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Upcycling discarded HDPE plastic bags for creative exploration in product design

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Upcycling discarded HDPE plastic bags for creative exploration in product design

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Abstract: Upcycling enables new product production out of clean materials through creative reuse of discarded materials. This paper presents a new structured process to support designers to use discarded HDPE plastic bags as useful and meaningful materials for creative exploration. The proposed process involves a four-step fabrication workflow using tools and machines widely available in design studios: (1) preparing a stack of plastic sheets, (2) fusing the stack of materials to create a new plastic sheet with intended thickness, (3) cutting and scoring the fused sheet to create parts, and (4) assembling the parts to build 3D artifacts. To assist the fabrication, we also present a custom design software as an add-on to an existing CAD environment and describe how we developed the fabrication-aware design features through a workshop with seven students. We demonstrate the feasibility and creative potential of the design and fabrication process by four application examples and expert reviews with three product designers.

Keywords: upcycling plastic bags; product design; creative reuse.

1. Introduction

Statistics show that on an average a plastic bag is used only for twelve minutes (Plastic Bags, n.d.). Despite the increasing attention and efforts to reduce the use of plastics, massive quantities are discarded which will not abate in near future (Howard, 2019; Regulatory landscape, 2018). In response to the urgency of environmental issues, design researchers have presented strategies to reuse, repair and recontextualize existing artifacts, proposing the value as a critical design practice (Buechley et al., 2009; Kim & Paulos, 2011; Houston et al., 2016; Blevis, 2007; Hanks et al., 2008).

The flexibility, weatherproof nature, ease of processing at low temperatures, and thermoplastic properties of the common HDPE (High-Density Polyethylene) grocery bag make it an attractive resource for product designers. While there are various 'making' techniques of upcycling plastic bags such as by weaving (Woven Plastic Bag, 2017),

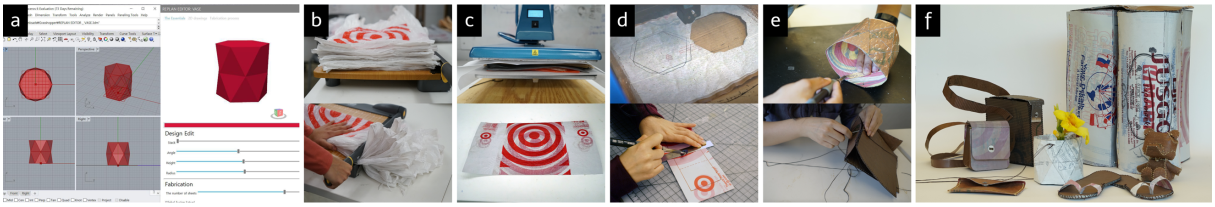

Figure 1. Upcycling HDPE plastic bags: (a) computational design, (b-e) proposed fabrication process using commonly-available machines and tools, and (f) application examples

knitting (Knit Plastic Bag, 2017), and crocheting (Nataliezdrieu, 2011), we are attracted to the transformative property of fusion-based fabrication -- a process in which different pieces of thermoplastic are attached through heat and pressure to transform thin and fragile plastic bags into a new rigid plastic sheet (Smith, 2016; Colombo, 2013). However, while some DIY tutorials have demonstrated plastic bag fusion using a clothing iron or an oven to bond multiple sheets of plastic bags, it is limited in terms of the quality, consistency and replicability, and most importantly, the overall structural process -- how fused plastic sheets can be designed with more intention and predictability and applied to produce feasible design products.

In this paper, we aim to expand the creative potential of upcycling abandoned plastic bags using the fusion-based fabrication technique. We introduce a full cycle of design and fabrication process using commonly-available tools in product design studios and demonstrate a series of application examples. Our fabrication techniques consist of four steps: (1) preparing a stack of plastic sheets out of discarded plastic bags, (2) fusing the stack to generate a new plastic sheet with intended thickness, (3) cutting or scoring the sheet to prepare parts, and (4) assembling the parts to make new 3D artifacts as desired. While numerous CAD programs today can be utilized to convert 3D objects to 2D fused plastic sheets, we also present a custom design editor as an add-on for Rhino Grasshopper to reduce tedious processes such as calculating machine settings depending on the number of fused plastic bags or making holes for sewing during assembly.

Our investigations into upcycling plastic bags unfolded across five phases: (1) an initial exploration of heat fusing discarded plastic bags through design heuristics to identify a problem space; (2) a systematic inquiry into the different fabrication parameters, leading to the formulation of the design and fabrication process; (3) a hands-on workshop with seven design students; (4) prototyping artifacts to demonstrate product design applications; and (5) expert reviews to evaluate the process involving tools and techniques.

2. Background

2.1 Upcycling plastics for sustainable design

Our approach of reusing and repurposing discarded materials is aligned with ongoing discussions about upcycling across the domains of Industrial Design, Manufacturing and Environmental Science. Upcycling is a way that reduces the amount of solid waste (Bramston

& Maycroft, 2014) and the need for a new product by (re-)creating a new artifact out of waste materials (Szaky, 2014; Richardson, 2011; Sung & Sung, 2015). It is often considered as an energy and cost-effective strategy compared to recycling which typically involves a higher expense for breaking down the original material and processing it into something else (Goldsmith, 2009). Reuse of materials and parts of a product is one of the critical strategies for sustainable design (Ljungberg, 2007).

Reusing discarded materials, specifically plastics, retains the benefits of upcycling and reclaims them from waste. This vision has led creatives, including Dave Hakkens, the founder of *Precious Plastic* (Precious Plastic Universe, n.d.), to share tools and techniques to direct more people towards reusing waste plastics. *Precious Plastic* is now a global community where over 80,000 people find collaborators to build open-source tools for plastic recycling and share instructions for innovative applications. Other individual projects in the maker community also demonstrate how discarded plastics can be used to create various household items, such as a woven handbag from plastic bags (Woven Plastic Bag, 2017), a desk organizer from plastic bottles (Nataliezdrieu, 2010), or a beaded curtain from plastic straws (DIY Beaded Curtain, 2020). Likewise, artists have used plastic debris such as bags or bottles as materials for sculpture or jewelry (Diana Cohen, n.d.; Calder Kamin, n.d.; Sarah Turner, n.d.). Their work *intercepts the plastic waste stream* and reframes waste plastic as an expressive medium with aesthetic potential (Project Vortex, n.d.). From these examples, we note that upcycling can be a creative practice for individuals to produce useful, evocative, and highly personalized artifacts (Stuedahl & Gauntlett, 2012; Szaky, 2014; Sung et al., 2014; Bramston & Maycroft, 2014). Yet, if the quality of the outcomes is unsatisfying, one's willingness for upcycling can be discouraged (Szaky, 2014). Our work presents a means to improve the quality of upcycled plastic bag artifacts through the uses of computational design tools and digital fabrication.

2.2 Sheet-based design and fabrication

Cutting, folding, and assembling sheet materials with a laser or vinyl cutter can be rapid ways of building three dimensional physical forms in contrast to 3D printing. In addition, sheet materials offer designers the opportunity to compose multi-material objects with different physical and computational properties. In the field of Human-Computer Interaction, researchers have demonstrated leveraging laser cutters to expedite or augment the 3D forms within sheet materials' capability such as stacking, cutting, and welding acrylic sheets into functional objects with moving parts (Umapathi et al., 2015) or selectively bending regions of a flat acrylic shape with a defocused laser (Mueller et al., 2013; C & Wigdor, 2016). Our proposed fabrication techniques enable users to create their own plastic sheets with intended thickness and flexibility from HDPE plastic bags and direct this reclaimed material to create 3D artifacts as desired by modifying the physical properties of this material with digital fabrication tools such as the laser cutter.

There is also a variety of software that supports prototyping 3D objects from sheet materials (Pepakura Designer, n.d.; Slicer for Fusion 360, n.d.). For example, FlatFab (McCrae et al., 2014) enables designers to construct 3D models by interlocking planar pieces. Platener (Beyer et al., 2015) supports rapid prototyping by deconstructing a 3D model into a series of lower resolution regions constructed from laser cut sheets and higher resolution regions constructed from 3D printed parts. In addition, platforms like Joinery (Zheng et al., 2017) supports parametric joint generation for laser cut assemblies with different types of materials. We are inspired by these software tools that facilitate fabrication awareness while constructing 3D assemblies from sheet materials.

3. Upcycling HDPE Plastic Bags

In our early stage of the exploration, we learned that the most common plastic shopping bags used in our daily lives, for instance, from a grocery store, are made of High Density Polyethylene (HDPE) (Naik, 2018). To ensure uniformity of the study we only used the HDPE bags for our experiments by confirming the resin identification code (Plastic Packaging Resin, n.d.) printed on the plastic bags we used, the number 2 being the code for HDPE. We began by following along existing DIY tutorials (Smith, 2016; Colombo, 2013) to familiarize ourselves with the techniques and challenges of heat fusing discarded plastic bags into HDPE sheets. Through this exploration, we identified two opportunities to address the missing pieces from the current DIY tutorials of fusion-based upcycling plastic bags: (1) a lack of systematized processes for fusing HDPE plastic bags into sheets, as well as (2) a lack of information on tools, techniques, and the overall process for shaping the resultant plastic sheets into meaningful products.

The workflow of our fabrication techniques is based on four steps, shown in Figure 2. We prepare a stack of plastic bags, fuse the stack by applying heat and pressure, cut and score the fused sheet to develop intended parts and folding nets (an arrangement of polygons in plane which can be folded), and assemble them to create 3D artifacts.

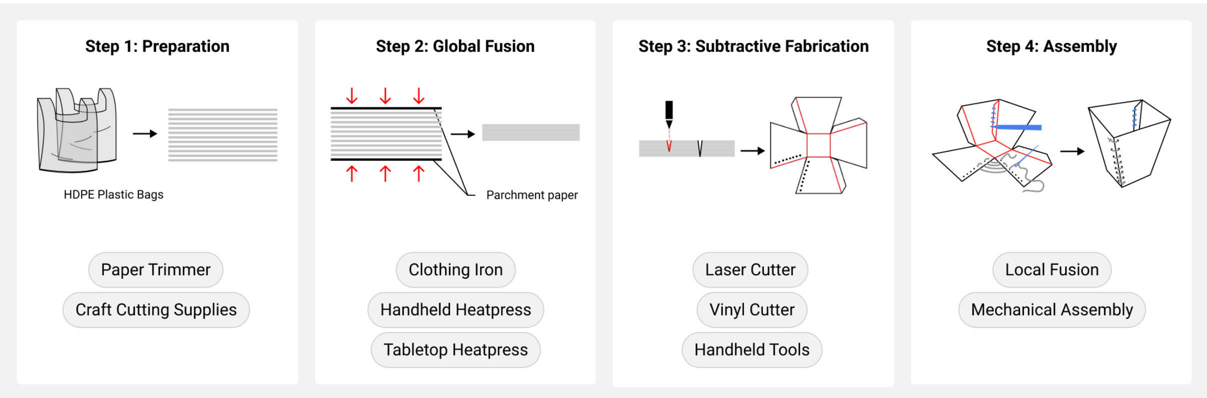

Figure 2. Fabrication workflow and tools used.

3.1 Preparation

The preparation step consists of planning the number of plastic bag layers to be fused, and subsequently cutting and stacking the plastic bag layers based on the design. We make a decision on the number of plastic bag layers based on the required thickness of the fused sheets and convert them to flat layers by cutting and flattening. We cut off the handles and the fused portion of the bottom of a plastic bag using a scissor or a paper trimmer. We then flatten and count the number of layers to form the desired stack of plastic layers.

3.2 Global Fusion

Global fusion indicates fusing the entire area of plastic bags with heat to develop a new plastic sheet with the intended thickness and rigidity. For this process, three machines can be used: a clothing iron, a handheld heatpress and a tabletop heatpress (Figure 3). We set two success criteria for fusing a stack of plastic bag layers to ensure the quality and consistency of the outcome. First, all layers should be fully fused together. When a sheet is cut through, individual layers shouldn't be visible, and it should not be possible to peel or separate layers from each other (Figure 4 a-b). Second, there should be no visible melting marks on either side of the new sheet (Figure 4 c-d). Melting temperature range for HDPE is known to be 210 – 270^{o}C, but from 120^{o}C it exhibits plastic deformation (Material Melt, n.d.), thus, we set the starting temperature for our experiment as 120^{o}C. While applying global fusion to the stack of cut plastic bags, we sandwiched the stack between two sheets of parchment paper to avoid the heat plates of the machines from getting damaged.

Clothing iron

A clothing iron is the most commonly accessible tool for global fusion. For our testing, we used the Black+Decker "The Classic" clothing iron. The clothing iron was moved around the stacked layers of plastic to cover the entire area by hand with the iron set to approximately 123^{o}C. We found that the clothing iron is effective in fusing a small number of plastic bag sheets (<60 sheets). However, this highly manual process means that the temperature and the pressure is not uniform over the layers of plastic. The only two conditions that can be controlled with the clothing iron are the number of layers of plastic bags and the setting on the iron. Due to the lack of uniform controlled temperature as well as pressure, finding time zones in which satisfactory fusion can be achieved is difficult.

Figure 3. Different tools for global fusion: (a) a clothing iron: Black + Decker "The Classic" model, (b) a handheld heatpress: Cricut EasyPress, and (c) a tabletop heatpress: HIX Swingman 20.

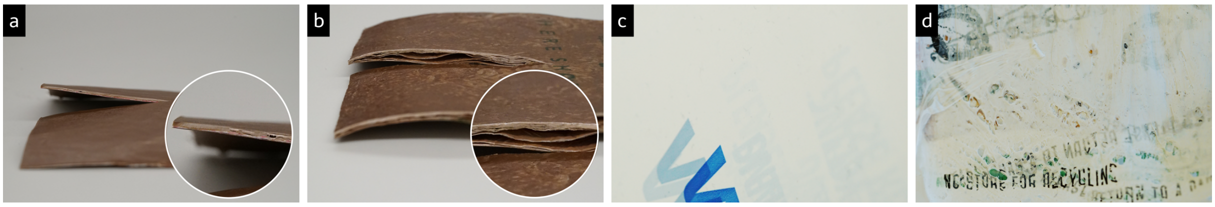

Figure 4. Global fusion outcomes: (a) a successfully-fused; (b) a failure case with separation of constituent layers; (c) smooth texture on the surface of a successfully fused sheet; and (d) a failure case due to melting and burn marks resulting in rough and uneven surface texture.

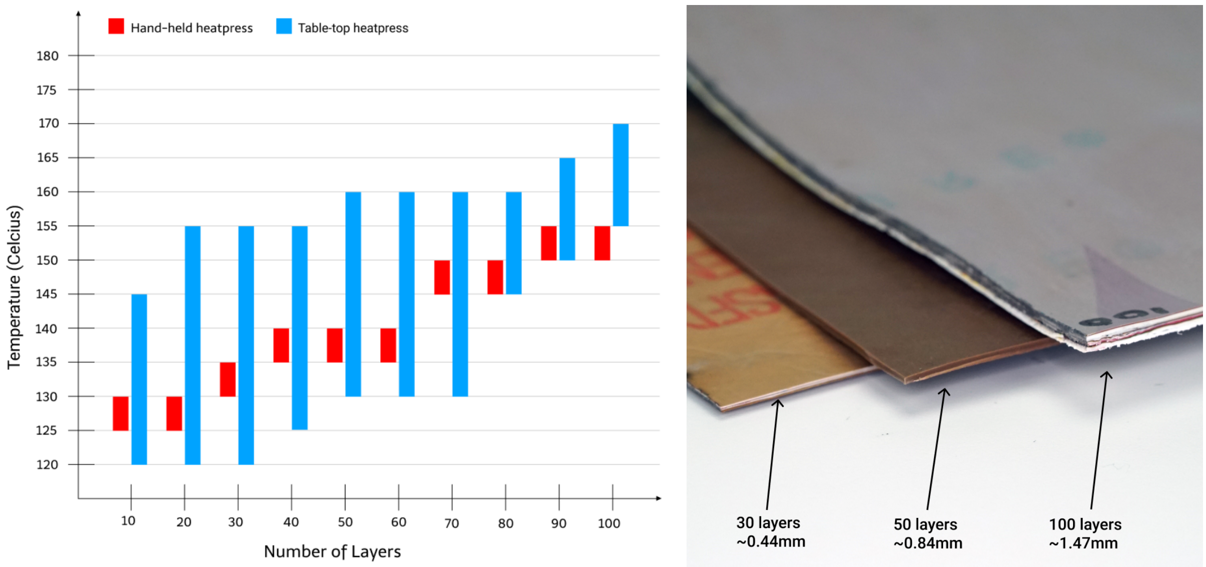

Figure 5. (Left) Successful global fusion temperature range versus the number of layers of HDPE plastic sheets ranging from 10 to 100, and temperatures ranging from 120 to 170°C. The applied time was 20 minutes (10 minutes on each side) for the handheld heatpress, and 1 minute on one side for the tabletop heatpress. (Right) Varied thicknesses of fused sheets based on the number of layers. 30 layers have more of a fabric feel, 50 layers have a leather-like feel, and 100 layers have a wood-like rigid thickness.

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Handheld heatpress

The model of the handheld heatpress we used was Cricut Easypress 2 (12" x 10"), which is also a low-cost, commonly used machine by hobbyist makers to apply heat transfer prints on T-shirts. We found that the handheld heatpress is effective in fusing between 10 and 100 plastic bag layers. The heatpress was placed on top of the samples using only its own weight (8.6lbs/3.9kg) as the applied pressure. Heat was applied to the stack of plastic bag sheets for 10 minutes; the entire stack was then flipped and heat was then applied for an additional 10 minutes. For 10 sheets, heat was only applied for 5 minutes on each side. Because the heatpress provides a relatively wide heat plate to be fused with uniform heat compared to a clothing iron, this machine reduces wrinkles in the produced sheet of plastic. Figure 5 shows our testing data from 10 sheets to 100 sheets.

Tabletop heatpress

We used HIX Swingman 20 (16" x 20"), a professional tabletop heatpress used for sublimation and textile heat transfer production. We found that the tabletop heatpress is effective in fusing between 10 and 100 sheets. Samples were placed in the tabletop heatpress and up to 1200lb of pressure was applied by the press. Heat was applied to the stack of plastic bag sheets for 1 minute. Due to its ability to provide strong pressure control, the need to flip the sheet was removed. The tabletop heatpress's ability to control pressure, temperature, and time greatly reduces human error in the global fusion process. Overall, using a tabletop heatpress enabled a broader range of available temperatures that successfully fused sheets compared to using a handheld heatpress based on a higher pressure application in a shorter length of time. Figure 5 shows the temperature sets we tested with 10 sheets to 100 sheets.

3.3 Subtractive Fabrication

Once the fused plastic sheets are created, we move on to the subtractive fabrication process, in which we apply cutting and scoring to produce intended folding nets and parts. For our testing, we used a laser cutter (Universal Laser Systems PLS6.150D), a vinyl cutter (Cricut Maker), handheld heat knives and craft supplies for cutting and scoring the sheets.

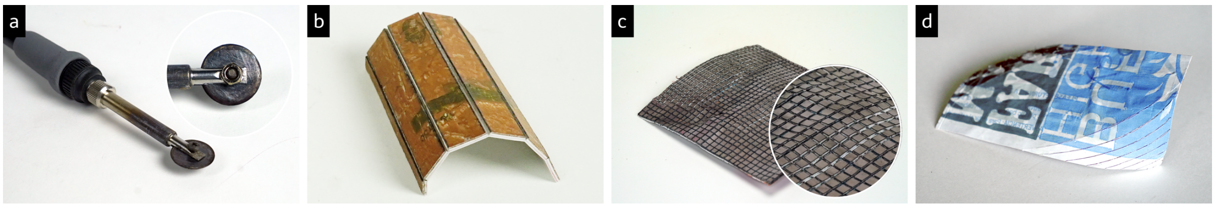

Figure 6 (a) The custom rolling heat knife consists of a modified (cut through the middle) soldering tip that houses a circular blade held in place with a nut and bolt. Different ways of scoring *pattern examples: (b) vertical scores for bending and (c) grid pattern for flexibility using a laser cutter; (d) curved scores for bending using a vinyl cutter.*

Laser Cutter and Vinyl Cutter

The laser cutter settings required for through cuts and score cuts are mapped to the number of the sheets through our experiments. For the ULS PLS6.150D, with the power set at 30% and speed set at 15%, we received the most consistent results with through-cuts by varying the number of passes. We can also use a vinyl cutter or any similar CNC routed blade depending on the thickness of material supported by the machine, for the same process. Applying scoring patterns (see Figure 6 b--d) enables interesting qualitative properties to the sheets of fused plastic such as unique textures and aesthetically pleasing effects.

Handheld tools

Handheld tools enable rapid, exploratory, and improvisational fabrication processes. Scissors, box cutters and Xacto knives work to some extent, but as the sheets get thicker, a heat-knife can cut through faster. We also created a rolling extension for a soldering iron that works like the heat knife (Figure 6 a) for easier manual cutting.

3.4 Assembly

Once the layers of plastic bags are globally fused, and cut and/or scored, we use the resultant sheets to make 3D objects.

Local fusion techniques

We refer to applying heat only to a specific area as local fusion. This process fuses the joint between two sheets of fused plastic through heat. For this final step, a soldering iron or a flat-iron (hair straightener) can be used (Figure 7 a-c). Empirically, the soldering iron temperatures up to 180^{o}C work well for local fusion. Figure 7 a--b shows the process of using a soldering iron for local fusion. For the flat iron, 130^{o}C works well but requires holding the joint within the flat-iron for a longer duration (Figure 7 c). For both the soldering iron and the flat-iron, we used aluminum foil between the irons and the plastic to shield the irons from molten plastic sticking to them.

Figure 7 (a-b) Local fusion using a soldering iron, (c) using a flat-iron, and (d) mechanical assembly using magnetic snaps.

Mechanical assembly techniques

For heatless assembly, we apply sewing or use fabric fasteners such as snap buttons or Velcro tapes (Figure 7 d). This also indicates that the fused sheet of plastic bags can be treated as a sheet of fabric and a variety of sewing tools and accessories can be utilized.

4. Design workshop

To gauge the usability of the proposed fabrication process, we recruited seven design students (all ages 20s, 4 females and 3 males). We ensured that they had basic knowledge and experience in making physical artifacts using digital fabrication machines because we set our first user test audience as experienced designers, those who would be aware of reasons for design decisions and limitations of the design task (Ahmed et al., 2003).

The workshop was held for 7.5 hours in a design studio equipped with the tools and machines required. We organized 1 hour for introduction of the project and demonstration of the fabrication techniques, 5 hours for design and building, and 1.5 hours for sharing the final creations and discussion. During prototyping, we documented participants' processes, asked questions on rationales behind their design decisions and challenges they were confronting. Participants worked alone or in pairs and fabricated any objects they wanted. Entire process of the participants was observed and audio-visually documented by three facilitators. At the end of the fabrication process, we facilitated a group discussion where participants shared their projects and reflected their exploration. Figure 8a shows the final artifacts.

Participants were satisfied about the quality and variety of the outcomes they produced. At the same time, based on the collected data from observation notes and group discussion, we identified four major issues: unfolding a 3D object to develop 2D parts, finding design templates, making holes for sewing, and spending time searching machine setup guide for global fusion and subtractive fabrication settings.

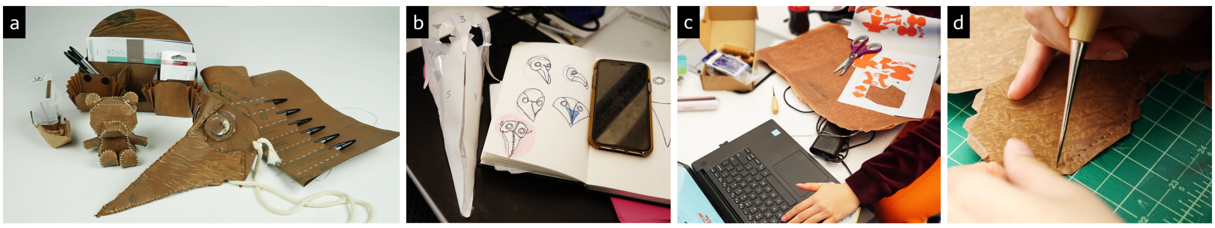

Figure 8. (a) Final creations from the workshop. Identified challenges: (b) paper prototyping, (c) online search for templates and customizing them, (d) the manual labor to pierce holes for sewing.

Visualizing 2D folding nets and parts for 3D artifacts

Participants spent quite an amount of time and effort in visualizing 2D folding nets and parts, for instance, through paper prototyping (Figure 8 b). This indicated a need to assist the design process, specifically designing 2D assembly parts with a 3D rendering view for the sheet-based fabrication.

Searching for templates of foldable 3D shapes and customizing

Two participants began with searching and downloading templates, printing, cutting, and customizing the design (Figure 8 c). This inspired us to add a library within the editor to enable users, in particular beginner designers, to get inspiration from various models, select one and customize parameters to design one's own model.

Punching holes in the sheets for sewing

Three out of the five objects applied sewing as a primary assembly method. Participants expressed that the motivation of sewing came from the flexible and leather/fabric-like soft texture produced by fusing a certain number of plastic bags (between 10-30 layers). Despite the softness of the fused sheets, however, they found the sheets were too rigid for manually punching the holes needed for sewing, even while using a large leather-stitching needle (Figure 8 d).

Searching for machine set-up guide for global fusion and subtractive fabrication settings

Participants used a printed booklet we prepared prior to the workshop to find recommended machine settings for heatpress machines and a laser cutter. Checking out the machine setup guidance repeatedly was cumbersome.

5. Fabrication-Aware Design

To design assembly parts for an intended model, any kind of CAD software that supports 2D vector drawings could be used to operate subtractive fabrication machines. However, visualizing 2D sheets to create 3D artifacts can be challenging, and it is cumbersome to figure out datasets to operate fabrication machines for each step manually, for instance, finding the right temperature of a handheld heatpress or the speed and power configuration of a laser cutter for the case of using 70 layers of plastic bags. Thus, to assist the design process, leverage the proposed fabrication techniques, and address the fabrication challenges identified through the workshop, we developed a design editor within Rhino Grasshopper, a design software widely used by product designers. It facilitates real-time updates to both the 3D product design and the 2D fabrication pattern. In addition, we use Human UI and Kangaroo plug-ins to create a graphical user interface and perform material simulation, respectively.

The editor starts from 'The essential' page. It provides the base 3D model of artifacts on the top and shows design parameters that users can choose through the sliders. Changes are computed and rendered in real-time. This parametric modeling feature is intended to help beginner designers to start with a customizable design template and develop their model by changing dimensions with the resulting 3D design simulation. For instance, Figure 9 b1--b2 shows the design of a bag with adjusted width, height, length, and depth parameters. On the bottom of the page, users can also set the number of plastic bags to be used, then the system accordingly modifies the fabrication instructions such as temperature and time required for global fusion using heat-press machines and subtractive fabrication using a laser cutter. After deciding the design configuration, users can download the flat fabrication patterns from the '2D drawings' tab where the user can add and adjust scoring patterns or apply sewing holes. For instance, Figure 9 c1--c2 shows exploring horizontal lines of stripe texture applied to the assembly parts of the bag designed above. These instructions are intended to assist users to make fabrication-aware design decisions and leverage the proposed fabrication techniques. The list of currently available models in our editor includes slippers, a flowerpot, a handbag, and a stool, and we expect to add more through a collaboration with the community of designers and makers. These items are selected to present multiple-levels of parametric design outcomes as well as the embedded fabrication-aware features in the editor through aesthetically pleasing and practical objects.

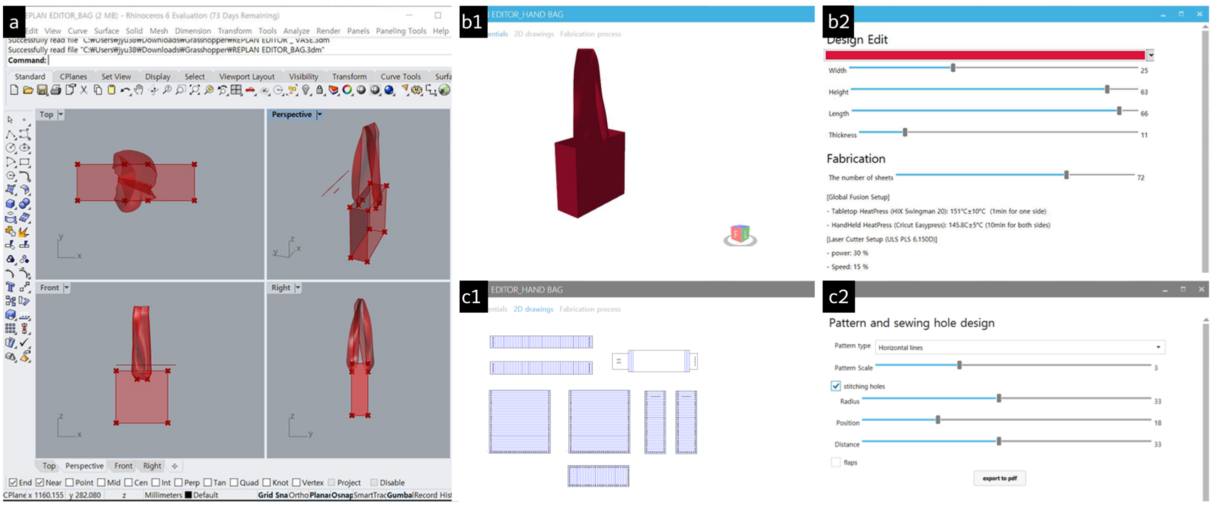

Figure 9. Design editor screenshots: (a) Rhinoceros 3D where the editor is housed as an add-on; Changing parameters in the editor (b1, b2) users can customize the loaded 3D model, and (c1, c2) adjust the 2D parts by adding scoring patterns and punching holes for stitching.

6. Applications

We present four prototypes that demonstrate the creative possibilities enabled by the proposed process including fabrication techniques and the design editor (Figure 10).

Application	Flower Pot	Hand Bag	Slipper	Stool
Number of Layers Fused	40	30, 50, 100	50, 100	200
Subtractive Fabrication Method	Vinyl Cutter, Laser Cutter	Laser Cutter	Laser Cutter	Handheld Tools
Assembly Method	Local Fusion	Mechanical Assembly	Mechanical Assembly, Local Fusion	Local Fusion
Design Editor Feature	Folded Geometric Pattern	Scoring Pattern, Stitching Locations	Scoring Pattern, Stitching Locations	Form Exploration, Grouped Objects

Figure 10. Application overview: we developed four prototypes applying different configurations of our processes.

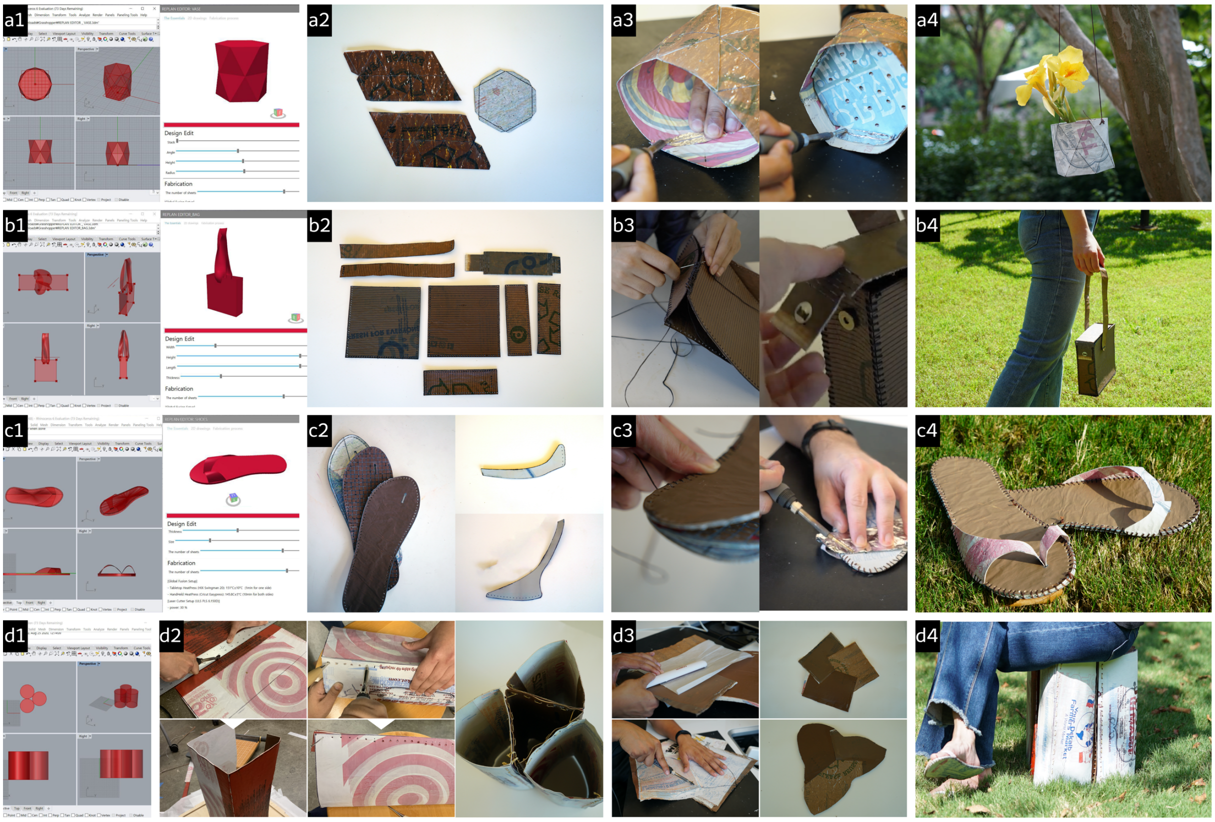

Figure 11. The processes of fabricating a flowerpot(a1--a4), a hand-bag (b1--b4), slippers (c1--c4) and a stool (d1--d4).

The flowerpot (Figure 11 a1--a4) highlights the unique material affordance of HDPE plastic bags. It is light, durable, and waterproof with appropriate drainage and has a hanger for growing. The design editor enables exploring an attractive triangular pattern design and generating the unfolded parts.

The handbag demonstrates the versatile materiality of sheets produced by our fabrication techniques (Figure 11 b1--b4). The design editor is not only used for the parametric design of the handbag, but also for adding holes for stitching and generating scoring locations to make the handbag's cover flexible. To make the top flap rigid for protection yet bendable for opening and closing the bag, scoring lines are applied perpendicular to the direction of motion at locations where flexibility is desired, creating a live hinge. Lighter scoring is also applied to the surface of the bag to create a pleasing and aesthetic visual texture.

The pair of slippers demonstrates the durability and the flexibility from using sheets of various thicknesses and textures for on-body application (Figure 11 c1--c4). The design editor supports adding scoring patterns and holes' locations for stitching as well as adjusting the size of shoes. Sewing is used to mechanically assemble the sole of each slipper and to attach the outer edge of the strap.

This stool demonstrates (1) sheets' rigidity and sturdy structure that highlight the wide range of transformation of HDPE plastic bags and (2) the use of handheld tools that enable exploratory construction by hand (Figure 11 d1--d4). The design editor assists in exploring the form factors by parametric design. The editor can also assist in defining the diameter of each leg to allow the parts to fit in the diameter of the stool. This application shows another combination of computer-aided design for the form investigation and handheld tools for a sense of handcraft and exploratory prototyping. Figure 11 shows the entire process of making these 4 artifacts through the design, fusion, cutting, assembly, and usage phases.

7. Expert reviews

We conducted semi-structured, one-hour long interviews, with three designers, to assess the feasibility of the proposed process and the creative possibilities for product designers. All invited experts (P1-3) have over 10 years of professional experiences as product designers and design educators.

Foremost, all experts felt that the workflow of the proposed processes is clearly understood and applicable for a broad range of product designers including both design students and professional designers. P1 appreciated enabling the process using multiple options of commonly available tools: "*You give some options on tools...the more options that exist, the more possibilities for different people to adapt it. Students will love to explore these sets of tools and materials which will give them the sense of different manufacturing processes."*

The experts discussed the versatile material properties enabled by the proposed upcycling techniques as a key success. P1 and P2, who were able to experience sample sheets in person, expressed excitement about the diversity of the produced materials. P1 was particularly impressed with the transformed textural qualities. Likewise, P3 said that the upcycled plastic sheet "*…could be better than cardboard for a lot of situations…"* since it is more durable and water-resistant. However, he also pointed out the limited size of the sheets and lacking color options as constraints since designers and makers might want to test real-size prototypes and apply various colors for the finish.

Additionally, the experts highly regarded the parametric adjustments and fabrication-supporting features in the design editor for design students. P1 appreciated the fabrication instruction provided in the editor: "*That tie between design domain to manufacturing instructions is really important to make any of those feasible and possible.*" P1, however, pointed out a need to add more information about the predicted sheets in the fabrication instruction. While the editor provides suggested machine settings based on the number of sheets, makers would want to know predicted outcomes to be produced (e.g., between 40 and 60 sheets for a waxed canvas-like texture or beyond 80 sheets for a rigid wall).

Lastly, the experts remarked upon the sustainability narrative impact of the overall process to the product outcomes. P3 mentioned, "*It's about the story that you wanna create along with it… I like the notion that you start out with a raw material that already is saving the planet.*" This narrative implication, however, raised concerns for P2 about brands of the plastic bags used appearing on the products: "*This one (pointing at a flower pot made from Walmart retail corporation plastic bags), I would not put out on my desk because I really don't want a Walmart vase.*" Consequently, she mentioned that more control over the final aesthetics such as coloring application is needed to make things truly sustainable: "*If the goal is to get plastics out of trash cans, these need to be objects people will keep after making.*"

8. Discussion

To begin with, the preparation step in our fabrication process is labor-intensive as straightening out plastic bags, cutting off the ends, and flattening the sheets is vital in standardizing the resultant fused HDPE sheet. Although we became more efficient through practice, it is still the primary bottleneck in the fabrication process. The bag collection process itself was also notable as it reflects our tendency to store things such as plastic bags that are perceived to be reusable. We were able to set up a donation box as well as ask our colleagues to provide used plastic bags to help our project. A more streamlined approach than ad-hoc collection can help in making the fabrication pipeline more efficient.

Next, our design editor is limited in terms of its features and application library. The current features of this editor are based on insights that emerged from our practices and the design workshop. We plan to grow the range of fabrication-aware features as we learn more fabrication techniques from the growing maker community as well as our further practices. For instance, as P1 suggested, designers need more information about the possible outcomes of the sheets to be produced for the fabrication. We plan to make the code available for free using Github under a GNU General Public License and continue adding more features, collaborating with other researchers and makers to grow the software.

Finally, more tools and techniques such as coloring techniques or material library are needed to improve the aesthetic potential of the fabricated products and enable upcycling plastic bags to become a practical method to design for material experiences (Karana et al., 2015). For instance, the outcomes from the workshop with seven design students show that people prefer to use brown plastic bags to produce a leather-like effect (see Figure 8a). All of them made conscious design decisions for the color in fusing the sheets as well as the thickness and texture. Ultimately, the aesthetic controllability plays a key role to encourage more designers to reuse discarded plastic bags and enable them to be able to make, as P3 mentioned, appealing *objects people will keep after making*.

9. Conclusion

Through our work, we foresee abandoned plastic bags can be further promoted as an exciting material resource for various prototyping practices in design studios with more computational systems, machines, and techniques that ensure clean and versatile material production with an advanced level of aesthetic control. This paper presents our progress to propose a full cycle of design and fabrication process for product designers using widely available tools and machines.

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