

PÅCKER: Making Large Laser-Cut Objects Easy-to-Store and Transport

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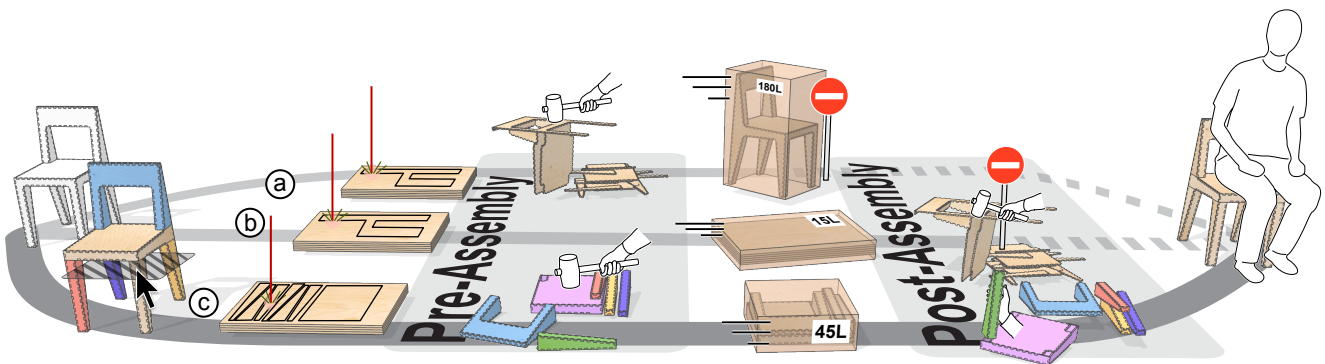


Figure 1: (a) Large laser-cut objects, such as furniture, tend to be hard to store and transport [37]. (b) Shipping the parts prior to assembly reduces shipping costs, but assembly may overwhelm customers [24]. (c) PÅCKER addresses this by allowing vendors to decompose the model into largely convex 3D components. Components are pre-assembled at the vendor’s site, yet still allow for efficient packing and shipping. Components feature familiar screw connectors, allowing customers with “IKEA-level” skills to assemble.

Abstract

We present PÅCKER, a software tool that makes large, laser-cut 3D objects efficient to pack and ship. Inspired by modern flat-pack furniture, PÅCKER achieves this by decomposing 3D models into multiple 3D components. Components are *pre*-assembled at the vendor’s site, shipped efficiently (since components tend to be convex, they pack well), and *post*-assembled IKEA-style at the receiver’s

site. PÅCKER users decompose models using our custom *split* tool, which requires them to specify *only where* to split the model; the tool then automatically selects the most suitable split plane and connector type. Models componentized using PÅCKER are robust: in our technical evaluation, they withstood 94Nm+ of torque. In our user study, participants assembled decomposed chair models about 3.6x faster than the control group and rated them as requiring less demand to assemble.



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CCS Concepts

• Human-centered computing → Interactive systems and tools.

Keywords

Personal fabrication; laser cutting; assembly; tensile load

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1 Introduction

Recent advances in software tools for laser cutting [7, 35] have enabled makers to produce objects of increasingly higher quality [2], utility [25], and attractiveness [32]. As a result, not only makers are downloading digital copies of models [50], but also commercial customers are becoming interested in purchasing finished physical artifacts as commercial products (*Etsy* [17], for example, already offers over a thousand laser-cut objects for sale at any time).

Unfortunately, *shipping* costs can interfere with this [8, 36]. As illustrated by Figure 1a, especially furniture [7, 25, 47], but also musical instruments [40], model airplanes [43], chandeliers [1] and so on—all tend to be extremely inefficient to package, as protruding features, such as legs and backrests, clash with cuboid-shaped packaging, resulting in huge packages that drive up shipping cost, easily beyond material cost.

The obvious solution, as illustrated by Figure 1b, would be to ship individual laser-cut plates and delegate assembly to customers. However, assembly of (large, load-bearing) laser-cut models tends to be non-trivial [7, 25], running a significant risk of overwhelming customers [45].

In this paper, we therefore propose a different approach. Very much inspired by vendors of modern flat-pack furniture, such as Swedish furniture company IKEA [24], we propose PÄCKER, a software tool that assists users in decomposing laser-cut models into largely convex 3D components, pre-assembling, packaging, and shipping these components, to then be “post-assembled” by the customer, thereby reducing the packaging volume (e.g., by a factor of 4x for the chair shown in Figure 1), while keeping assembly easy for customers.

2 PÄCKER: walkthrough

Figure 1c illustrates the process that is enabled by the PÄCKER software. (1) Users use the PÄCKER’s *split* tool and click where to split the model, which allows them to decompose the digital 3D model into (largely convex) 3D components. PÄCKER selects the screw connector that best matches the local geometry and inserts it into the model. (2) The vendor *pre-assembles* the components and ships them in space-efficient flat-pack packaging. (3) The customers *post-assemble* the model using the screw connectors. The result is a large, load-bearing (and typically custom) object that was stored and shipped efficiently (Figure 2).

As illustrated by Figure 3, we designed the *split* tool to perform most split actions with a *single* click. (a) Users load a closed-box structure model into our prototype 3D editor, select the *split* tool, and click the model. PÄCKER responds by selecting the most likely split plane that passes through the click location; i.e., it picks a



Figure 2: (a) A foldable guitar stand, (b) IKEA KALLAX shelf decomposed using PÄCKER, and (c) a chair [25].

split that yields components that are flat and convex (see Section “Algorithm”). (b) Based on this split plane, PÄCKER subdivides the model.

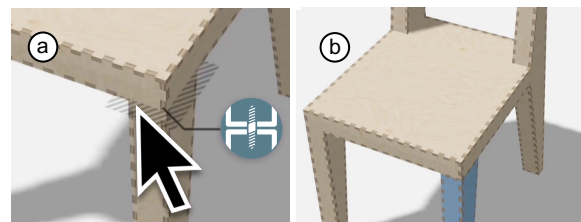


Figure 3: (a) When users click the model using the split tool, PÄCKER responds by rendering the most likely split plane (b) and decomposing.

As illustrated by Figure 4, the split tool also accommodates a wider range of splitting by allowing users to cycle through via a floating pop-up menu [42]. The menu offers the full factorial of up to four alternative split planes (horizontal, vertical, two 45° planes) and up to four connector types. In the shown image, the user cycles

through (a) splitting a leg and adding a connector called a *double-ended screw*, (b) the same splitting but adding single-screw with a dowel, or (c) cutting along a different plane and (d) adding two single-screws. (see details in “Selecting Connectors Based on Local Geometry” selection).

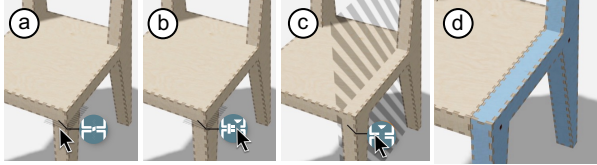


Figure 4: The *split* tool’s floating pop-up menu [42] allows users to cycle through alternative split planes and connector types.

When users decompose a model using the *split* tool, P CKER inserts additional internal structure into the resulting components. Figure 5 shows this for the (a) double-ended screw connector. It allows connecting two closed-box structures, here a chair leg and the chair’s seat. It allows the resulting joint to handle tensile loads with the help of (b) one or more internal plates perpendicular to the screw, (c) connected to the model with the help of a T-joint. (d) Customers assemble the components by spinning the leg.

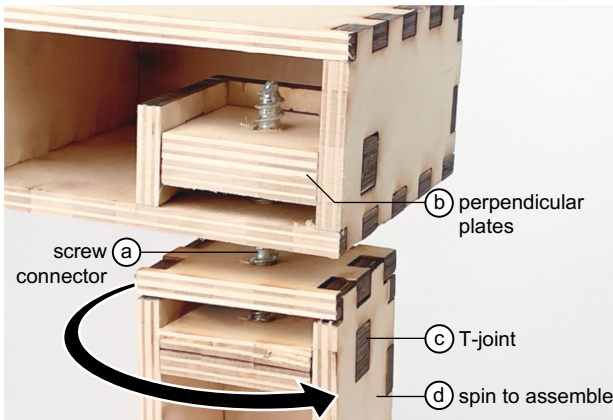


Figure 5: (a) P CKER inserts additional internal structure into the resulting components, here chair leg and seat. (b) Internal plates perpendicular to the screw (c) connected to the model using T-joints allow the connector to withstand tensile loads. (d) Customers assemble the components by spinning the leg.

3 Use cases

With its tool-oriented, direct-manipulation approach, the *split* tool provides users with sufficient freedom to create custom decompositions optimized for different objectives. It thereby supports two classes of use cases.

3.1 Use Case 1: Shipping vs. Assembly vs. Stability

As illustrated by Figure 6, P CKER’s *split* tool allows users to explore the trade-off between shipping efficiency, the number of components for post-assembly, and structural stability: (a) Decomposing the chair into convex components minimizes packaging size, here making it 4.1x more compact than the original model. However, the resulting model requires users to assemble eight components. (b) The decomposition into six components offers a good tradeoff between packing efficiency and post-assembly effort (3.6x more compact than the original model). (c) This model is only 2.25x more compact than the original model, but is particularly robust against users rocking the chair.

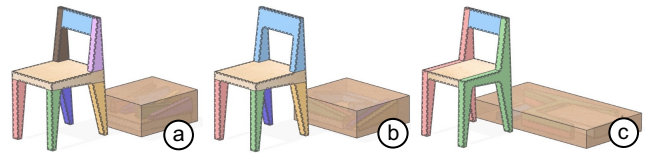


Figure 6: (a) Chair optimized for shipping (44-liter package), (b) trade-off shipping vs. Assembly (50 liters), (c) optimized for stability during rocking (80L liters).

Figure 7 shows the fabricated model from Figure 6b. (a) The user unpacks the model and (b) assembles it using the connectors. (c) The resulting chair is load-bearing.



Figure 7: Figure 7: (a) The user unpacks the decomposed chair, (b) assembles the components with the connectors. (c) The resulting chair is load-bearing.

3.2 Use Case 2: Space-Saving Furniture

P CKER’s second application area is for *repeated* assembly/disassembly. To enable this application, P CKER offers *cam-fitting* connectors, a staple of flat-pack furniture, that do not cut into the wood, thereby allowing for repeated use.

Such *camlock-fittings* (also known as *cam fasteners*) are two-part fastening systems. As shown in Figure 8a, users assemble *cam fitting connectors* by inserting the cam-dowel connector into the cam-nut. (b) After that, they rotate the cam nut using a driver outside the closed-box structure.

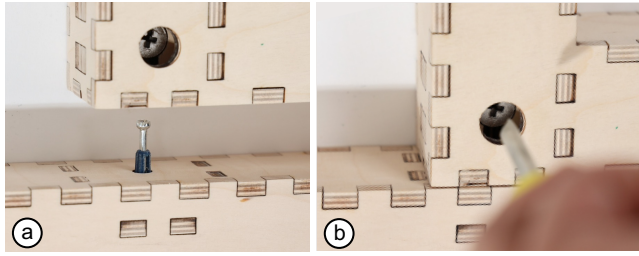


Figure 8: Cam fittings do not cut into the wood, thereby allowing for repeated use.

Figure 9 shows the internal structure PÅCKER generates for cam fittings. It resembles the internal structure of the double screw connector, except that internal plates are coplanar with the incoming bolt, as opposed to perpendicular to it.

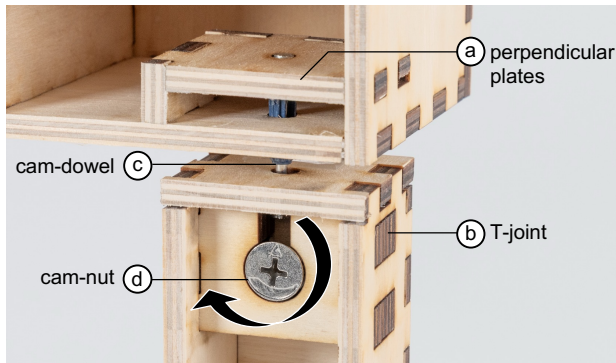


Figure 9: PÅCKER’s cam fitting connector allows repeated assembly/disassembly.

As illustrated in Figure 10, cam-fitting mechanisms enable the fabrication of a wide range of shape-changing objects, including reconfigurable furniture.

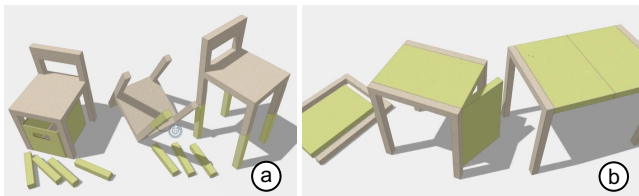


Figure 10: Cam fitting mechanisms allow (a) this play chair to turn into (b) a highchair and (c) this working desk into (d) a dining table.

One common application of reconfigurable objects is travel, as shown in the guitar stand in Figure 11.

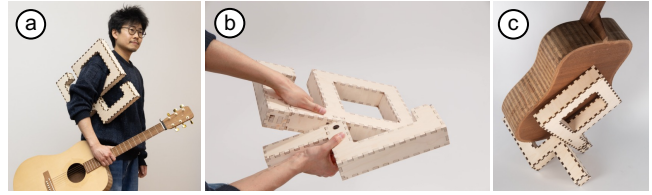


Figure 11: (a) This flat sculpture (b) pivots around its cam-fitting connector, (c) becoming a guitar stand.

As illustrated in Figure 12, angled connectors allow objects to be “straightening” making them easier to store.

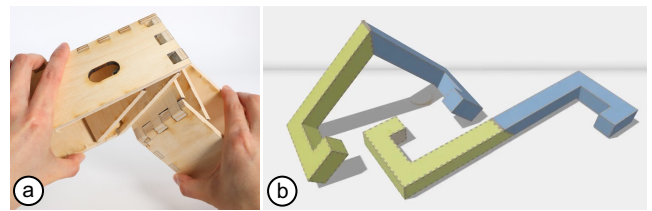


Figure 12: (a) Angled connectors allow (b) straightening out angles in 3D models.

4 Contribution, Benefits, and Limitations

PÅCKER’s main technical contribution is a novel interactive workflow for decomposing laser-cut models, consisting of three key components: (1) a split tool that allows users to decompose their laser-cut models efficiently, (2) an algorithm that automatically selects optimal split planes, and (3) an algorithm that automatically selects connector types. We integrated the split tool and algorithms into an existing laser-cut modeling tool (Kyub [7]).

The split tool and associated algorithms allow PÅCKER to port the concept of flat-packed furniture, which has been highly successful in mass production, to personal fabrication. By helping makers make their physical models available to (non-technical) customers, we give the work of these users greater impact. The resulting physical objects are packing- and nesting-efficient and easy-to-assemble. By enabling the transport of large, load-bearing objects, we extend users’ capabilities from selling figurines and earrings on Etsy to selling these items.

Limitations: (1) PÅCKER works for laser-cut object-based on closed-box structures [7], but not for objects based on cross-joints [35] or plate stacks [40]. PÅCKER’s splitting operation supports only binary planar partitions, and therefore cannot represent decompositions that require multiple simultaneous partitions and curved splits. (2) Our evaluation considered a limited range of geometries and design scenarios, primarily focusing on furniture. While the results demonstrate the usefulness of PÅCKER for representative closed-box models, broader validation across more diverse geometries, decomposition strategies, and application domains remains future work.

5 Related Work

PÅCKER builds on research on creating and assembling load-bearing laser-cut objects, shipping, decomposing 3D models into components, and creating joints and connectors to join these components.

5.1 Personal Fabrication Enables Makers to Create Products

Research in personal fabrication technology has enabled makers to produce high-quality, complex functional objects. This research includes development platforms that simplify embedding electronics (*Lilypad* [6], *MechCircuit* [19], *CurveBoards* [56], *Lacir* [11], *RElectrode* [49]) and software that translates designs into machine instructions, simplifying the use of fabrication machines such as laser cutters (*Cut-cad* [21], *Cuttle.xyz* [15]), knitting machines (*Knit-Picking* [22]), and weaving (*AdaCAD* [20]).

Researchers have also simplified the fabrication process through automatic calibration routines (*Kerfmeter* [26]) and automated selection of correct settings (*SensiCut* [16]). More recently, researchers have developed novel methods to interact with fabrication machines, increasing the expressivity and complexity of the artifacts produced (*Adroid* [51], *Clay-Dough* [9], *CoilCAM* [10]).

This research has allowed makers, and to some extent non-experts, to transition from fabricating objects for themselves to producing *products* for sale. This is visible on platforms such as *Etsy* [17], which offer more than a million 3D-printed, laser-cut, and milled products for sale at any given time.

5.2 Shipping is a Key Challenge in Selling Products

To sell a product, designers need to consider not only functionality and usage but also manufacturing and logistics, including shipping. The Organization for Economic Co-operation and Development (OECD) reports that logistics, including shipping, often constitute a business bottleneck for small and medium-sized enterprises (SMEs) [36]. Similarly, Bayes et. al. point out that “Almost 40% of the cost of selling online takes place after the customer presses the Buy button.” (*E-commerce logistics and fulfillment* [8]).

For large, bulky objects like furniture, this is a more serious issue. Since many carriers calculate shipping costs based on dimensional weight (*DIM weight*) [18], which reflects the space a parcel occupies rather than its actual mass. This results in large differences in shipping costs for objects that have the same mass but different dimensional weight, e.g., the *VIHALS* table (around 6kg) from IKEA has a DIM weight approximately 22 times higher when assembled than when disassembled.

5.3 Assembling Laser-Cut Objects is Difficult

As discussed, one approach to shipping large laser-cut objects is to ship their parts. If packed well (*Fabricaide* [48], *PacCam* [44]), these parts consume a small amount of space.

However, assembling 2D parts into the final model is a non-trivial task. Researchers have explored how to simplify this process, for example, by preventing assembly errors (*FoolProofJoint* [38]). *Daedalus in the Dark* [12], *Roadkill* [3], and *HingeCore* [4] generate

2D layouts that eliminate search and simplify joining parts; however, these layouts themselves require significant space and still consume time. *Mallet-Based Assembly* [25] proposes an algorithm that optimizes assembly orders to facilitate easier assembly using a mallet. However, in the same paper, the authors identify that non-experts have difficulty assembling large objects with concave edges, which are very common in furniture (e.g., between legs and sheets).

Researchers have also addressed this issue through computational design tools that enable users to make foldable (*Foldabilizing* [31], *Fold and Fit* [23]) or stackable objects [30]. This enables vendors to fully assemble the object and then fold it for shipping.

However, modern furniture companies, like IKEA, approach this with a technique called *flat-pack*, which introduces fewer design constraints and does not compromise structural stability (*ready-to-assemble furniture* [54]). They decompose the original object into smaller components that are preassembled by the vendor and then shipped. The consumer then assembles the object using specialized load-bearing connectors.

PÅCKER draws inspiration from flat-pack furniture to solve this problem, bringing the concept from mass production to one-offs.

5.4 Decomposing 3D Models

Decomposing a 3D model is a well-known operation, such as the Split command in *Rhino 3D* or *Blender*. Recent state-of-the-art techniques have simplified the decomposition of 3D printing models. *Dapper* [13] performs decomposition with the additional goal of packing multiple parts into a single volume by decomposing a concave *pyramidal* shape. *Chopper* [33] decomposes 3D objects to fit the volume constraints of a given 3D printer. *Chopper* further considers structural stability and avoids stress concentration by avoiding splitting the model at concave locations.

PÅCKER simplifies the decomposition of laser-cut models. Primarily, by suggesting those *split* operations to the user that create largely flat, convex components, enabling efficient packing. Splitting the 3D model increases the number of parts to assemble, making decomposition a matter of tradeoffs.

For PÅCKER, we chose a single-tool interaction design rather than automating the decomposition process [13, 33]. The reason is that automation would require users not only to provide catalogs of shipping options and material costs, but also to estimate the speed and hourly rate of the people performing the individual assembly tasks, which is not knowable in advance.

5.5 Generating Connectors to Assemble Flat-Pack Furniture

In the CAD and computational fabrication domain, a range of joint-generation approaches has been proposed, including custom CNC milling joints (*Tsugite* [28]), laser cutting (*Joinery* [55]), 3D printing [14, 34, 46], and computer-assisted manual woodworking [52]. Adding off-the-shelf connectors to a 3D model is well established in CAD. For example, *Biber* [37] allows for manual assignment of *Cam-fitting* joints to plate assemblies, facilitating modular construction. *PTC Creo* [39] provides a fastener library that automatically suggests and inserts appropriate hardware components based on

detected geometric features in a model. Similarly, Lau et al. proposed an algorithm that converts 3D models into furniture with connection assignment [29].

Building on these ideas, PÅCKER introduces a new CAD tool that automatically assigns appropriate connectors to join decomposed components.

For the connectors themselves, we again take inspiration from flat-pack furniture, where they are commonly known as *knock-down joints*. The key element is that these connectors should be load-bearing and easy to assemble. PÅCKER's connector library includes four such connectors that we have adapted for use with load-bearing laser-cut objects.

6 Generating The Internal Structure

In the following, we explain in detail how PÅCKER's underlying algorithm generates the internal structure and the design rationale in detail.

6.1 Step 1: Generating a Box Structure Inside

The main objective of PÅCKER's connector designs is to allow the connectors to take large tensile loads. PÅCKER achieves this in three logical steps: (1) PÅCKER provides the screw connectors with geometry to screw into, then (2) anchors that geometry with the rest of the component, and (3) reinforces the component, if necessary.

Figure 13 illustrates these steps. (a) We start with the simple model of a cocktail table, which the user has split into a table surface and a stand, held together using one of the aforementioned *double-ended screw connectors*. We discuss the table surface component: (b) PÅCKER creates a hole that allows the screw to enter the component through the table surface's base plate b . (c) To anchor the screw connector, PÅCKER inserts a plate perpendicular p to the screw connector (optionally multiple such plates to take large loads, see Figure 5). It adds a small pilot hole into the perpendicular plate p to help users position the connector. (d) PÅCKER surrounds the perpendicular plate p with a four-sided frame f . This frame transfers the tensile load onto the base plate b .

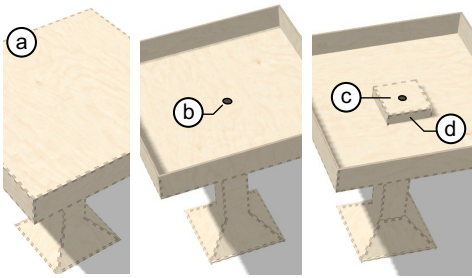


Figure 13: (a) PÅCKER generates the connector for this cocktail table by (b) placing a hole into base plate b , (c) inserting a perpendicular plate p with a pilot hole, and (d) mounting p using four frame plates f .

6.2 Step 2: Removing Redundant Geometry

The case described above, in which the connector connects to the center of a volume, is not the most common case. More commonly,

components are located close to the existing exterior structure. For example, many connectors will be located along edges or even corners.

As illustrated by Figure 14, PÅCKER detects such internal structure, allowing it to align and perform a union operation to drop redundant plates. (a) While the geometry from the previous figure requires a four-sided frame f , (b) a connector placed along a side of the component allows PÅCKER to merge its support structure with the surrounding plates, resulting in only four frames f being added. (c) Moving into a corner allows dropping another redundant plate f . (d) Attaching a connector to a beam allows dropping yet another redundant plate f , and (e) if the connector happens to have neighbors all around, as is the case, for example, with chair legs, PÅCKER places no frames f at all.

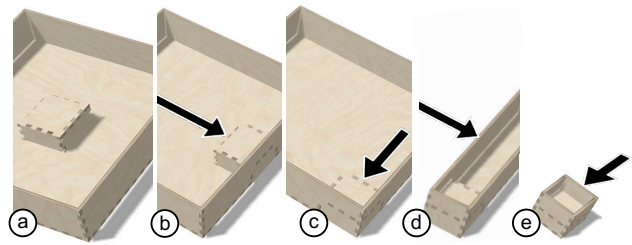


Figure 14: PÅCKER eliminates parallel plates when redundant with internal structure.

6.3 Step 3: Merging with Reinforcement Structures

Connectors generated by PÅCKER are often subjected to significant tensile loads. Conceptually, such loads may result from a force directly pulling on a component. Much larger tensile moments, however, as illustrated in Figure 15 (a), tend to occur when connectors are attached to *small* connection points, such as the table leg shown here. When applying a perpendicular load to the end of the component, the edge of the component now acts as an anchor point of a lever, converting the bending moment into a tensile force, magnified by the lever's length.

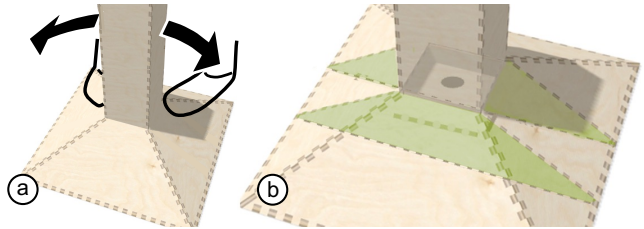


Figure 15: (a) Long appendages attached to small connection points lead to very large moments. (b) PÅCKER addresses them with internal reinforcement structures (green).

(b) To handle the resulting high forces, components often contain internal support structures (*FastForce* [5]), and by merging frame f with this support structure, PÅCKER produces sturdy results.

Alternatively, PÅCKER creates such support structures by extending two of the four plates, f_1 and f_2 , so as to cut across the component, leading to the results shown. By anchoring the internal support plates to the surrounding plates with T-joints, PÅCKER turns the component into a (double) I-beam, allowing the resulting compound of top, bottom, and parallel plates to withstand very large bending moments.

7 Selecting Connectors Based on Local Geometry

As we described in the walkthrough section (Figure 3 and Figure 4), we designed the *split* tool to be single-click. This means that, while users *may* choose to cycle through connector types by clicking the floating pop-up menu, the *default* is automatically picked by PÅCKER’s algorithm.

PÅCKER performs this as a 3-step process: (1) PÅCKER filters out geometrically impossible connectors, (2) rank remaining joints, and, finally, (3) users may manually overwrite PÅCKER’s selection by picking a lower-ranked joint from the floating pop-up menu. Here, we present this process in detail.

7.1 1. The Default: Component Mounted by Rotating

Whenever possible, PÅCKER deploys the aforementioned *double-ended screw connector*. The reason is that it uses the fewest parts, requires no tools, and thus allows for the easiest assembly. This connector is also the default for a wider range of flat-pack furniture, including IKEA’s famous LACK table (product number: 304.499.08).

As shown earlier (Figure 5), users assemble *double-ended screw connectors* by placing the connector into the pilot holes of both components and rotating.

7.2 2. Mounting Components at Multiple Connection Points

When components need to be connected by multiple connectors, a double-ended screw connector is no longer suitable. This occurs, for example, when the contact area is large (e.g., the side panel of the shelf in Figure 16) or when the components have multiple contact points (e.g., the backrest in Figure 6b). While the first double-ended screw connector can be installed by rotating the workpiece, doing so prevents the workpiece from being rotated again, making it impossible to install the remaining double-ended screw connectors.

PÅCKER therefore instead replaces the connectors with multiple *screw connectors*. As illustrated by Figure 17a, users mount *screw connectors* by accessing the screw head with a screwdriver through an additional hole PÅCKER places *across* from the connector. By default, PÅCKER uses so-called *Conformit screws* [53] that are known to be particularly load-bearing.

PÅCKER automatically analyzes the interface between split components and inserts multiple screws according to the following criteria: if the interface consists of multiple disconnected contact regions (e.g., a chair backrest), PÅCKER assigns one connector to each region; if the interface is long in one dimension (greater than 10 cm in our implementation), PÅCKER inserts two connectors;

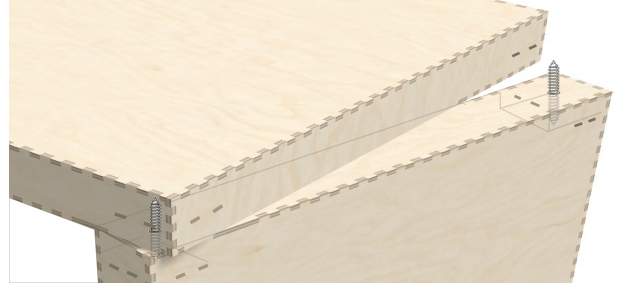


Figure 16: These two shelf components are to be connected by two connectors. After the first one is mounted, the board cannot spin, preventing the use of a double-ended screw connector.

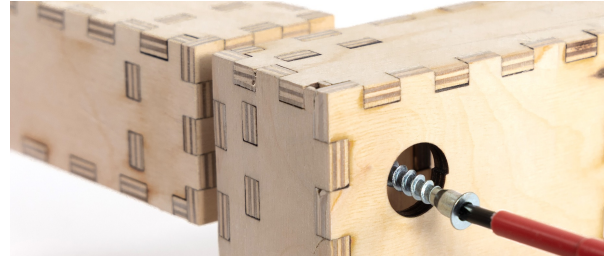


Figure 17: Users mount *single screw connectors* by accessing the screw head with a screwdriver through an additional opening.

and if the interface is large in both dimensions, PÅCKER inserts four connectors.

The internal structure PÅCKER generates for the component located at the end of the *single screw connectors* is comparable to the internal structure of a *double-ended screw connector* (Figure 5). For the component at the head of the screw, PÅCKER generates the same structure, but cuts a loose-fitting opening into the perpendicular plate to allow the screw to spin freely. If the additional openings should be in visible positions, users may choose to cover them. As illustrated by Figure 18a, PÅCKER accomplishes this by cutting a hole and a plug in the shape of an Archimedean spiral [26, 41], allowing users to tighten the plug using a screwdriver.

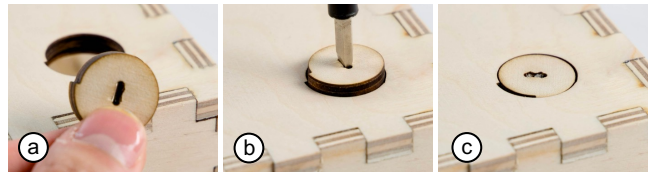


Figure 18: (a) User inserts the screws from the opposite side of the connections.

Figure 19 shows that our shelf model uses these connectors.

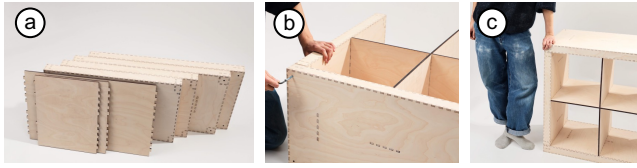


Figure 19: (a) The parts of this shelf inspired by IKEA KALLAX are held together using (b) single screw connectors.

7.3 3. Connectors For Hard-to-Access Geometry

As discussed earlier, single screw connectors require access to the “back” of the component. However, for some models, such as the one shown in Figure 20, such access is difficult.

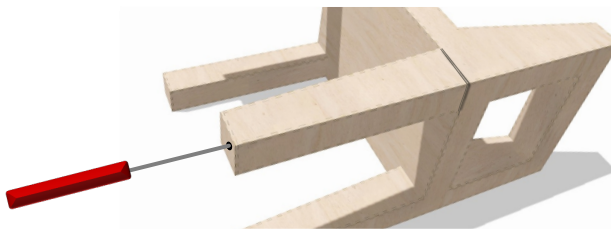


Figure 20: (a) For some models, single-screw connectors are hard to access.

PÅCKER addresses this by instead using the cam fitting connector type we already showed in Figure 9: these can be mounted *from the side*. PÅCKER generates *cam fitting* connectors as shown in Figure 21. (a) PÅCKER generates the mount for the cam from a stack of plates *orthogonal* to the base *b* each of which contains a cutout that matches the cam nut and a passage for the fastener. (b) As before, PÅCKER creates a frame *f* between the *orthogonal* plate and base *b*. This frame transfers the tensile load onto the base plate *b*. Note that the frame *f* consists of only two plates to provide access to the cam. Users optionally cover the hole using the Archimedean spiral mechanism presented earlier.

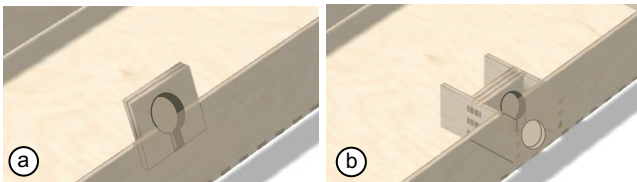


Figure 21: (a) PÅCKER generates the internal structure for cam fitting connectors by inserting plates bearing cam-shaped cutouts orthogonal to base *b* and (b) constructing a two-plate frame *f*.

7.4 4. Preventing rotation

Components with two or more connection points are inherently robust against torque. However, preventing rotation is often desirable also for components mounted using a *single* connection

point. As illustrated in Figure 22, PÅCKER prevents rotation by complementing the *single-screw* and *cam fitting* connector with a dowel that act as a catch.



Figure 22: PÅCKER allows preventing rotation by inserting a dowel parallel to single screw connectors.

7.5 Summary of Connectors Selecting Algorithm

Figure 23 summarizes the selection algorithm based on local geometry. PÅCKER runs the three tests described above to determine which connector types are possible, and suggests a dowel with a screw and cam-fit if it is only one contact point. “No side access” indicates whether there is a side from which users can access the cam, as shown in Figure 8.

	no access across	no side access	multiple points	must not spin
double ended			-	-
single screw	-			+dowel
cam fitting		-		+dowel

Figure 23: PÅCKER’s connector picker algorithm starts with the full set, then drops non-matches (‘-’) according to three hard criteria, and then picks the connector ranked highest in this list.

7.6 Split Planes Ranking Algorithm

PÅCKER suggests the split planes, which cut through the plate the user clicked and align it with the local grid system [27]. As shown in Figure 24, since this provides multiple candidates, PÅCKER ranks split planes using a (manually-tuned) weighted sum that tries to optimize two criteria: (a) Since fewer plates generally result in sturdier models [7] and minimize pre-assembly effort, PÅCKER favors split planes that create components made of fewer plates. (b) Create components that are (largely) convex. PÅCKER assesses this by computing the volume of the convex hull of the candidate divided by its volume.

8 Implementation

We implemented PÅCKER using the 3D modeling software *Kyub* [27] with a *plate-and-volume* data structure [40], which supports CSG operation of split and allows exporting a decomposed model with laser-cut joints and holes, along with assembly instructions.

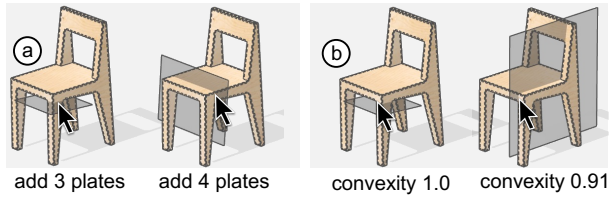


Figure 24: PÄCKER favors split planes that produce (a) fewer plates and (b) convex components.

8.1 Examples

We used the *split* tool to decompose a range of large objects from the Kyub repository for efficient flat packing. Figure 25 shows the results.

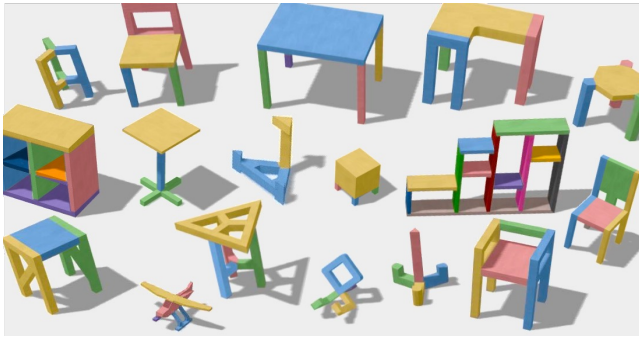


Figure 25: A selection of objects decomposed using the split tool for efficient packing.

9 evaluation

To evaluate PÄCKER’s split tool and connectors, we ran a user study on the split tool’s usability and the assembly of decomposed objects, and tested the bending resistance of each connector.

9.1 User Study of Assembly

To validate our claim that models componentized using PÄCKER are easy to assemble, we conducted a user study. Our main hypothesis was (1) all participants would assemble their models substantially faster in “post-assembly” of 3D models, and (2) participants would rate “post-assembling” and also “pre-assembling” (due to the model having fewer “concave joints” [25]) models as less demanding and frustrating than assembling from traditional plates.

We recruited 12 participants (average age = 22; 2 female) from our institution, who together assembled 24 chairs. Three of them had experience with assembling laser-cut objects. All participants completed the study within 120 mins.

Interface Conditions: There were three interface conditions. In the *post-assembly* condition, participants assembled the model from decomposed components with mechanical connectors. In the *pre-assembly* condition, participants assembled the decomposed

components from laser-cut plates. In the *control* condition, participants assembled the original model from individual laser-cut plates.

Task and Procedure: Participants performed three trials (within-subject design, counterbalanced). During each trial, participants used a mallet to assemble a 1/2 scale model of the chair shown in Figure 1, made from 6mm birch plywood. The box joints were calibrated to ensure a tight press fit. For the *pre-assembly* and *control* conditions, the 2D layouts were aligned with the state-of-the-art layout instructions [3], and the edges of the models were engraved with pairwise numbers [35] representing the assembly order to prevent deadlock during assembly. At the end of each condition, participants completed a questionnaire based on NASA-TLX.

Results: Figure 26 illustrates the assembly time for all participants. As expected, participants spent less time assembling the post-assembly, 9.9 minutes on average, while an average of 36.1 minutes was spent on assembling the traditional laser-cut parts. Differences were significant ($t(11) = 6.02$, $p < 0.001$, $d = 1.74$), and the effect was substantial: average assembly time was 3.6x faster in the post-assembly condition.

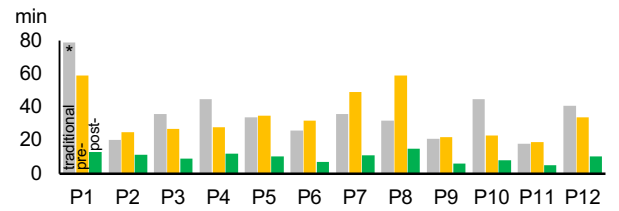


Figure 26: Participants assembled the chair model on average 3.6x faster with the post-assembly than with the traditional assembly of individual plates (* did not complete the task).

The questionnaire results are shown in Figure 27. As expected, participants rated both pre-assembly and post-assembly as less mentally- and physically demanding, and less frustrated than assembling from traditional laser-cut parts on average.

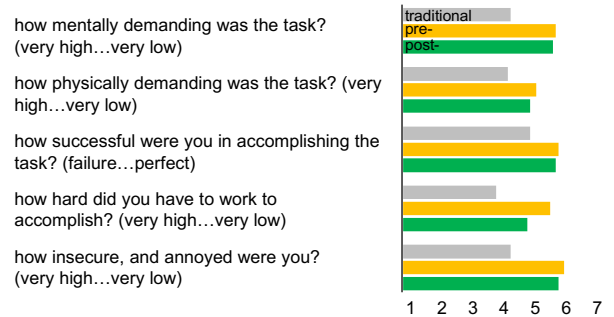


Figure 27: The results of the questionnaire that was conducted after the participants had completed the respective study.

Discussion: our study allowed us to observe componentized models built with PÅCKER in action and compare them with traditional assembly. As expected, the IKEA-style post-assembly was faster and less demanding than the traditional assembly.

While most participants successfully assembled the model using traditional parts, P1 failed to complete the task due to a “concave joint” issue [25], which required partial disassembly, and damaged parts prevented continuing assembly. P3 also mentioned that “large plates are difficult to assemble because the joints don’t align.” This is consistent with the discussion in the previous work and implies that assembling objects directly from individual plates can impose substantial challenges for consumers.

We observed that decomposing models into largely convex components is a practical strategy for vendors, as it incurs only a modest increase in assembly effort and manufacturing cost. First, participants spent a similar amount of time pre-assembling the componentized models (avg 34.3 min, SD = 12.1 min) as in the *control* condition (avg 36.1 min, SD = 9.7 min), with no statistically significant difference. The questionnaire results indicate that the pre-assembly conditions are the least mentally and physically demanding. P1 and P11 remarked that assembling the componentized models was easy because “completing each component gave them a sense of accomplishment”, which kept them motivated. P3 noted that it was “less complicated because the assembly process is all repetitive because they were all box shapes.” Second, the chair model also included six connectors containing more than six internal plates each, for a total of 38 additional plates. As shown in Figure 28, these plates are small, resulting in only a modest 10% increase in material consumption.

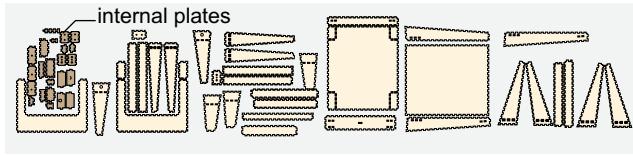


Figure 28: The componentized chairs had 38 additional plates. However, the additional plates are small, thus accounting for only 10% additional material consumption.

9.2 User Study of Split Tool

We conducted a user study to evaluate PÅCKER’s split tool and hypothesized that participants would be able to realize the intended decompositions (1) quickly, (2) with few undos, and (3) would find the tool easy to use.

We recruited 12 participants (average age = 21, 1 female) from our institution. Each participant used PÅCKER’s split tool to perform 12 trials (6 models x 2 different decompositions each). The models were a chair, a chandelier, a guitar stand, a stool, a large table, and a 5-legged table (from Figure 25). In each trial, participants were shown a decomposition and replicated it using the split tool, requiring 2 to 5 split operations. Participants then filled in a questionnaire.

Results: Our study results support all three hypotheses: All 12 participants successfully decomposed all 12 models. The average completion time was 26 seconds per model (SD = 11 seconds). The

average “undo” rate was low at 11% (SD = 5%). Participants accepted the split tool’s default suggestion in 54% of cases (SD = 9%). Participants rated the split tool as easy to use (6.1/7, SD = 0.6).

9.3 Technical evaluation of Bending-Resistance

As illustrated by Figure 29, we performed fracture testing on the four connector types. Test models were made from 6mm 5-layer birch plywood.



Figure 29: Fracture-testing apparatus.

As shown in Table 1, all screw-based connectors performed equally well. As expected, the cam fitting offers less stability.

Table 1: Breaking points of our connectors

	double-ended	single screw	screw + dowel	Cam fitting
Bending	94Nm	96Nm	98Nm	37.5Nm
Equivalent to tension	3780N	3850N	3920N	1500N

To put these numbers into perspective, we also fracture-tested a non-componentized chair, which withstood 283 Nm, with most of the difference due to connectors attached to the *center* of the contact surface between components, thus benefiting from only half the lever.

10 Conclusion

We presented PÅCKER, a software tool that makes large, laser-cut 3D objects efficient to pack and ship. Inspired by modern flat-pack furniture, PÅCKER achieves this by decomposing 3D models into multiple 3D components. Our custom *split* tool supports users by automatically selecting the most suitable split plane and connector type. The resulting models are load-bearing and can be post-assembled with consumer-level skill. Zooming out, by enabling the transport of large, load-bearing objects, PÅCKER extends users’ capabilities from selling figurines and earrings on Etsy to selling and shipping large, load-bearing objects.

As future work, we plan to combine the approach presented here with automated structural analysis.

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