and sequencing, and more [19]. The limitations of automated crafting often do not allow opportunities for creative exploration that are more common to experts; finding serendipitous discoveries [33], conversing directly with the materials [4], and feeling ownership by making by hand [30]. Despite clear benefits, weaving using traditional tools such as rigid loom and heddles can be challenging to novices, if not trained in interpreting drafts and sequencing. Recently, a great blend of digital/craft tools have presented a new design space. Advances in digital fabrication have already begun to contribute to this by facilitating fabrication of supplemental tools (e.g., [17]), and members of both 3D printing and weaving communities have started taking advantage of digital fabrication to complement their handwork.

In this work, focusing on weaving as one of the craft practices that can offer users ample opportunities for creative exploration, we aim to augment the design space of hand weaving by computational design that creates new workflows for weaving activities that we refer to as affordances. The new weaving affordances will complement the current weaving techniques with new weaving experiences driven by the computationally designed and fabricated tools.

Our on-going research questions that lie around using digital fabrication to assist handwork are:

- How can we leverage material properties and fabricated tools to support hand-weaving activities?
- What is a design space for weavers, that could be augmented by digital fabrication and computational design?
- How people envision the future of craft weaving?

We first discuss our observations and findings from a formative study to understand novice hand weavers, that led us to propose three novel fabrication techniques to gradually recast weaving for just textiles to weaving for objects, which promotes new creative affordances in weaving. Interplaying with different materiality that became available for 3D printers, we propose (1) water-soluble drafts to synchronize design intention and practice, easily integrating various weaving styles (e.g., herringbone and houndstooth), (2) flexible warps to guide various patterns, and (3) rigid global geometry of woven objects. Example applications showcase what 3D printing can add to traditional weaving to expand the design space. With the introduction of EscapeLoom, a computational design tool to augment weaving by generating custom 3D printable tools from creative design inputs, we provide planned workflows that combine computation and fabrication for hands-on experiences with weaving for novices. Ultimately, we discuss future outlook on potential new opportunities that the blend of digital fabrication and hand craft has presented us with.

2 RELATED WORK

2.1 Computational Tools to Aid Craft Oriented Fabrication

Research in HCI has focused on the digital fabrication and computational design tools to *assist* people with traditional crafts. Plushie helps sewers design flat pieces of fabric, to later cut, sew and then shape 3D stuffed toys [20]. Weavy enables users to design and simulate card weaving to create patterned threads [12], and Knitty further facilitates creating a knitted 3D object by converting a 3D sketch into a knitting pattern [11]. WeaveMesh is a system that converts 3D models to construct them in volume with laser-cut tapes, to bring about spaces for tinkering with materials [32]. ProxyPrint facilitates improved quality and speed of making for wiring art in jewelry making, inviting users to experience computational support for a popular craftwork [33]. The beauty here is, users become more engaged in the activity and have more control over the process that sparks creative exploration, instead of simply delegating production to digital fabrication machines. Hybrid fabrication has shed light on the vision to integrate crafts with digital fabrication, to empower fluid conversations between designers and materials [35], preserving expressivity from manual work [38], and adding intelligence to a hand device to assist designers with haptic feedback to achieve their design intention [24, 37]. The idea of combining a 3D pen with a 3D printer [30] let users be deeply immersed into creative making with 3D printed scaffolds and tools, offering new 3D printed affordances for creative exploration.

We are inspired by this body of work that aims to assist crafting activities, rather than taking over them through automation. The ability to make design decisions about the intended artifact using modern computational design tools would allow users to seamlessly convert their design ideas to implementable drafts, preserving the experience of hand-making.

2.2 Computational Fabrication for Maker Oriented Learning

As digital fabrication has permeated into our lives, there has been an increase in research to use fabrication technology to support traditionally manual processes, allowing more spaces for creative exploration that were previously reserved for professionals. Craft does not only refer to the use of *low-tech* materials in making, but also embraces various hands-on techniques and computational materials to make artifacts [3]. Researchers have argued for the use of fabrication with computational support in a learning setting stating that "Computers enhance craftwork most surprisingly because they allow for new languages, new formalisms to be developed around the creation of artifacts; and these new languages allow the student to think in novel, productive terms" [6]. The rise of *Pervasive Fabrication* opens up a dialogue about the kind of educational settings and concepts that can benefit from computational fabrication and new design literacy [5]. Following that, existing works explored the combination of crafting activities with technology to show its impact on learning and enhancing expressivity. Using low cost material and computational devices, researchers have begun to explore the impact of paper crafts on the process of learning [18, 21]. Textile soft material has leveraged how the handcrafting of electronics can have expressive results [25]. We are inspired to empower novices with customizable tools that can not only enable them to understand hand weaving as a craft, but also enable expressivity in design with the computational aids, that are particularly helpful in maker oriented learning for novices and programmers [14, 15] opening up new avenues for creativity.

Hand weaving is a craft where a novice needs to understand not only the terminologies and tools such as warps, wefts, heddles, looms, etc but also how they relate to each other and thus contribute to the outcome [26]. This learning curve can be softened with the help of computational aids that can help learning through tangible experiences. Our work sits at the intersection of computational design and the use of different materials that has the potential for hands-on learning as a low cost facilitator in making and education using fabricated tools and computational aids, which can be positioned as *middle tech* as described in [6].

2.3 Material Explorations to Bridge Craft and Computing

New opportunities that fabricated tools cater to users constituted a new avenue for employing material *properties* into the novel design workflows. They push the boundary of traditional crafts in terms of what they can create, bring in new material properties to craft so as to enable new interactions with those artifacts in craft activities. Now, 3D printed objects can serve as proxy for hand-crafted metal works [33], and hybrid materials change the assembly processes of fabricated objects [2]. Combining 3D printed rigidity with tension and softness of textile enables users to consider material specific behaviors in devising sensing and actuation [27], while 3D printed objects can be used as guides for hands-on 3D doodling [30], and now 3D printed parts can even replace patches that were previously made of fabrics in textile craft [31].

Material properties also play an important role in how the existing fabrication tools and techniques can be modified to support a new type of hybrid-fabrication, demonstrated by 3D printing with yarns for interactive plush toy bears [10], and felts for soft interactive objects [23]. It is also possible to directly manipulate material properties through computation to generate interesting applications. Creative use of material properties can produce applications such as creation of wood texture for sculptures by burning the wood particles in heat-sensitive filament [34], and self-curved folding utilizing shape-changing properties for previously hand origami-oriented crafts [29].

We take similar approaches that employ new material properties into design of new objects, which induce new interactions with 3D printed objects by using existing fabrication techniques that were previously not imagined within the context of hand-weaving by leveraging material properties of the 3D printing filaments.

3 FORMATIVE STUDY

We first crafted ideas for digital fabrication to help the process of weaving, such as fabricating custom tools (e.g., heddle) used in weaving, then implemented a prototype for a computational design tool for non-expert users, which would generate files to fabricate custom tools based on users' design inputs. We conducted a design workshop with 12 participants to understand what the tool can afford as well as the frustrations and needs arising from the tool.

3.1 FabWeave: A Computational Design Tool to Produce Custom Weaving Tools

Inspired by existing parametric draft design tools to weave smart textiles (e.g., [8]), we implemented FabWeave (Figure 2). FabWeave is a computational weaving design tool prototype, to let users design drafts and then generate digital files to enable fabricating custom supporting tools to aid hand weaving, allowing them to design a weaving draft based on design parameters of number of warps (width of textile), wefts (height of textile), and input color. The system then generates design files to fabricate tools that are customized through user design, such as looms, heddles, and printed draft with color code. We used Processing to implement the design interface, and the user design data is streamed to OpenSCAD to generate custom tools by parametric script, which then generates solid geometry for 3D print and/or vector lines to laser cut, using basic CSG operations. The default interval between warps is set to 1.5 mm, which is compatible with a commercial acrylic yarn but can also be customized.

Overall, we found that a variety of designs could be made through different pattern design and unique properties of yarns used in weaving. Fabricated tools can also afford their own creative re-use with various materials in practice. For example, improvising the use of heddles, such as changing the order of heddles, or using them more than just once as instructed in the original draft, or inserting heddles in different directions can result in layers in parallel, and with the changed layers, we were able to weave double-sided fabric or fabric with pockets. Although this technique requires some experience, it demonstrates that the fabricated tools can support traditional weaving in various ways with impromptu changes, such as non-linear weaving which was previously not possible using conventional generic weaving tools.

3.2 Design Workshop

To verify that FabWeave can assist novice users, we designed a design workshop to (1) observe users' general weaving activities using our prototype in personalized weaving practice, (2) evaluate tool-effect on the actual weaving activity, and (3) identify hidden challenges and implications to further augment design space.

3.2.1 Overview, Procedure, Participants. In a workshop setting, we provided common tools for weaving such as needles and various yarns, and let participants freely create their own patterns using the FabWeave design system. One of the authors facilitated the workshop, answering questions if necessary, commenting on the potential complexity of the result. We recruited 12 students (P1–P12) from the university (female = 5, male = 7, mean age = 22.5), four of them were grouped in one session. We intentionally chose novices/casual makers with no or limited weaving experiences as participants, as our target audience are beginners in weaving. Eight of the participants (except P1, P2, P4, and P11) self-reported that they had woven or knitted a coaster or muffler before. We allowed participants to talk to each other in order to freely discuss designs and share processes. Due to the time limitation of the workshop and understanding the long process time to 3D print different custom looms, we designed the session with the fixed scale and dimension of a 3D printed loom. We provided unified pre-printed looms (70 by 80 mm), so the dimension of the draft was pre-determined. Each participant received approximately $50 for their time (3 hours), and the study was conducted before the COVID-19 pandemic.

3.2.2 Results and Observations. Figure 3 showcases the outcomes of the design session of woven fabric and their design. The design session let us pay attention to the pain points in the participants' processes, while questioning what design parameters will grant more space to play with the process.

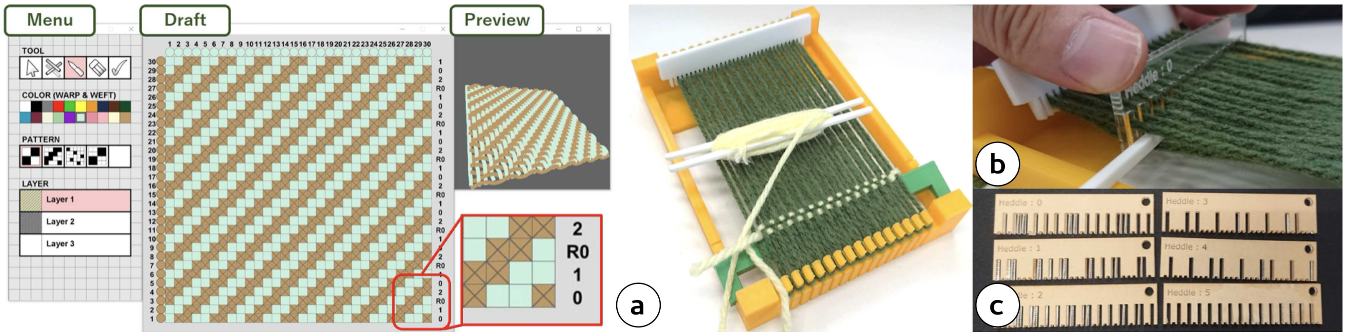

Figure 2: FabWeave is a design system of a weaving draft (left), and fabricated tools: 3D printed loom (a), inserting custom heddles into the warp (b-c) matching the pattern shown in the draft.

Figure 3: Various resultant patterns of the design session using FabWeave to design pattern and generate the custom weaving tools. Insets on the top-right corner show the user's original design, which was printed as a draft.

O1. Weave-Draft Synchronization. We observed unattended gaps between draft design and weaving in-play. Participants had a hard time following the draft while weaving, sometimes getting lost with respect to reading and weaving, as they needed to go back and forth between the printed draft and their weaving loom. Participants took an approach similar to pixel art drawing to design textile patterns using FabWeave and tried to draw complex images such as Chinese characters in calligraphy, and animation characters in various colors. These are very creative ways of designing drafts but not common among professionals or skilled weavers, and they can make the actual weaving overly difficult for non-skilled users. We found that interpreting a compilation of *pixels* with consecutive yarns was not simple, and using a regular loom, this draft design inevitably made weaving difficult in reality for the participants. As shown in Figure 3, P2 tried to weave a recurring character, which took him more than 3 hours to complete only one third of the entire design. P5 and P6 seemed overwhelmed when designing drafts, saying "*I was excited when designing, but I realized that this pattern is almost impossible to weave, I lost my energy [motivation]*" (P6). One other reason that we think synchronising the process became harder for some of the participants was their choice to pick up different colored yarns than the ones in the draft.

O2. Creative Improvisation. Beauty of handwork often aligns well with potential for creative deviations by *improvisation*. Indeed, many participants changed the design choices, mainly colors, as they made design decisions in-situ with the given materials. For example, P4 found his chosen colors in design were not satisfying, and so changed the color in part. Participants tended to choose yarns for warp and weft in-situ around the time the patterns began standing out in the woven result; several participants also considered harmony of the color (soft pink vs. hot pink). One participant commented "*I found weaving with two colors [in one weft] is hard*" (P4), as in the common loom, entire row is often made of one weft yarn. The current tool is still limited in supporting creative alteration of potential parameters. Users are also limited to design a flat, square textile, which may restrain the boundary of possible applications.

O3. Interactions with the Weaving Process. Several participants were not able to understand the relationship between the

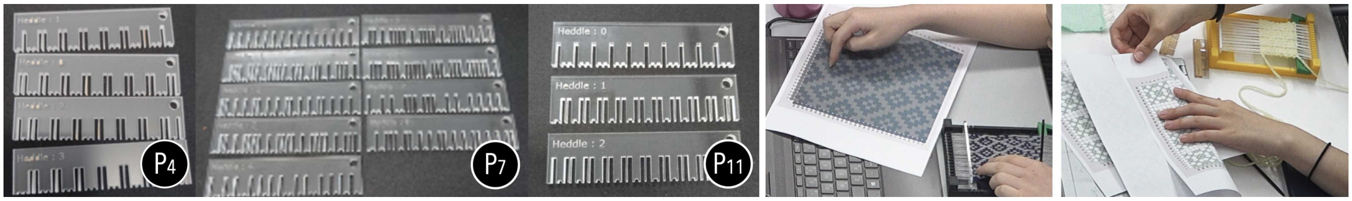

Figure 4: Examples of custom heddles from design session. Each design generates unique heddle shapes that help users easily create paths for wefting through warps. The number of heddles differ from 1 to 10, regardless of the complexity of draft (Left). Participants attempt to synchronize the sequence of heddles and the pattern by marking on the printed draft (Right)

weaving draft and actual weaving, which is common for beginners, making it hard to synchronize the design intention (draft) and outcome (textile). Interestingly, while P7 did not know which yarn would come at the front and back of warps at first, he simply inserted heddles in sequence to realize the pattern. As custom heddles were provided based on unique draft designs, they eased the weaving if simply the sequence (Figure 4 (left)) was followed. Observing this process made us ask how those custom tools can aid individual's hand work, providing unique interactions that may change their weaving experiences. For some participants, synchronizing the position of insertion, the number of the heddle as well as the sequence of insertion was confusing, making them count lines, fold and mark on the printed draft (Figure 4 (right)).

3.2.3 Reflections. To identify further potential, we sent follow-up questionnaires to selected participants and obtained six responses. Here, we further discuss the potential to augment weaving through improved computational aids.

R1. Learning by Weaving, Pride by Achieving Complex Pattern. Participants quoted various challenges that they had, either engaging or demotivating. As confirmed by P1, understanding the relationship between the draft and actual weaving was hard, yet, many participants quoted that they started appreciating how the draft guides the work, as they found their intended design gradually appear through the hands-on experience. P4 mentioned that he felt very proud when a very sophisticated pattern showed up from the woven outcome at the end. Similar to our observation O1, participants (n=3) also found that designing the draft and the actual weaving are somewhat detached, and made them put extra effort in synchronizing the work. However, while weaving, they were able to learn the details of weaving activities; as they were able to see their intended outcomes appearing progressively. This echoes the significance of direct interaction with tools and materials to facilitate creative exploration, by synchronizing design process with gradual outcome [16, 35] to gradually understand the design process.

R2. Balancing Expressivity & Feasibility. When designing, some participants started by searching images online, hoping that they could directly import source images and convert them into patterns. They quoted back that images of a calligraphy, a favorite drawing, or a set of existing pixel art would be cool to weave, but at the same time, they expected FabWeave to guarantee the feasibility of weaving, as designing a weaving draft is not simply pixelating a source image. As part of a continuing discussion on the impact of *creative exploration* on *learning-by-doing*, we expect the new design techniques will facilitate users to find joy in weaving, expanding the room for expressivity with wider design options with new design parameters introduced. Albeit hard to achieve together, new tools must afford interaction that also lower complexity, as we also saw what custom heddles catalyzed; complex patterns that looked almost impossible to weave were easily achieved by simply employing custom heddles in sequence, which guided step-by-step weaving.

R3. Desire to Create Practical Examples. Participants paid less attention to the various material properties such as yarn type and thickness, which otherwise would have facilitated a variety of custom looms through design parameters as input. However, the complex pattern design such as calligraphy or anime character, was due to their desire to make something *practical* like blankets. Thus, we asked *"if you can customize the loom (size and shape based on material properties), which feature would you like to explore and what kind of artifacts would you want to weave?"* through online survey. To induce wider ideation, we also showed furniture with a bamboo strip woven seat and a hand bag woven using ripped fabrics for inspiration. Answers varied in scale, material type, and usage of weaving result; potential to weave a larger item using a scaled loom using thick yarn or straw, and durable objects that could actually be used in daily life. P7 also commented *"I would like to [try] a combination of different weaving technique such as lace"*, indicating that more creative designs will spark if we provide users a space to think of *use case* of woven things beyond pattern design. *"[I want] something that can be used in real life."* (P12)

In sum, our observations (O1-3) and reflections (R1-3) provided guidelines to improve our prototype, serving as three design goals towards new workflows of weaving augmented by computational design as follows:

- The design should enable ease of learning, aiding a gradual understanding of the weaving process through tangible experiences.
- The design must address the translation gap between a pattern draft (digital) and the actual weave (physical).
- The new user experience should empower creative exploration with weaving of practical, usable objects.

4 WOVEN TEXTILE TO WOVEN OBJECTS: NEW DESIGN WORKFLOWS WITH NEW 3D PRINTED TOOLS

Integrating the observations and reflections from the formative study, we present novel fabrication techniques to augment the design space of weaving, leveraging computational design, digital fabrication tools, and new materials available for 3D printing.

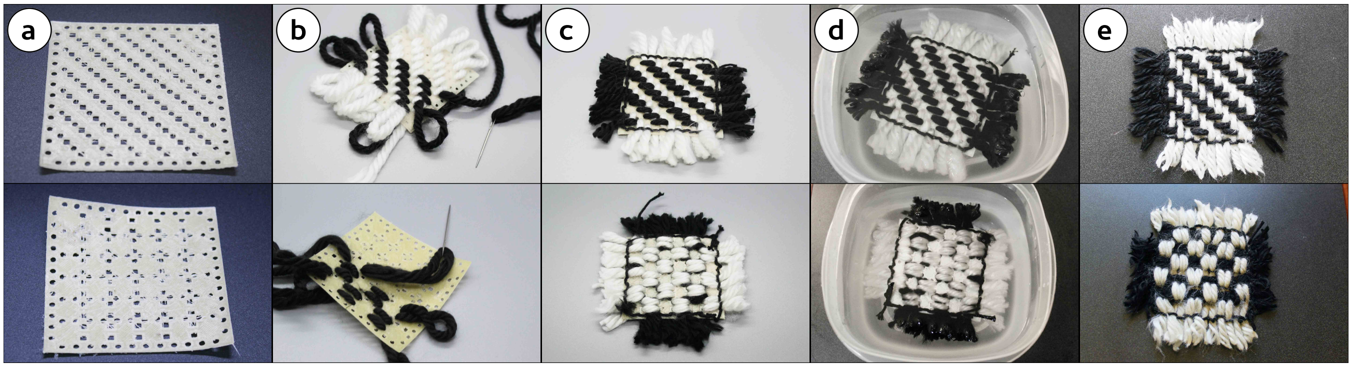

Figure 5: Process of using PVA looms in the Twill (top) and Basket (Bottom) weaving: (a) 3D printed PVA plate guides (b) weaving by following the structure that generate (c) woven patterns. (d) Immersed PVA looms in water leave (e) final patterns

Through our applications we address the challenges uncovered during formative study, as well as encourage creative exploration within weaving. We identified three fabrication techniques in which digital fabrication tools can aid users in weaving, introducing a new perspective towards design of woven objects: (1) water-soluble looms as guides (2) flexible warps to generate patterns, and (3) rigid frames as looms to construct 3D objects with soft sections.

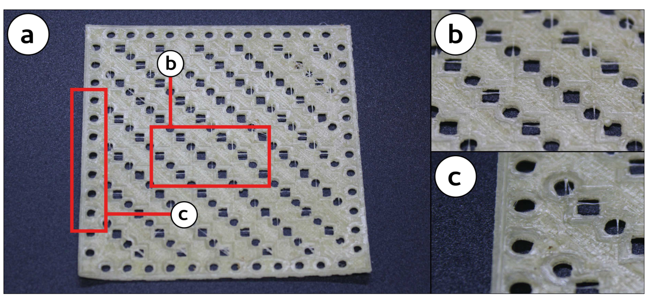

Figure 6: Structure of a PVA guide with twill pattern as an example: (a) Guide is divided into two parts, holes for warps and wefts, and outer holes (b) holes for warps and wefts are shape coded – circular holes for warps and square holes for wefts, (c) Outer holes form the boundary of the guide allowing for fastening ends of the warps and wefts with a string

4.1 Water-soluble Looms as Coded Guides

From our formative study we found that there was a sharp learning curve for our participants in locating the implication of a design draft on the subsequent weaving process in practice, and it also required cognitive context switching in synchronizing (O1). Modern 3D printing leverages properties of materials such as PVA and TPU, empowering us to explore new possibilities in fabricating tools that can aid weaving process. 3D printed looms with these materials can become guides for novice weavers to approach weaving based on the patterns, obtaining specific shapes and images in their weaves that are 3D printed.

PVA (Polyvinyl Alcohol) is a biodegradable material that dissolves in water, often found in detergent pods. With its special property and inspired by water-dissolving support material available for high-end 3D printers, off-the-shelf filament quickly became available for low-cost FDM machines. Hand weaving consists of constant communication between the pattern draft and the process of weaving which can get tedious and difficult to follow, especially with complex custom patterns as can be seen from the formative study (O1). With PVA's water-soluble property, we found a potential to create guides for novice users such that once the pattern has been woven onto the PVA guide, the guide can be dissolved when finished, leaving behind the woven pattern. 3D printed guide plates with holes indicating the positions for weaving warps and wefts with shape coded holes (e.g., circular holes for warps and square holes for wefts), would allow novice users to understand and follow the pattern while weaving on the PVA plate (Figure 6). Holes on the edges of the guide plate allow fastening the ends of the yarns to the plate, similar to fixing warps. Figure 5 shows the process of using a PVA guide plate made for a twill and basket weave pattern.

PVA plate design could be pre-defined, or customized based on the way a pattern draft is designed. A weft string will go over and under a number of warp strings based on the pattern followed. Wherever the string needs to go over or under, a hole is made so users can understand the complex relationship between the weft and warp by simply following the unique coding each PVA guide provides. We also created a PVA pattern library that can be used for the purpose of learning new patterns by novice users. This technique will touch upon R1, in that, it would be helpful for users to learn about different patterns of weaving, the structure or even the process of weaving. We expect novices to learn the relationship between yarns and how the pattern comes through through weaving, being empowered to achieve complex patterns that various guides ease to realize in practice. It can be an entry level method of teaching weaving and eliminates the need to jump between the process of following the pattern draft and actual weaving, allowing users to focus on the process.

4.2 3D Printed Warps as Pattern Generator

For users, deviating from traditional weaving pattern is not an easy task even for skilled weavers, whereas improvisation can grant more creative exploration (O2). Warps are always required to be straight and to be held taut in order to properly weft through. Therefore, different shapes of weaves can only be created by manipulating the wefts in conventional weaving practice. TPU (Thermoplastic Polyurethane) presents flexible, stretch, and bend properties when

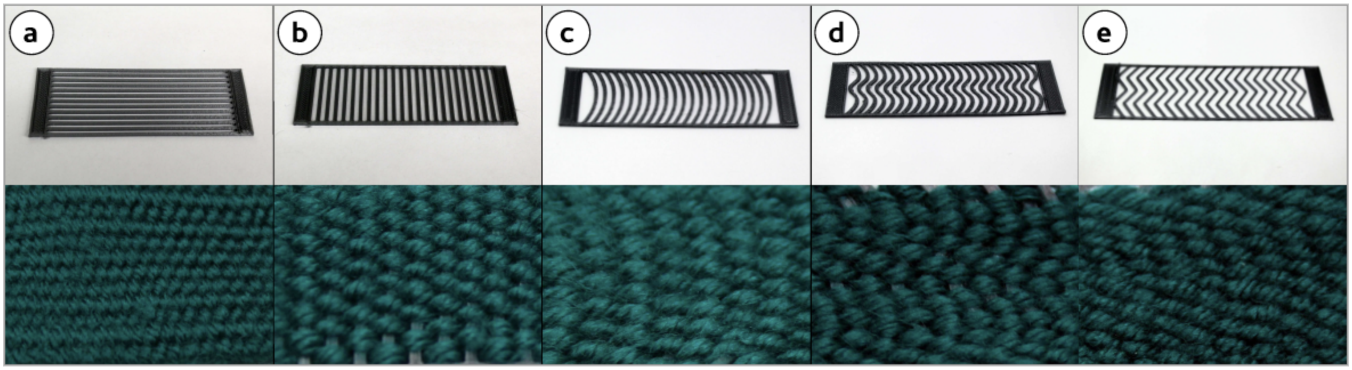

Figure 7: The modification of the aesthetic of a plain weave by manipulating the shape of 3D printed warps in TPU (a)Horizontal warps, (b)Vertical warps, (c) Curved warps, (d) Wavy warps, and (e) Zigzag warps

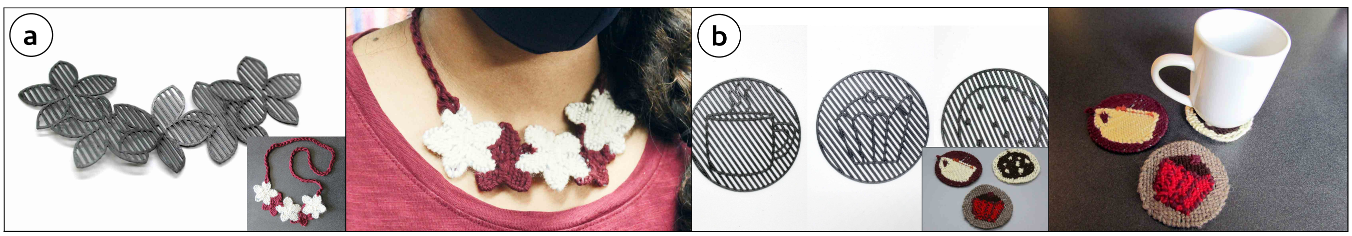

Figure 8: 3D printing TPU looms as guides for specific shapes (a) necklace of flowers (b) coasters, make it easy for users to differ colors and patterns with creative deviations in practice

integrated into certain geometries[1], the materiality becomes very similar to regular yarns. By varying the thickness of the printed object, we can manipulate the flexibility of TPU to resembles warps. Often the process of warping can also be challenging for users, as it needs certain density, intervals, and height that are tightly coupled with looms' given physical dimensions. 3D printable warps can be geometrically planned ahead with their desired specifications in scale and warp properties, enabling specially shaped warps such as in a wavy form or varying directions. Designing the warps hence becomes a deliberate decision on the part of the maker depending on their intended outcome during the design, adding another parameter in the weaving process that can be controlled and modified. Figure 7 shows the various shapes that the warps can take and ultimately augment the aesthetic quality of the final weave, even if it is a simple plain weave.

The warps can also be placed in a shape that the resulting fabric will be formed in, integrating that shape into the final object. This technique enables us to customize the shape of the entire loom, divide the loom in parts through different shapes and fill these shapes in with warps in various shapes and directions. Arbitrarily changing the direction of warps results in a variety of patterns on the woven fabric only through orthogonal weaving, without a complex draft to enable it, and also makes changing of color for each shape segment possible, such as using red and white yarns for different flowers in the flower pattern, for example, or differently shaped coasters, as shown in the Figure 8. The new process thus recasts the current pipeline for making soft objects using fabric, as users can plan the shape of fabric before they make the textile by weaving, and easily associate colors needed in weaving parts, along with shapes, offering unique interaction with the target objects such as woven necklace with flower pattern, coasters, etc. Once woven, the textile immediately becomes the ready-to-use soft artifact, touching on R3 i.e. the participants' desire to create practical examples. This process also touches on R2, in that, users can generate custom shapes on their weaves while also making sure that the pattern would be weavable since, in the formative study we observed that users were eager to weave complex patterns but found that doing so in practice was not accessible even with the custom tools that we provided.

4.3 3D Printed Global Geometry

Weaving is conventionally associated with fabricating 2D textiles, but is also found in many 3D objects using various materials such as jute yarn, rattan and PVC cord, as it appears in baskets and woven furniture. In that way, weaving could be perceived more unique as users can consider weaving some parts for individual artifacts (O3). For novice users, however, learning to weave while creating an abstract object such as a textile remains challenging, as they might weave plain frames of furniture that can be woven but it is nearly impossible to turn their favorite collection of furniture in 3D form into woven artifacts. 3D printing offers the possibility to design objects with rigid global geometry having soft woven parts. We propose deconstructing a 3D model of an object into a rigid skeleton frame or structure and the soft parts, wherein, the

[1] If a volumetric 3D object such as a cube is printed in TPU with 100% density, it does not make a huge difference with the rigid plastic

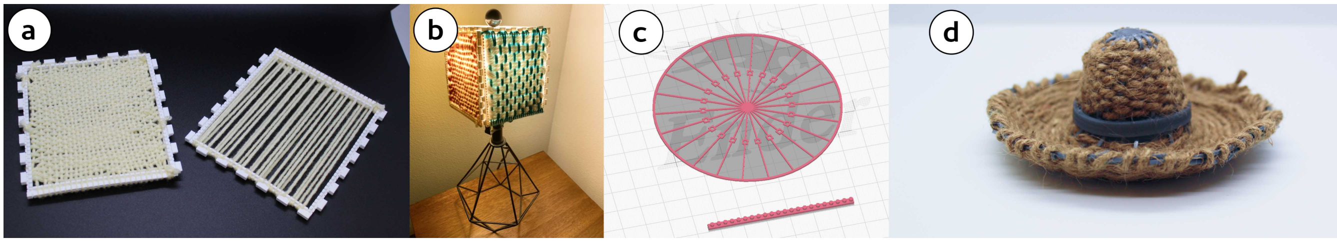

Figure 9: Combination of a rigid frame with soft woven parts printed in modules and assembled to form a lamp shade (a-b), Bending TPU warps to weave a scale model of a hat (c-d)

rigid structure would be 3D printed allowing the rest of the parts to be woven. The rigid frames have the ability to be printed in modules, and later assembled into the final object. The frames can have notches for manual process of attaching warps for the woven soft parts of the object (Figure 9 a–b), or assembly joints if the warps are separately printed. This approach allows articulating, functional objects to be built in a modular fashion with soft woven sections as are needed in forms of furniture such as chairs and cots. Combining the TPU warps with a rigid frame, can enable soft 3D shapes with a rigid anchor as is needed in applications such as baskets. It is also possible to print TPU warps such that, when they bend, they form the required 3D shape like a hat (Figure 9 c–d). If the end result of the weaving session is a functional, usable object, the weaver's motivation can be maintained through the generation of the feeling of ownership over that object and the potential joy of having created a usable object (R3).

5 ESCAPELOOM: COMPUTATIONAL DESIGN TOOL FOR AUGMENTED WEAVING

We introduce EscapeLoom, a computational design tool to aid hand weaving with digital fabrication. With various design parameters that users can consider in designing weaving such as 3D global geometry that can be borrowed from existing 3D objects, number of warps, warp shapes and directions, weaving patterns, printing material, and more, users can produce new affordances for weaving facilitating the three techniques introduced above. The tool helps users in designing custom 3D printed aids for our proposed techniques, providing planned workflows that combine computation and fabrication and allowing the creation of various artifacts from flat textiles in various patterns to 3D objects.

5.1 Implementation and Workflow

Here, we describe the implementation and workflow of EscapeLoom that facilitates computational support for the three techniques. We implemented the tools using Rhinoceros and Grasshopper and other relevant libraries (Pufferfish, Elefront, HumanUI, and SelectablePreview, etc.) as a series of scripts, and users can switch the tool by selecting a script.

5.1.1 Creating PVA Guide Looms. While users can import popular weaving patterns such as plain weave, users still can use design interface used in FabWeave, to customize their draft. Based on a pattern represented as a binary value of 0 and 1, the script generates a plate with holes to thread a yarn. Square holes indicate combing position for wefts, while round holes indicate combing for warps. These yarns are located onto the plate determined by the direction (i.e., see Figure 11). To customize the plate hoping to create textiles in scale, or to use chunky yarns, users can set the parameters: the thickness and interval of a yarn, thickness and margin of the plate, hole size, and a pattern, which can be previewed on the Rhinoceros window (Figure 10a, b). Similar to the original FabWeave tool, we implemented UIs using Processing, in that generated patterns can be sent to the script using the OSC communication (Figure 10c, d). With the binary information in the draft, the script creates discrete points in a wavy row and interpolates them into curves, which corresponds to the warp and weft yarns, respectively. For example, given 0 (i.e., warp over weft), the script moves up a point of the warp and moves down a point of the weft. By interpolating the line of points in each direction, the script generates curve geometries, which represent woven yarns. By extruding a square and circle shape along this curve, we obtain the geometry of a pattern. The script computes the intersection between a plate and the yarn using Euclidean solid operations leaving holes in coded shapes onto the plate. Once satisfied with the preview, users can export it in the STL format to 3D print in PVA.

5.1.2 Creating TPU Printable Warps. To create free-drawn warp patterns that are not in traditional straight lines, or shapes of the resulting textile objects, users create 2D vector drawings and import into Rhinoceros to the script. Then the script searches regions to be filled with the warp. In the option window, users can set parameters (yarn thickness, intervals, etc.) and the type of a pattern of the warp as shown in Figure 7 (Figure 12a, d). In addition to the default parameters related to the input material for weaving (Figure 12b), this script requires several pattern-specific parameters such as the rotation of the warp, frequency and amplitude of the wavy pattern, as user may change the direction of warp in petals vs. leaves in flower, for example. The script can import additional curves to extend the frame. The curves are connected to the input vector and converted into the frame structure. We also employ diverse options to fill a region with appropriate patterns; narrow regions and short warps that are nearly un-weavable are automatically removed with a threshold set by default, and users can deselect an unnecessary region by putting a point on the vector drawing. To find such regions in drawing, the script splits a surface made with an input 2D vector (e.g., background, cake, crease in paper cups in the cup-cake coaster, see Figure 12c). Next, the script splits a row of curves, which covers a region like in a striped pattern. Then the region outlines split curves into inner and outer, removing outer lines to leave inner curves to become the warps that are in each

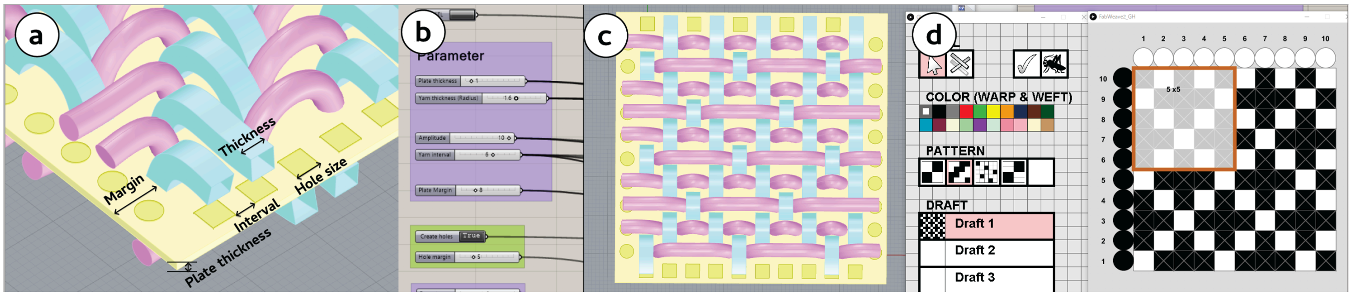

Figure 10: Tool for generating a PVA guide plate. Various input parameters are set (a-b) and user can get PVA printable plate (c) by either exporting existing pattern library or customizing using the draft design UI (d).

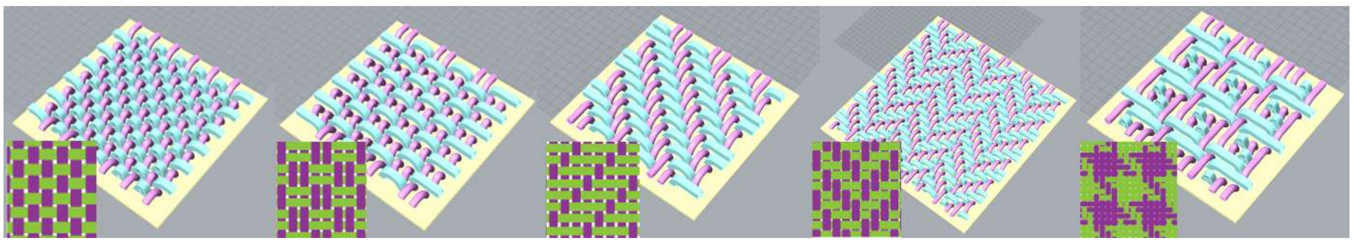

Figure 11: Library of PVA loom to generate the five most common weaving draft patterns: plain, basket, twill, herringbone, and houndstooth weave (from left to right). Insets show traditional drafts.

region. Once warps are split according to regions segmented by outlines, users can rotate the warps to tweak the patterns as needed. Finally, the frame and warps are merged into a single geometry, so it can be exported as the STL file.

5.1.3 Creating Weavable Surface from 3D Object for Assembly. This technique utilizes 3D objects on Rhinoceros as a global geometry. Users select surfaces from the geometry on UI where they want to weave using soft materials, to convert the surfaces to frames constructing the global geometry of the loom. If multiple surfaces are selected, they are converted into frames and the joints are created in between every frame to assist assembly. The process helps print a large geometry such as furniture frame using relatively small home 3D printers, as well as reduce print overhang by enabling 3D printing in parts for assembly. A selected surface is hollowed and the notches to fix warps and joint are created on the edge of the surface. Thus, this script needs to know parameters of intervals and thickness of these notches according to the yarn properties and the number of finger joints in addition to the basic parameters on a yarn and frame. This script can handle three types of inputs: planar surface, curved surface, and closed surface (e.g., a cylinder). In the case of the planar surface, the surface is simply converted into the frame structure and a joint structure is added to its edge if there is an adjacent surface. Also, if a surface has a hole, (e.g., hole to insert light bulbs in the lamp shade design) beams are extended and connected to the frame (Figure 13c). Organic curved surface can be also converted into frame structure directly, because there are no vertical frames as in square surfaces, it is necessary to add warps that are parallel to those curves to construct its surface (Figure 13d). In addition to the warp, a closed surface requires additional columns (currently, the position of column is determined by the length of the circumference).

To generate these frame structures, the script first extrudes the input surface in the direction of its normal and expands its area. If the surface is connected with an adjacent surface, the periphery of each surface comes into contact. By calculating this intersection, the script creates a geometry to be used to generate joints in between. Next, by placing rectangular shape primitives on the frame at a fixed interval and perform a solid differences between the frame and the rectangular shapes as joints, the script creates the notch where warps will be fixed. Finally, the script exports the frames as the STL. It is also possible to send the generated geometry to the Rhinoceros, to further customize the shape of the 3D object or other parts if necessary.

5.2 Validation with Application Examples

To validate EscapeLoom in creating new applications, we created basket and twill woven textiles that were showcased in Figure 5 using the library pattern we provide in the script as default, a woven face mask designed from 2D drawings and printed in TPU (Figure 14a, b), and a scaled version of a chair with soft seat and back (Figure 14c–e). Weaving using the PVA guide, users now can easily synchronize weaving patterns of sophisticated design (O1), they do not need to employ strategies to put their full cognitive abilities in matching design and outcome. The tool affords creative improvisations for users to weave with in-situ material choices of their own (O2), enabling to create a ready-to-wear mask with crochet yarns and match the fabric well with the lace design. Finally, being able to afford unique interactions with every single weaving process (O3), users can create various applications such as furniture. Another property we experimented with is the delicacy of

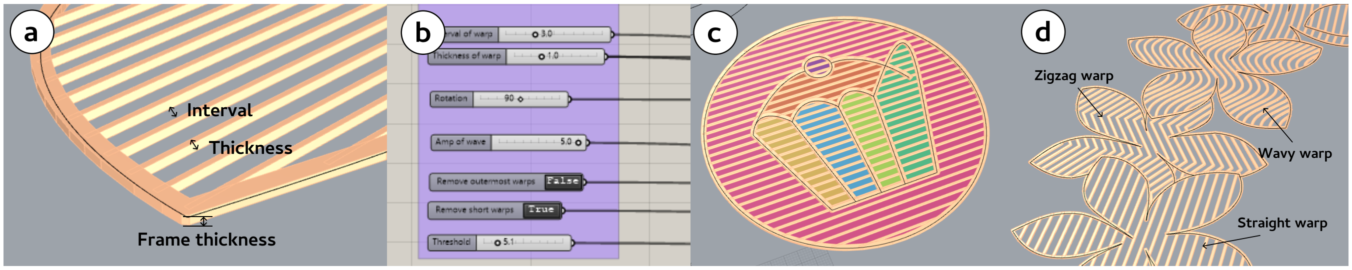

Figure 12: Tool for generating TPU warps from 2D vector data. Various input parameters are set to generate the warp (a-b). The script splits the input 2D vector data to regions (c) and can apply various patterns to each region (d).

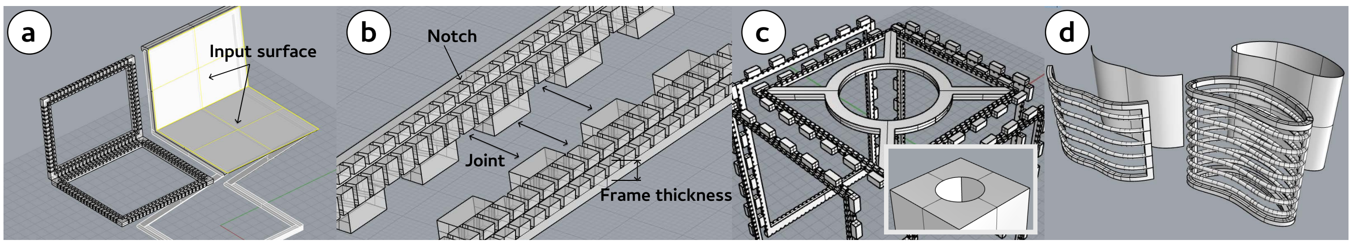

Figure 13: Tool for generating the frames for a global geometry. The frames with the notch and joint are generated from input surfaces (a–b). The script creates a frame from a planar surface as well as a surface with a hole (c) and curved surface (d).

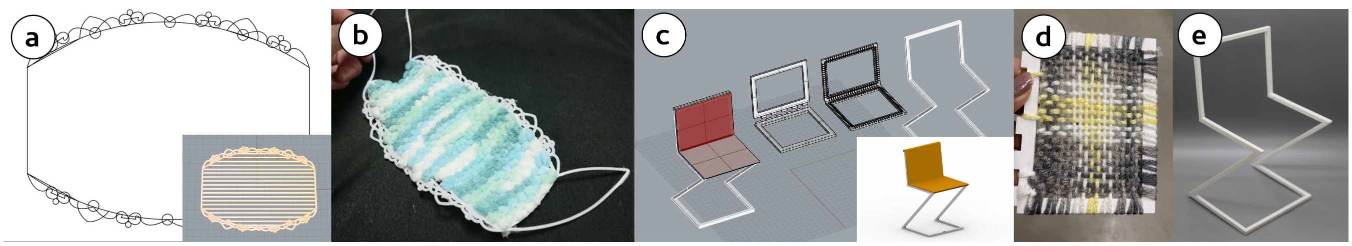

Figure 14: Users can draw shapes of the artifact (a) to generate warps and global shape to print in TPU (inset) and weave a face mask decorated with laces (b). Users can segment an input 3D model (c) to weavable surfaces (inset: by Hamza Genis retrieved from GrabCAD on 9/13/2020) (d) and other rigid parts (e) to print and assemble, to create a chair shown in Figure 1(d).

TPU printed shapes when printed very thin, similar to lace. While printing the mask, we found that it was hard to distinguish between the lace-like parts, and the outlines and warps due to the uniform extrusion of the filament. The tool could help users separately design the extrusion of these shapes by drawing shapes in black and laces in red, so that they can be interpreted differently in the script, similar to the hope one participant had in our formative study about lace structures. Through linear extrusion in different thicknesses, we can print thin lace as well as sturdy loom warps to hold yarns tight. In addition to the lamp shade where we demonstrated the tool's function in creating rigid geometry from 3D object (Figure 9), we further demonstrate the potential in importing 3D object from shared 3D models. Novice users often find sophisticated 3D object designs from existing repositories, taking the benefit of recent proliferation of free 3D models online, such as Thingiverse and GrabCAD. We imported a 3D model of a chair from GrabCAD[9] created by Hamza Genis, converted the model into frames with notches to be 3D printed, wove and assembled it to form a chair.

5.3 Limitations in Design Tool

Firstly, the size of the 3D model/2D vector drawing would not perfectly match the real scale from user input. For example, users can import miniature furniture, not knowing how it will scale before they create notches to tug yarns for warping. If the user simply scales the model in a slicer, it would not match the intended yarn thickness at the time of design. Also currently, default parameters in the tool are set to empirical values that match well with the commercial acrylic/cotton yarns in the market. Although users can customize them by changing input parameters, the tool does not guarantee that user inputs will match with yarn intervals. For example, larger gaps may be left when woven using very thin yarns, or warps may become too tight when woven using chunky yarns. More data in-the-wild will help us to create parameter profiles for each material for weaving (e.g. jute yarn, bamboo strips), to accompany other types of material yarns that may help users in making design decisions. Lastly, the tool follows a script-based approach using Rhino-Grasshopper. Although we can provide a

GUI using the HumanUI library, the script-based software may be difficult to utilize for novice users. The immediate future work in tool support is to integrate the three techniques together and create a beginner-friendly UI for using the tool. Combination of techniques would be a useful feature for users that want further customization, for example, including specific shapes into a 3D printed frame for a lampshade will create various shadow effects.

6 DISCUSSION & FUTURE WORK

Material Inclusivity Materials play a critical role in the process of weaving both for 3D printed parts as well as the hand-woven parts. As makers explore more materials that can be used for weaving, the techniques proposed in this work tend to be more inclusive of those materials, not limiting the design space and transferring control and the ability to choose to the users. In the current tool, the type of material to be used for weaving also determines the user inputs for the computational tool. The controlling parameters provided to the users include changing the density and size of the printed warps, modifying the size of holes on a PVA plate based on yarn thickness, and distributing notches on a 3D printed rigid frame. Even though our experiments have been conducted using fiber-based yarns such as cotton, wool, jute, and acrylic yarns of various thicknesses, using other types of material would require modification of the same design parameters. Flexibility of different natural materials used for weaving differs [13] and could affect the hole intervals in PVA plate guides or the intended flexibility of the TPU warps to allow easy weaving. Using material such as "plarn", i.e., yarn made from plastic bags, can make the design process interesting as the material stretches quite a bit, changing its thickness in the process. This can allow users to model the size of the holes on the looms or the distance between warps in a particular pattern and then stretch the plarn in places to achieve that pattern.

Support for In-situ Creative Exploration and Improvisation Our techniques also allow improvisational modifications and creative exploration. The design parameters can allow users to modify areas of the pattern to vary between dense and sparse weaves. Even though the distance between holes on PVA plates can determine such areas allowing users to intentionally design a combined pattern, users can also skip holes to achieve the same result. Since the material can be easily cut, PVA looms can allow improvisation such as changing hole sizes using hand tools, or making in-situ holes. Users could also combine multiple PVA plates in a pattern and weave the pattern all together. Even with the TPU warps, the user can decide the angle of wefts with respect to the warps in-situ. The choice of yarn can provide impetus to creative exploration as well. As seen in Figure 14b and d, the yarn used changed its color at short intervals similar to self striping yarns used for crochet and knitting [28], resulting in different colored and checkered patterns on the woven parts. Users can thus explore the creative implications of using different types of yarns with the same looms, making modifications to realize different patterns. The ability to enable improvisations and modifications creates an environment for makers to experiment with their ideas and designs, enabling easy prototyping and validation of ideas, as well as artistic exploration in the combination of techniques or possibly using the techniques in ways we haven’t yet thought of.

Augmented Weaving for Handicraft Communities and Makers As 3D printers are becoming cheaper by the day, the future where they become commonplace in homes and local communities has already arrived [1]. With the combination of a hand-craft such as weaving and commonplace desktop fabrication machines and tools (e.g., 3D printer and laser cutter), an opportunity for makers to expand their fabrication activities to establish a home-business has flourished, which may grant more space for women who previously had more constraints that affect their pay due to higher needs in work-flexibility (e.g., [7]). Furthermore, with the rampant pandemic and the people sheltered in place, the proposed techniques can be employed for an online webstore based business opportunity as it is already popular for DIYers to sell their products through Etsy for example, bringing in some form of remuneration for makers. Our tool enables the creation of real artifacts through weaving instead of just textiles, such as custom shaped woven jewellery, modular woven furniture using the 3D global geometry technique, handbags and whatever more the makers can think of weaving. Through EscapeLoom, communities traditionally involved in handicrafts can use their skills in weaving and expand their portfolio of products.

Computational Toolkits for Tangible Learning There are various benefits to teaching weaving to children including developing hand-eye co-ordination, problem solving skills, and an understanding of patterns and sequences [19]. The local weaving expert we interviewed explained that the simple motion of “over and under” required for hand weaving can be a great way to improve fine motor skills for children as well as adults with special-needs, giving us a direction for future user studies with the aforementioned user groups. Offering tangible experiences to play with the material [22] for making their own woven objects with their own patterns can spark creativity and learning among kids and adults alike. Once equipped with the simple plain weave, thinking of advanced warp and weft patterns can introduce computational thinking in designing patterns, and what physical activities can be interpreted into numeric forms so as to be presented as design parameters.

Integrating Sustainable Craft Materials Another potential area of learning is about sustainability concerns. We interviewed an expert from a local textile gallery and club to solicit feedback on our prototype and EscapeLoom techniques. Being excited about the potential to integrate our new proposal of techniques to her existing weaving workshops, she proposed ideas of integrating existing materials and introduced them as new design parameters. She showed some examples of creating yarn out of discarded plastic bags and integrating it into weaving. She enjoyed the random colors, texture, and the appearing patterns, showing us excitement over fully-controlled texture achievable through existing draft. She also showed us how discarded objects such as old drum rings can be used as loom frames displaying different woven pieces. This discussion gave us another direction for future work and workshops where reusable discarded material such as old furniture frames, discarded PVC pipes, cross sections of plastic bottles and more can be inculcated into our techniques. This opens up an avenue of future work of developing computational toolkits for tangible learning through the choice of input materials.

7 CONCLUSION

In this work, we proposed three novel techniques : (1) water-soluble draft to synchronize design intention and practice, (2) flexible warps to guide patterns and to shape resulting object, and (3) rigid global geometry for woven artifacts in 3D, to use 3D printing to aid hand-weaving, obtained through the insights gathered from a formative study to understand critical needs to educate novices with new design and weaving workflows. We also provide a computational tool that can help users explore the newly expanded design space of hand-weaving through pattern generation, shape integration and 3D artifact creation, while maintaining the beauty of the handcraft. Through the use of 3D printing and various materials that are available for low-cost 3D printing, we believe EscapeLoom has the potential to facilitate the learning of hand-weaving.

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