PopCore: Personal Fabrication of 3D Foamcore Models for Professional High-Quality Applications in Design and Architecture

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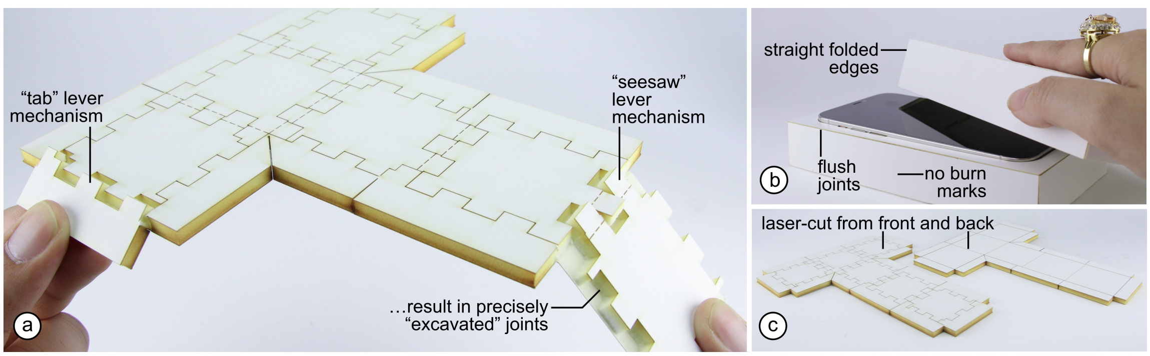

Figure 1: We present *PopCore*, a fabrication technique that laser-cuts *high-quality* 3D models from paper-foam-paper sandwich materials. (a) Its key elements are two laser-cut lever mechanisms that allow users to break off surrounding residue material, thereby "excavating" joints with *very* high precision, giving models (b) a look that is cleaner and more homogeneous than any prior fabrication technique. (c) PopCore achieves this by laser cutting from both the front and the back. PopCore's clean appearance allows personal fabrication to tackle fields that require a *professional* look, in particular industrial design, architecture, and high-end packaging design.

ABSTRACT

PopCore is a fabrication technique that laser-cuts 3D models from paper-foam-paper sandwich materials. Its key elements are two laser-cut lever mechanisms that allow users to break off surrounding residue material, thereby "excavating" joints efficiently and with very high precision, which PopCore produces by laser cutting from the top and bottom. This produces flush joints, folded edges that are perfectly straight, and no burn marks—giving models a homogeneous, clean look. This allows applying personal fabrication to new fields, including industrial design, architecture, and packaging design, that require a visual finish beyond what traditional personal fabrication delivers. We present the algorithms and a software tool that generates PopCore automatically. Our user study participants rated PopCore models significantly more visually appealing (7.9/9) than models created using techniques from the related work (4.7/9 and 2.3/9) and suitable for presentation models (11/12 participants), products (10/12 participants) and high-end packaging (10/12 participants).

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CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); Interactive systems and tools.

KEYWORDS

Personal fabrication, Laser cutting, Rapid prototyping, Manual assembly

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1 INTRODUCTION

While tools automating the personal fabrication of 3D models have been very successful with makers (*CoilCAM* [Bourgault et al., 2023], *Makers' marks* [Savage et al., 2015], *FusePrint* [Zhu et al., 2016]), these tools have not yet found their way into professional design disciplines, such as industrial design, architecture, or packaging design. Thus, even though the use of fabrication machinery in these fields goes back much further than the maker movement, designers in these fields continue to design and engineer their models using traditional fabrication techniques and software tools that provide full control (e.g., AutoCAD [AutoCAD, 2024]) while forgoing the speed and convenience that could be achieved with the recent maker tools.

One of the key reasons for this is that the professional design disciplines *demand* high-quality finish ([Fiorineschi and Rotini, 2019], [Becerra, 2016], [Reimann et al., 2010]), while it is only *desirable* for makers. Thus, while laser cutting software addressing makers tends to create cross joints [McCrae et al., 2014] and box joints [Baudisch et al., 2019]—these, however, produce visual artifacts so prominent that they distract from the actual design intent [McCurdy et al., 2006]. Professional designers and architects instead tend to focus on stacking plates [Knoll and Hechinger, 2007], (manually cut) miter joints [Knoll and Hechinger, 2007], and in some cases butt joints [Lansdown, 2019]. These in turn require substantial manual skill, resulting in untrained users - such as makers - producing results that are much less sturdy—thus affording mostly only decorative objects. As a result, we see two separate fields—makers on one side and professional designers on the other side—each using their own techniques and technologies.

Recent work has made a promising step towards bringing the two together: "HingeCore" [Abdullah et al., 2022] produces box joint constructions, which are reasonably sturdy and afford fast assembly, yet offer a *somewhat* clean look: HingeCore folds paper-foam-paper "foamcore" sandwich material ([Ku and Demaine, 2016], [Muntoni et al., 2019]) into 3D structures, but hides the box joints behind one of the paper layers [Abdullah et al., 2022] (see also "related work" and Figure 2).

Unfortunately, HingeCore introduces its own set of artifacts in the form of gaping and uneven edges (Figure 3). In our user study, participants found the resulting quality suitable for *internal* prototyping, but not for creating customer-facing use cases, such as presentation models and products for industrial design, architecture, and packaging (see "user study").

In this paper, we address these issues with a new take on laser-cut foamcore. We introduce *PopCore*. As illustrated by Figure 1, PopCore is a fabrication technique that produces 3D models with an artifact-free look. (a) PopCore's key design elements are two laser-cut lever mechanisms that allow users to break off surrounding residue material, thereby "excavating" joints efficiently and with very high precision. (b) This results in flush joints, folded edges that are perfectly straight, while avoiding burn marks, resulting in 3D models with a homogeneous, clean look. The resulting high-quality look allows PopCore to address fields that require high-end visual finish, including industrial design, architecture, and, as illustrated here, packaging design. (c) We present an algorithm and a software tool that generate PopCore automatically by laser cutting not only from the top, but also from the bottom.

2 CONTRIBUTIONS AND LIMITATIONS

Our main contribution is a personal fabrication technique that produces the look required by professional design disciplines, including industrial design, architecture, and packaging design. PopCore's key design elements are two laser-cut lever mechanisms that allow "excavating" joints efficiently and with very high precision. We present a software tool that converts 3D models to PopCore automatically, either as a stand-alone tool or integrated into a laser cutting framework (kyub [Baudisch et al., 2019]).

The main benefit of PopCore is that it allows producing 3D models that are free of artifacts, thus enables use in fields that require high-end visual finish, including industrial design, architecture, and packaging design. We present a series of samples, including examples fulfilling the key seven qualities of packaging, e.g., physical protection, marketing, security, etc. We support these claims with a user study in which participants rated models created using PopCore significantly more visually appealing (7.9/9) than models created using the prior art (HingeCore [Abdullah et al., 2022]) (4.7/9 and 2.3/9). As a consequence of higher visual quality, participants rated PopCore as being suitable for presentation models (11/12 participants), products (10/12 participants) and high-end packaging (10/12 participants)—use cases not achieved by previous personal fabrication techniques.

PopCore is subject to three main limitations. (1) PopCore consumes an extra 12 mm of material around the perimeter of the layout in order to complement parts with "tabs". (2) User effort from flipping the workpiece in the laser cutter. (3) While the prior art removes residue using heat-shrinking [Abdullah et al., 2022], PopCore requires users to manually actuate lever mechanisms. This takes 15% additional time, such as 40 seconds in the case of the chair model shown in Figure 18.

3 RELATED WORK

The work presented in this paper builds on research on high-fidelity prototyping, laser cutting from both sides, and laser-cut sandwich materials.

3.1 High-fidelity personal fabrication

Creating high-fidelity models is an essential aspect of professional design disciplines like industrial design and architecture [Becerra, 2016]. Specially for packaging design, research has shown that products in aesthetic packages are preferred over products in standardized packages [Reimann et al., 2010]. Personal fabrication has been successful in simplifying the creation of complex 3D models (*CoilCAM* [Bourgault et al., 2023], *Makers' marks* [Savage et al., 2015], *Crane* [Suto et al., 2023]), and adding functionalities (*Oh*

Snap! [Schmitz et al., 2021], *Mechamagnets* [Zheng et al., 2019]). However, one key challenge for personal fabrication is to enable non-experts to produce models with a high-quality clean finish.

McCurdy et al. define form and visual appearance as key aspects of a model [McCurdy et al., 2006]. In the case of a prototype these aspects dictate the "closeness with the final product in terms of scale, aesthetical appearance, tolerances, etc." [Fiorineschi and Rotini, 2019]. Diana et al. demonstrate that physical models that closely represent the actual product in terms of aesthetic and visual fidelity illicit critical assessments [Rueda et al., 2013].

However, current fabrication technologies tend to leave visual traces, such as injection molding showing seams and FDM 3D printing showing layer outlines. Traditionally, several rounds of sanding and putty filling are required to create a clean finish or heat treatment to melt the surface removing imperfections (e.g. for PLA). To mitigate FDM artifacts, researchers have proposed controlled acetone vapor smoothing [Havenga et al., 2018] (e.g. for ABS), partitioning models to reduce the staircase effect ([Wang et al., 2016]), hiding gaps in multipart models in areas of low visual impact (reducing visual artifacts [Filoscia et al., 2020], Chopper [Luo et al., 2012]), and creating precise geometry to fix broken objects [Lamb et al., 2019]. Researchers have also explored adding fine textures [Yan et al., 2021] and surface patterns [Tricard et al., 2021].

3D printing techniques such as Stereolithography (SLA) resin printing or powder bed fusion (PBF) provide a higher quality finish since layer lines are less visible. However, parts still require some post-processing, such as media blasting to give PBF 3D printed artifacts a smooth finish or sanding and polishing SLA parts with sandpapers. As these advanced 3D printing techniques and precise CNC milling become more accessible, affordable, and user-friendly, they would offer an alternative for producing high-fidelity artifacts.

Laser cutting is particularly challenging when it comes to creating high-quality models. While 3D printing remains the go-to technique for small-scale artifacts, laser cutting is considerably faster with large-scale models (Platener [Beyer et al., 2015], Roadkill [Abdullah et al., 2021], HingeCore [Abdullah et al., 2022]), especially those that require structural stability e.g., box jointed furniture (kyub [Baudisch et al., 2019]). However, box joints form highly visible artifacts. While wood working hides such joints with various forms of miter cuts, laser cutting lacks this capability. Recent work HingeCore [Abdullah et al., 2022] hides box joints behind a paper layer but introduces its own set of artifacts (see Figure 3).

3.2 Laser-cut sandwich materials

The most common foldable material is paper. It has been used for paper craft [Song et al., 2006], metamaterials [Signer et al., 2021], and packaging [Koyama et al., 2023]. Sandwich materials go a step further in order to exploit the combined benefits of different materials. Sandwich materials thereby enable more complex structures, such as embedded foldable mechanisms (LamiFold [Leen et al., 2020]), circuitry (Lasec [Groeger and Steimle, 2019], FoldTronics [Yamaoka et al., 2019], Fibercuit [Yan et al., 2022]), or self-folding (Self-shaping Curved Folding [Tahouni et al., 2020]).

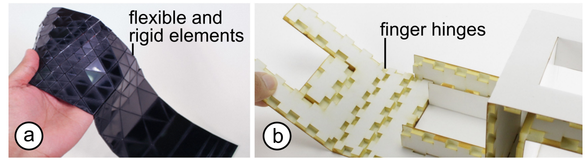

Figure 2: (a) Foldem [Perumal and Wigdor, 2016] creates flexible and rigid artifacts by laser cutting half-way. (b) HingeCore [Abdullah et al., 2022] uses this principle to create foldable, yet sturdy box joints (aka finger hinges).

Foldem [Perumal and Wigdor, 2016] introduces laser cutting sandwich material halfway (Figure 2a), a key technique that allows creating artifacts with both rigid and flexible properties in one go. (b) HingeCore builds on this by laser cutting foamcore halfway thereby producing "finger hinges" [Abdullah et al., 2022]. Finger hinges speed up assembly by allowing users to fold models, while simultaneously allowing for sturdy construction based on box joints.

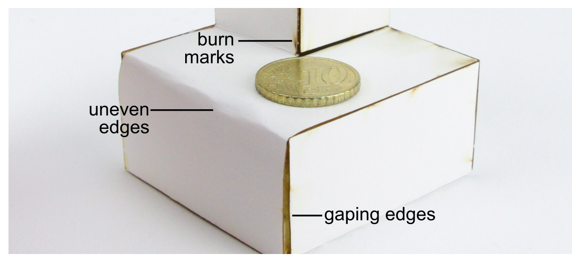

Figure 3: Artifacts introduced by HingeCore.

In the context of this paper, the key benefit of HingeCore is that it introduces hidden box joints, thereby introducing the *vision* of sturdy 3D models with an artifact-free finish.

Unfortunately, as illustrated by Figure 3, HingeCore introduces its own set of artifacts: visible edges tend to get burnt, edges appear uneven, and joints tend to gape.

Figure 4 illustrates why joints tend to gape: (a) picking out the material blocks between fingers (aka "residue"), (b) commonly leaves bits of foam behind. When assembling the model, the leftover foam prevents fingers from entering all the way, resulting in the aforementioned gaping. The heat-shrinking polystyrene mentioned in [Abdullah et al., 2022] faces the same issue—here it is the shrunk material left behind in the cavities.

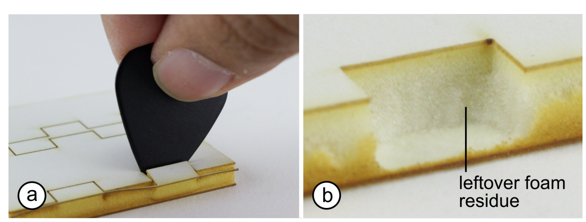

Figure 4: Why HingeCore tends to gape: (a) Pulling residue out, (b) frequently leaves bits of foam behind.

The uneven edges are also responsible for gaping. In Figure 5, the uneven edges on the left cause the top plate to shift to the right, misaligning it with the fingers in the front plate, causing them to gape.

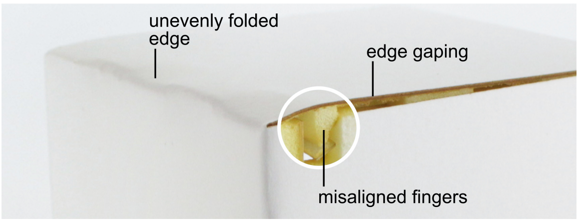

Figure 5: Unevenly folded edges also lead to gaping (image inside circle is showing the inside of the model).

3.3 Laser cutting from both sides

While multi-pass laser cutting from the same side is feasible in laser cutters, laser cutting a workpiece from both sides requires additional steps. Jigs are typically used to align the work piece after flipping it over. Laser cutters such as Glowforge [Glowforge, 2024] and Trotec [Trotec, 2024] come with vision systems that simplify the alignment task. MARCut [Kikuchi et al., 2016] proposes using special shape and command markers to simplify the process.

The typical use case for double sided laser cutting is engraving parts from both sides. PopCore, in contrast, uses double-sided cutting to create novel types of hinge mechanisms.

3.4 PopCore and its two lever mechanism

The key elements of PopCore are two lever mechanisms. Their main purpose is to pull out residue easily and cleanly.

Figure 6a illustrates the tab lever mechanism. Rather than producing isolated blocks of residue (Figure 4), tab mechanisms connect the material to be removed to material located outside the part. Generally, all fingers along an edge form a single such tab. (b) During assembly, these tabs act as levers. Users jerk the tab downwards in an experience participants in our user study refer to as "easy" (6/7), "fun" (5.9/7), and "addictive" (5.7/7) (see "User study"). Jerking the tab downwards causes (c) the residue to be pulled upwards, thus ripping it out of its cavity—until the tab finally breaks off. (d) Since the cohesion of the foam is higher than the adhesion to the paper layer, the foam stays in one piece, leaving a cavity that is perfectly clear ready to be joined with its counterpart.

The key element that creates the lever is a shallow straight cut across the bottom paper layer, hinted at in Figure 6a by a pair of black triangles and revealed in (c). This cut forms the fulcrum of the lever. The bottom paper layer is inaccessible from the top, as it is partially hidden behind the fingers, which is why PopCore creates them by cutting from below.

Figure 7 illustrates the seesaw lever mechanism. It allows creating joints located along a folded edge. Figure 7a illustrates the isolated blocks of material that need to be removed. Tab levers do not apply here, as this configuration lacks the extra material required to form the tab. (b) Instead, seesaw levers connect each piece

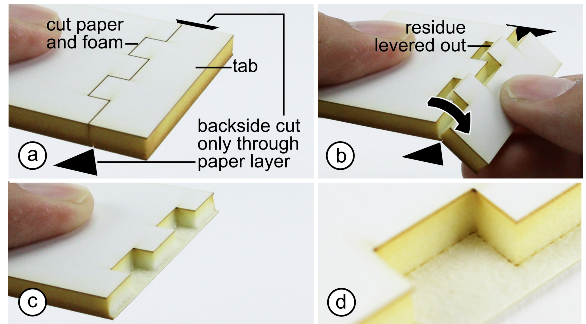

Figure 6: PopCore enables complete removal of residue by creating (a) tabs along the edge that connect to the residue, (b) lever it out along a shallow cut at the bottom and (c) break off.

of residue with the finger located across. Seesaw levers achieve this by replacing the respective cut lines with perforation.

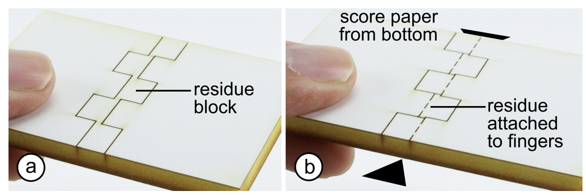

Figure 7: (a) In order to remove these blocks of residue, (b) Seesaw levers attach blocks of residue to their respective opposing finger using a perforated edge.

Similar to tab levers, the lever is created by a shallow straight cut across the bottom paper layer (indicated using the pair of black arrows in Figure 7b). Seesaw levers, however, do not cut through the paper, but merely "hint" the material where to crease by scoring the paper. As illustrated by Figure 1b, the crease line causes hinges to break open when folded, giving folded hinges and joints a similar, uniform look.

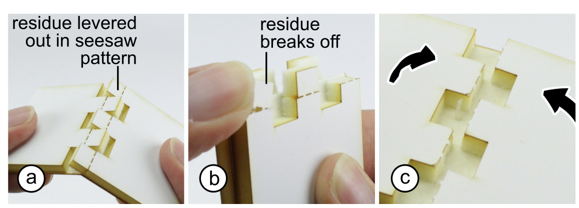

Figure 8: (a) Users lever out the residue in a "seesaw" pattern by folding down, and (b) breaks it off from the fingers. (c) Resulting in a residue free joint ready to be folded.

During assembly (Figure 8a), users jerk the hinge downwards (forming a so-called *mountain fold* [Lang, 2012]). This causes all seesaw levers to simultaneously detach their respective pieces of residue from the paper layer and "excavates" the residue blocks located at the ends of all fingers. (b) Users now break off the residue from the fingers. User study participants rated this step as "easy" (5.8/7), "fun" (5.2/7) and "addictive" (4.65/7) (see section "User study"). (c) The residue-free edge is now ready to be folded.

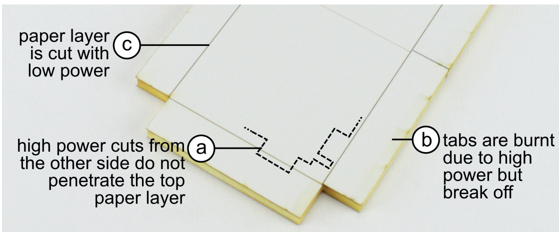

Figure 9: PopCore layouts are not subject to burning.

As illustrated by Figure 9, tab levers and seesaw levers also protect the model from burn marks. The figure shows the bottom of the layout, which forms the outside of the model once assembled. (a) PopCore cuts the outline of the model with high power. However, the model's perimeter is now formed exclusively by tabs. When these are removed during assembly, so will be any burn marks. (b) The joint pattern is cut into the other side of the model, separated from the model's outside by a paper layer. (c) By cutting only through the outer paper layer, finally, PopCore cuts using less power than what could produce burn marks. As a result, PopCore produces a clean burn-mark-free look, without requiring burn-reduction techniques, such as masking tape [Sinclair, 2019].

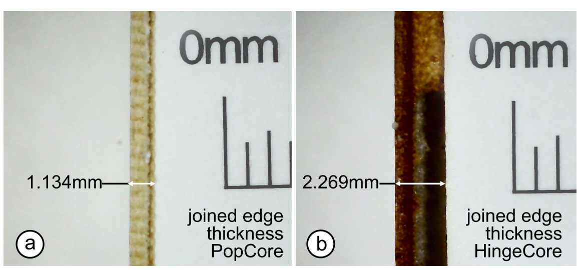

Figure 10: (a) PopCore cuts are shallow and light, thus carry much less "visual weight" than (b) a typical laser cut, here in HingeCore (twice as wide and 4.7x darker).

As Figure 10 takes a closer look at these low-power creases from Figure 9c: (a) the shallow cuts are very narrow and very light, thus carry much less "visual weight" than a typical laser cut. For context (b) plates joined using HingeCore (Polyurethane foamcore) form an edge that is twice as wide and 4.7x darker (comparing the average gray scale i.e., luminance values of the edge).

The combination of all of the above, i.e., the elimination of gaping and burn marks, as well as the reduction of the visual weight of edges is the key to the improved visual quality of models produced using PopCore.

3.5 Additional features: non-rectilinear geometry, different material thicknesses

As shown in Figure 11, PopCore not only supports rectilinear geometry, but also slanted and rounded geometry. Rounded edges are created using the same techniques as HingeCore.

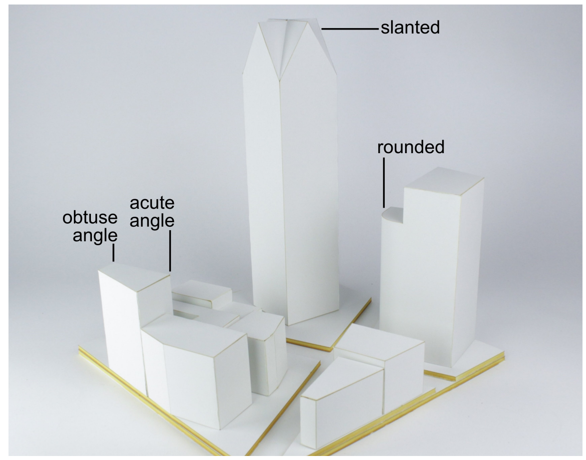

Figure 11: PopCore supports rectilinear, rounded, and slanted geometry.

As illustrated by Figure 12, obtuse angles are a straightforward extension of the regular tab/seesaw design, in that only the residue blocks to be removed are shorter.

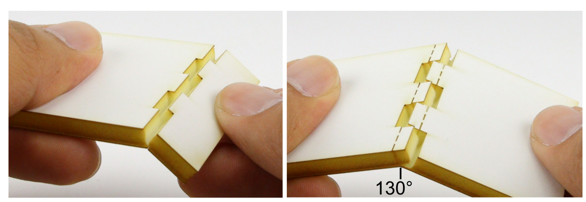

Figure 12: Lever mechanisms work as is for obtuse angles.

Acute angles below 40°, however, require additional precaution. As Figure 13a shows, acute angles require larger blocks of residue to be removed. The surface area covered by the residue for a 35° angle, for example, is larger than for a 90° angle. Thus the 35°-tab lever requires more torque. (b) This causes the material forming the tab levers to buckle (beam theory [Marghitu, 2001]), rather than ripping off the foam. (c) The PopCore algorithm solves this by subdividing tab levers (below 35°) into multiple narrower levers essentially reducing the surface area of each lever.

For angles below 25°, tab levers fail and PopCore reverts to manual residue removal. However, such angles are uncommon (the HingeCore evaluation dataset [Abdullah et al., 2022], for example, contains only 2/100 such models).

Seesaw levers for angles below 45° (Figure 14a) run into a similar issue: here the additional adhesion causes the perforation of the lever mechanisms to break prematurely. (b) PopCore addresses

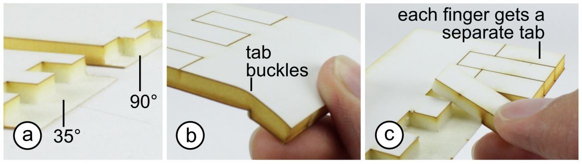

Figure 13: (a) Foam residue in acute angles covers larger surface area, resulting in (b) tabs buckling. (c) PopCore solves this by creating a separate tab for each finger.

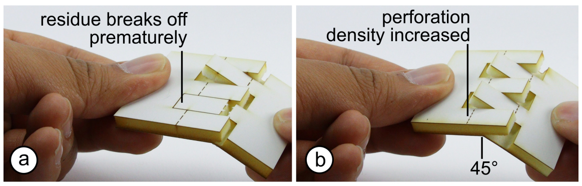

Figure 14: PopCore allows consistent removal of residue by increasing perforation density for acute angles.

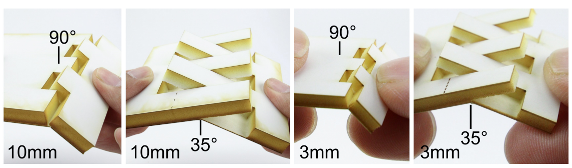

Figure 15: PopCore scales the lever mechanisms based on the depth of the box joint geometry, allowing them to work with 10mm and 3mm thick foamcore.

this by creating perforation with fewer and shorter incisions. This technique works up to 35°.

While the examples above are 5mm thick foamcore, Figure 15 shows that both lever mechanisms work well with thicker (10mm) and thinner (3mm) foamcore. Material thickness affects the depth of the box joint pattern [Baudisch et al., 2019], i.e., the surface area of residue and the cross section of the levers. PopCore accommodates for these changes by increasing/decreasing the width of the tab lever and the perforation of the seesaw mechanisms proportionally to the depth of the box joint pattern.

A variation of PopCore's seesaw levers allow embedding magnets into plates by cutting through the paper and foam layers essentially creating a seam in the surface. As shown in Figure 16a, folding down opens up the plate excavating a space for the magnets while creating a barely visible crease on the outside surface. (b) The magnets are pushed into the soft foam layer securing them under the paper layer. (c) Folding up the layout closes up the seam holding the magnets in place. (d) Embedding magnets allows PopCore objects to attach securely to each other (and other objects) enabling new use cases including easy stacking, construction kits (Figure 25), and transformations (Figure 24) etc.

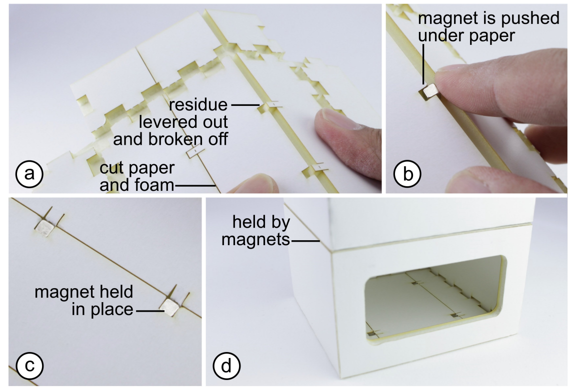

Figure 16: Modified seesaw mechanism allows embedding magnets into surfaces, allowing PopCore objects to attach to each other.

3.6 Engravings and finger hinges on either side

As a side effect of cutting from both sides, PopCore naturally allows placing arbitrary features on either side. In the example shown in Figure 17, this allows engraving a recessed press-fit channel. (b) The engraved channel allows press-fitting the frosted acrylic panels that act as diffusers for (c) a lamp which we replicate from [Abdullah et al., 2022].

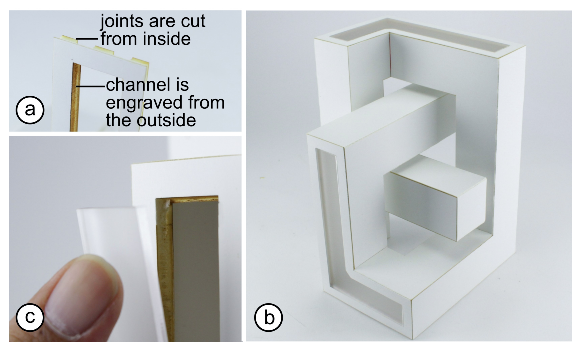

Figure 17: PopCore supports engraving and cutting from either side.

Cutting from both sides allows creating a particularly sturdy chair, since box joints (aka finger hinges [Abdullah et al., 2022]) are placed even along valleys folds that would otherwise be paper-only hinges (Figure 18).

3.7 Alternative materials

While the generic, white appearance of foamcore is typically most desirable for industrial designers, packaging designers, and architects, PopCore also allows producing a more targeted appearance by fabricating from custom materials. Figure 19a shows a custom composite created by laminating 1mm acrylic to 3mm acrylic using a spray mount (*3M display mount*). (b) The PopCore tab levers work well here since the adhesion between the two materials is lower than the cohesion of the 3mm acrylic layer. (c) As with foamcore,

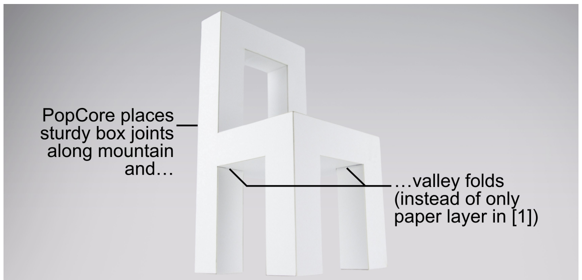

Figure 18: PopCore allows placing box joints along all edges.

acrylic PopCore minimizes the visual weight of material edges by hiding the box joints; (d) additionally, it now produces a reflective look.

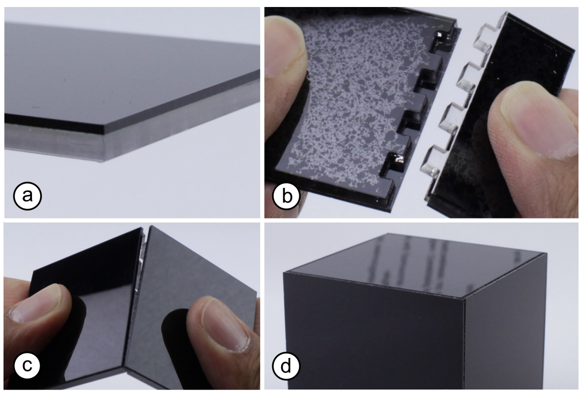

Figure 19: PopCore's tab levers work with custom-made composites, in this case 1mm black acrylic bonded with 3mm transparent acrylic.

Finally, we can optimize PopCore for sustainability by applying it to easy-to-recycle materials. Figure 20 illustrates this at the example of standard corrugated fiberboard, commonly used to create shipping boxes. This material consists of recycled paper laminated onto the same type of paper and thus allows for easy recycling. The concept of PopCore works here as well, because cohesion of the inner (paper) layer is higher than the adhesion between inner layer and outer layers. This allows the (a) tab and (b) seesaw lever mechanisms to pull out the residue cleanly allowing the model to be (c) assembled by folding. We have used Foamcore throughout this paper, since it is the most common sandwich material used by architects and industrial designers. However, a similar clean white finish can be achieved by using white corrugated cardboard.

4 APPLICATION EXAMPLES: POPCORE ENABLES PACKAGING DESIGN

In the previous sections, we showed application examples from industrial design (Figure 17) and architecture (Figure 11), and a brief example of packaging design in Figure 1. In this section, we will take a more detailed look at packaging design. Packaging design is the science, art, and technology of enclosing or protecting

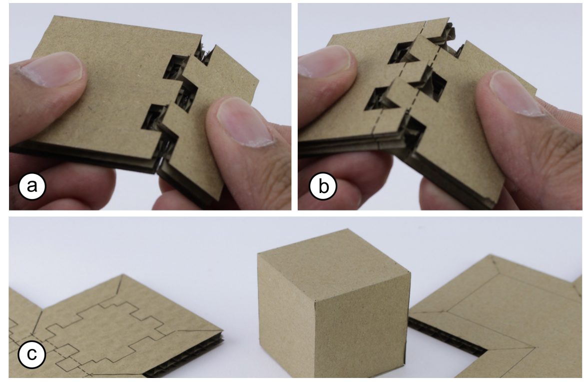

Figure 20: Sustainable PopCore made from corrugated cardboard.

products for distribution, storage, sale, and use [Soroka, 2002]. Packaging design is a complex field that addresses a wide range of challenges, ranging from physical protection and convenience to security [Emblem, 2012]. Comparable to industrial design and architecture, packaging design is its own field, with the global market size valued at US $21.9 billion in 2020, and projected to reach $31.9 billion by 2030 [Allied, 2022].

Product developers hire packaging designers to design the packaging for their products and outsource prototyping to them. Since production requires fabrication machinery, packaging designers outsource fabrication to manufacturers. The manufacturers require a minimum batch size, which places a financial burden on founders and small businesses making it expensive to create packaging for one-off prototypes or small batch productions. PopCore, in contrast, allows users to create packaging in batches as small as 1 and using a class of machine already commonly used for making the product itself (e.g. the laser-cut speaker shown in Figure 23).

While the appearance of packaging is crucial, packaging fulfills a wide range of additional requirements. Below we show examples of how PopCore packaging tackles these requirements.

4.1 Physical protection

21 shows an example of a class of PopCore packages designed to physically protect fragile products, e.g. (a) medicine delivered in glass ampules, against mechanical shock. While this type of packaging is already known to withstands compression of about 60 kg [Abdullah et al., 2022] it is also very effective in absorbing mechanical *shock*. To validate this claim, we produced a package, which passed the egg drop challenge from 3 meters using the same style of packaging. (b) Inserts separate the product from (c) the outer packaging layer and absorb mechanical shock on impact (d) protecting the product from harm.

As shown in Figure 22, PopCore packages incorporate French-fits and cut-outs that secure the product in place while showcasing it on unboxing, a feature that is important for high-end products. This benefits small companies in the process of prototyping a new product, e.g., (a) smartphone or (b) a series of custom 3D printed clay mugs since these products need to be housed in high-end packaging for initial feedback from Kickstarter backers/reviewers.

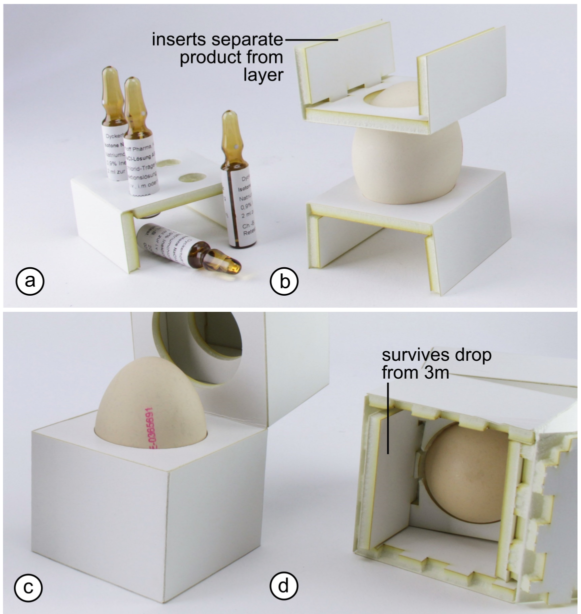

Figure 21: PopCore packages protect (a) fragile products against mechanical shock by using (b) inserts. (c) This package design successfully protects (d) an egg dropped form 3 meters.

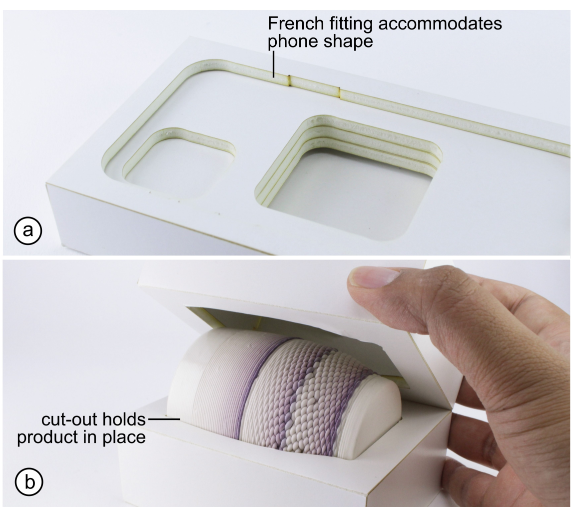

Figure 22: PopCore packages secure products in place by incorporating (a) custom French fitting e.g., for one-off prototypes and (b) custom cut-outs e.g., for a 3D printed clay cup.

At this initial stage before product mass production, the cost of ordering a custom-made package is extremely high since minimum orders are for bulk quantities.

Figure 23: PopCore cuts and engraves from both sides and thus allows engraving decorative designs on this speaker package.

4.2 Decoration or information transmission

Another important consideration is adding labels to the package. These could either be purely for decorative or marketing purposes or could contain information like how to transport, use, recycle, or of the product. Since PopCore laser-cuts from both sides it also supports engraving both sides. As shown in Figure 23, this allows creating decorative patterns on a package for a laser-cut speaker.

4.3 Marketing

Packages are also designed to reflect the brand's identity and act as marketing material. Figure 24a shows a PopCore package that (b) opens to reveal the product, in this case house keys. (c) The package transforms into a house shaped piggy bank, embodying the brand of the real estate company. Magnets hold the package in shape in both states.

Figure 24: Transforming PopCore package turns into a house serving as a marketing instrument for the "real estate" company while also allowing reuse as a piggy bank.

4.4 Reuse

This is an important element in creating sustainable packaging design. As shown above (Figure 24), PopCore packages enable reuse by transforming their shape and purpose. Similarly, Figure 25 shows a set of packages for toy building bricks that are embedded with magnets allowing themselves to be used as large toy building bricks.

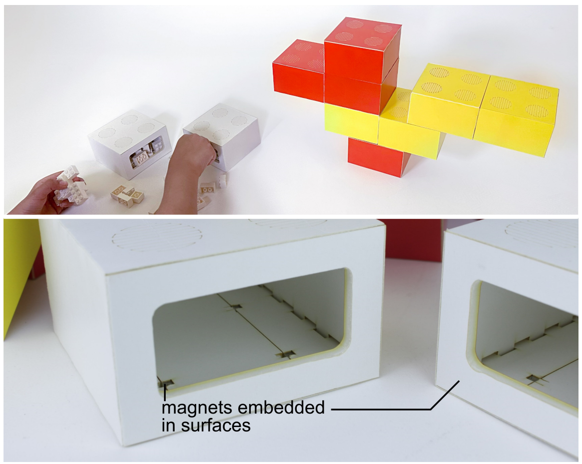

Figure 25: PopCore packages with embedded magnets are easy to stack and reusable as toy building blocks.

4.5 Convenience

A key consideration in packaging is ease of distribution, display, stacking etc. Figure 25 shows PopCore packages embedded with magnets that connect together for easy stacking while Figure 26 shows a packaging inset that protects the product during transport and then is used as a convenient rack to dispense medication at the doctor's office.

Another important aspect is distributing the packaging itself to the customer who wants to package a product. As shown throughout this section, PopCore produces 2D layouts and they can be easily flat packed and shipped to the customer, who can then *fold* the packaging on site.

Figure 26: The PopCore package protects the glass vials during transport and acts as a convenient rack to display and dispense medication, in this case at the doctor's office.

4.6 Security

Packaging plays a key role in mitigating security risks. Figure 27 shows an example of tamper proof packaging created with PopCore for a premium credit card. (a) The product is sealed inside the package. To open the product, the user has to twist off the top half, breaking the package in the process. A cut around the package with designated break-away tabs enables this action. (b) This leaves an obvious mark that the package has been opened or tampered with and resealing the packing is also impossible. By reinforcing the edges with glue on the inside, the package cannot be opened any other way without damage.

Figure 27: (a) Twisting the top half (b) breaks open the package, leaving an obvious mark that the package has been opened.

4.7 Recycle

PopCore works with recyclable composites such as corrugated cardboard. Once the PopCore packages are opened, it is possible to *unfold* them into a 2D layout again, making it easy to reuse the material or dispose of the package.

5 THE MECHANICS OF CUTTING POPCORE LAYOUTS

Figure 28 illustrates the cutting plan created by PopCore, at the example of a 5x5x5 cm cube. The laser cutting process takes place in two passes.

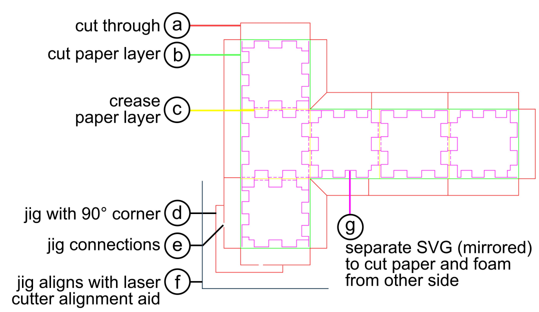

Figure 28: The laser cutter fabricates PopCore by executing the first half of the cutting plan (a-c). Users then flip the workpiece in the laser cutter and align it by pushing (d) the 90° jig into (f) the alignment aid of the laser cutter. (g) Now the laser cutter cuts the remaining lines shown in magenta.

First, the laser cutter executes the (a) red (cut through), (b) green (cut top paper layer), and (c) yellow (crease top paper layer) lines. To simplify laser cutting from both sides PopCore also creates (d) a rectangular corner as part of the layout.

Users now flip the layout and (f) align the rectangular corner against the alignment aids commonly found in laser cutters along the top and left edges (e.g. seen in Trotec [Trotec, 2024], and Glowforge [Glowforge, 2024]). This process produces precision substantially beyond what PopCore requires. (g) PopCore lays out the second side under this assumption, so cutting can start right away without further calibration activities. This allows aligning the mirrored cutting plan with its physical counterpart. The laser cutter now creates the finger hinges shown in magenta by cutting "half-way", i.e., through the top paper layer and the foam layer.

(e) Small breaks in the red outline keep the layout connected to the jig during flipping but allow for easy removal later. Settings to laser-cut at different layer depths are machine specific and based on [Abdullah et al., 2022].

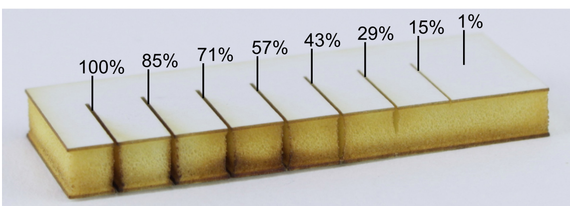

Figure 29: An example cutting depth calibration gauge with different power settings cut on a Trotec speedy360. Cutting another two gauges between the range of 43-57% and 1-15% power provides settings to cut at precise depths required for PopCore.

5.1 Calibrating the cutting depth

We created a custom calibration gauge to find settings required to achieve different cutting depths. To calibrate the speed is fixed and the gauge shown in Figure 29 is cut with eight cut lines of different power (1, 15, 29, 43, 57, 71, 85, 100). This cutting speed and max power is defined by settings for a known material, (here, e.g., 4mm plywood on the Trotec speedy360 [Trotec, 2024], cutting speed at 1.75%). After cutting the gauge, the cutting depth is observable from the side. For example, the setting for "cut paper layer" needs to break through the paper layer to the foam while "crease paper layer" should visibly cut the paper but not reach the foam on the other side. After cutting two more gauges between the power ranges of 43-57% and 1-15%, we find appropriate settings by observing cutting depths from the side.

The settings remained unaltered for six months on our Trotec speedy360. The same procedure also worked well on the Glowforge [Glowforge, 2024] using known settings for cutting EVA foam as a starting point.

5.2 The PopCore Algorithm and software

We now present the PopCore algorithm, which we implemented in the form of a software tool, which we call *PopCoreMaker*. PopCoreMaker extends HingeCoreMaker [Abdullah et al., 2022] to which it adds the lever mechanisms and the features that allow laser cutting from both sides. We implemented PopCoreMaker as a standalone tool and also integrated it into an interactive system for laser cutting (*kyub* [Baudisch et al., 2019]). Users can either import .obj or .stl files or use *kyub* to model slanted or rounded features, set the material thickness, etc.

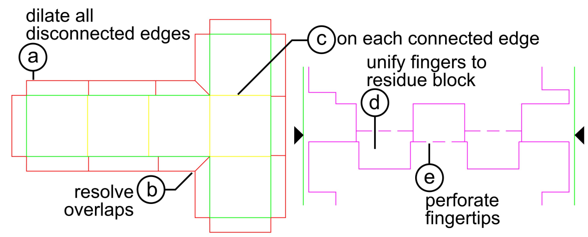

Figure 30: PopCoreMaker converts 3D models into 2D cutting plans and adds tab and see-saw lever mechanisms.

After converting 3D models into 2D cutting plans [Abdullah et al., 2022], PopCoreMaker generates tabs (Figure 30), by first (a) *dilating* all outward-facing (green) edges, resulting in the red cut lines. (b) PopCoreMaker then resolves overlaps between tabs by altering their outline. PopCoreMaker then creates the see-saw mechanisms for (c) edges that are connected in the layout, by (d) *unifying* connecting fingers to the residue on the opposing side and (e) adding perforation *where the tips of the fingers used to be.* For edges that are part of acute geometry, PopCoreMaker adjusts the perforation as discussed earlier.

Finally, PopCoreMaker adds the outlines for the jigs and splits the cutting plan into two parts, each encoded as its own SVG. It forms the top SVG from the red lines (cut through), green lines (cut top paper layer) and yellow lines (crease top paper layer); it forms the bottom SVG from the (mirrored) magenta lines (cut paper and foam layer).

6 USER STUDY ON QUALITY AND USE CASES

To validate our claim that PopCore offers higher visual finish and therefore enables new use cases, we ran a user study. We conducted the study in three sessions with three different sets of participants in each session: In the first session, participants assembled cubes that we had created using PopCore and two HingeCore methods [Abdullah et al., 2022] (as shown in Figure 1). In the second session, participants rated the visual finish of the cubes assembled in the first session. Finally, in the third session, participants indicated which of the three fabrication methods they considered suitable for which use cases. We hypothesized that participants in session one would find PopCore's lever mechanisms as easy and fun to use as HingeCore, that participants in session two would find PopCore models more appealing and that participants in session three would deem only the PopCore models suitable for high-quality use cases.

Algorithm 1 Adding tab and seesaw lever mechanisms to the cutting plan

```
create_residue_removal_structures:
Input: cutting_plan{open_edges, connected_edges}
Output: cutting_plan*
//create tab levers
for all edges ∈ open_edges:
    tab_polygons = edge.extend(edge points, joint angle, length, width)
for each tab_polygon ∈ tab_polygons:
    overlapping_tab_polygons = find_overlaps(tab_polygon, tab_polygons)
    if overlapping_tab_polygons is empty and find_overlaps(tab_polygon, cutting_plan) is empty then
        add tab_polygon to cutting_plan*
    if parent edges of any overlapping_tab_polygon and tab_polygon share a point then
        fixed_overlap_tab_polygon = fix_overlapping_tab(tab_polygon, overlapping_tab_polygon, overlap_point)
        add fixed_overlap_tab_polygon to cutting_plan*
    // discard overlapping polygons with non-adjoining edges or the model itself
//create seesaw levers
for each pair of connected_edges:
    for each edge ∈ connected_edge:
        for each finger ∈ edge:
            finger.perforate_edge(degree of perforation)
    for one edge ∈ connected_edge:
        for each finger ∈ edge:
            finger.extend_sides(finger points)
return cutting_plan*
```

6.1 Session 1: Assembly experience

We recruited 12 participants (2 female, average age = 23.75) from our institution. Four of the participants had previously assembled "a few" non-foamcore laser-cut models.

6.1.1 Interface conditions. There were three interface conditions.

In the *HingeCore heat shrink* condition, the 2D folding layout had been created from 5mm polystyrene foamcore where the residue was heat-shrunk by the laser using the code presented in [Abdullah et al., 2022].

In the *HingeCore manual* condition, the 2D folding layout had been created from 5mm polyurethane foamcore using the code presented in [Abdullah et al., 2022]. Here participants removed residue manually using a guitar pick (as shown in Figure 4).

In the *PopCore* condition, the 2D folding layout had been created by laser cutting 5mm polyurethane foamcore from both sides.

No masking tape was applied to any of the layouts during laser cutting.

6.1.2 Task and Procedure. Participants performed one trial each for each of the three interface conditions (within-subject design). During each trial, participants assembled one cube from a strip of 6 plates (as shown in Figure 1). In the case of the HingeCore manual and PopCore conditions, they also removed residue. Participants were asked to assemble models carefully to produce the best possible result. The study was counterbalanced using a Latin square.

Before performing each trial, participants viewed a 30-second training video, which showed how to remove residue and assemble a joint using simplified artifacts (Figure 6 and Figure 7) for both HingeCore and PopCore. Participants could also interact with the training artifacts after watching the video.

After completing the conditions, participants filled in a questionnaire. All participants finished the study within 20 mins.

6.1.3 Hypothesis. Participants would find excavating joints using PopCore's lever mechanisms easy, fun, and potentially "addictive".

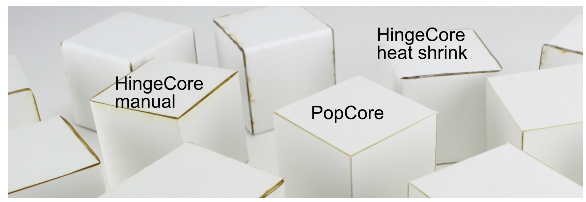

Figure 31: A set of models created by the participants during the user study on assembly experience.

6.2 Session 2: Assessing visual quality

We recruited a different set of 12 participants (3 female, average age = 24.75) from our institution. Three participants had previous experience with laser cutting.

6.2.1 Model Set. The model set consisted of 36 cubes (12 PopCore/12 HingeCore-heat shrink/12 HingeCore-manual) assembled in session 1 (shown in Figure 31).

6.2.2 Task and Procedure. Participants' task was to pick up one cube model at a time, inspect it from different angles and assign a rating of perceived visual quality. Participants were encouraged to think aloud. Each participant rated all cubes produced in the first session performing 36 trials (within-subject design). All models were accessible to the participants and they were allowed to rate them in any order. The participants took 15 mins on average to perform the task.

6.2.3 Hypothesis. Participants would find the models created using PopCore visually more appealing.

6.3 Session 3: Assessing use cases

We recruited a third set of 12 participants (4 female, average age = 24.08) from our institution. 3 participants had previous experience with laser cutting.

6.3.1 Model Set. Participants were shown 3 groups of 12 cubes each (12 PopCore/12 HingeCore-heat shrink/12 HingeCore-manual) assembled in session 1 (shown in Figure 31. Participants were also shown pictures of 3D models of 4 hypothetical example models (light sculpture, city model, packaging for a $20 product, packaging for a $800 product).

6.3.2 Task and Procedure. Participants' task was to visually inspect models in each group to perceive their finish. Then for each group, participants were asked if they would use the respective method to create models considering 7 different use cases across 4 hypothetical example models. Participants were asked to base their answer on visual appearance only. Participants took 10 mins on average to perform the task.

6.3.3 Hypothesis. Participants would find PopCore as the appropriate choice for use cases that demand a higher quality finish.

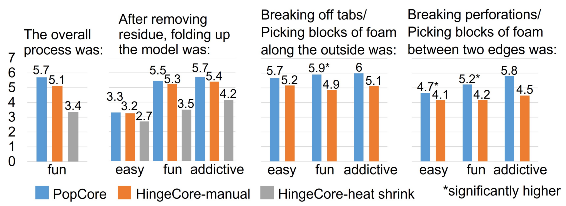

Figure 32: The results of the post-study questionnaire. Participants regarded removing residue using the lever mechanisms as easy, fun, and "addictive".

6.4 Results session 1: Assembly Experience

As expected, HingeCore-heat-shrink was the fastest condition with 1:52 minutes on average, followed by PopCore with 3:32 minutes on average and lastly HingeCore-manual with 6:21 minutes on average.

The results of the questionnaire from the first part of the study are shown in Figure 32. Participants enjoyed removing residue using the lever mechanisms and rated it as very easy, very fun and highly addictive.

Breaking off PopCore's tab mechanisms was rated significantly more fun ($p = 0.032$) than picking out HingeCore's individual foam blocks. Similarly, PopCore's seesaw mechanisms were rated significantly easier ($p = 0.021$) and fun ($p = 0.016$) to use compared to the traditional HingeCore method.

6.5 Results session 2: Assessing visual quality

Figure 33 summarizes participants' ratings of the visual quality of the resulting models from Figure 31. As expected, participants rated the models created using the PopCore condition as more visually appealing (7.9/9 on average) than HingeCore-manual (4.7/9) and HingeCore-heat shrink (2.3/9) models.

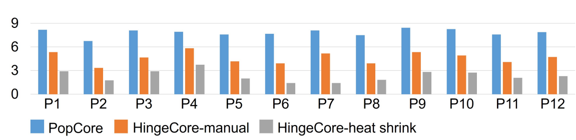

Figure 33: All participants rated the perceived quality of PopCore models significantly higher than HingeCore models.

Differences in visual quality were significant: (1) PopCore vs HingeCore-manual ($t(11)=20.608$, $p < 0.001$, $d = 5.949$) and (2) PopCore vs HingeCore-heat shrink ($t(11)=35.293$, $p < 0.001$, $d = 10.188$). Repeated measures ANOVA ($\alpha = 0.01$) as proposed by [Norman, 2010]; pairwise comparisons were Bonferroni-adjusted.

6.5.1 Qualitative results. Most participants (8/12) mentioned open seams (gaping), scorched edges, and uneven edges as criteria for their ratings. In addition, P2 found the HingeCore models unappealing due to the inconsistency between folded and straight edges adding "some were having rounded edges and non-rounded edges, [this did] not look good".

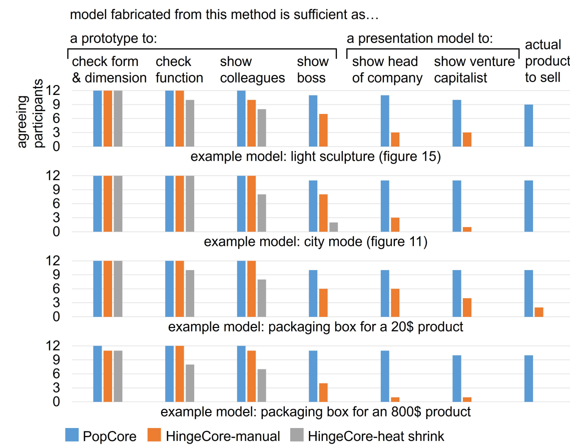

Figure 34: The results of the study indicate that the visual finish afforded by the PopCore method enables use cases beyond typical prototyping.

6.6 Results session 3: Assessing use cases

The results are shown in Figure 34. The majority of participants found all three methods appropriate for basic prototyping to "check form and dimension" (11.8/12) and "check functionality" (11.3/12). We averaged the scores over all four models and methods.

However, they specifically rated PopCore as the only technique appropriate when creating presentation models to "show to head of company" (10.8/12) and "show to a venture capitalist" (10.3/12), i.e., for cases where high quality would be deemed important. Compared to HingeCore (3.3/12, 0/12) respectively. This polarization was particularly strong for the "expensive product packaging" example model. We averaged the scores over all four models.

Participants even agreed to creating products to be sold using the PopCore method (10.0/12), something they considered largely unacceptable with HingeCore.

This confirms our second hypothesis that PopCore enables use cases that demand a high-quality finish, such as presentation models and products.

6.7 Discussion

The concept of fabricating presentation models and products for sale is a powerful one. In Figure 35, we think this idea through. PopCore allows the shown model to ship in a flat-pack envelope. Upon arrival, PopCore's lever mechanisms allow users to "excavate" parts quickly and cleanly. Parts then assemble efficiently. The assembled 3D models, finally, are free of gaping and burn marks as one would expect from a product.

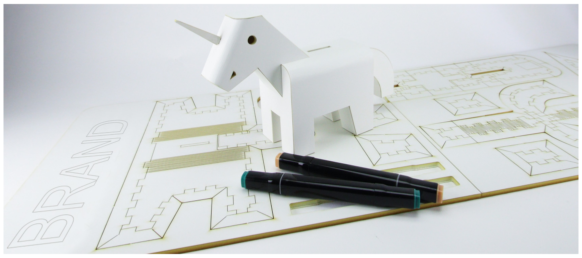

Figure 35: Envisionment of a product fabricated using PopCore

7 CONCLUSION

In this paper, we presented PopCore, a set of novel fabrication techniques and geometric structures that increase the visual quality of laser-cut foamcore models to the level of professional design disciplines, such as industrial design, architecture, and packaging design. The key is the underlying concept of an embedded, laser-cut lever mechanism, which produces very high quality, while being fast and enjoyable to use. We user-tested our design and illustrated it with thirteen models from these fields, including eight examples of packaging design.

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