Magic Furniture: Design Paradigm of Multi-function Assembly

Qiang Fu*, Fan Zhang, Xueming Li, Hongbo Fu

Abstract—Assembly-based furniture with movable parts enables shape and structure reconfiguration, thus supporting multiple functions. Although a few attempts have been made for facilitating the creation of multi-function objects, designing such a multi-function assembly with the existing solutions often requires high imagination of designers. We develop the *Magic Furniture* system for users to easily create such designs simply given multiple cross-category objects. Our system automatically leverages the given objects as references to generate a 3D model with movable boards driven by back-and-forth movement mechanisms. By controlling the states of these mechanisms, a designed multi-function furniture object can be reconfigured to approximate the shapes and functions of the given objects. To ensure the designed furniture easy to transform between different functions, we perform an optimization algorithm to choose a proper number of movable boards and determine their shapes and sizes, following a set of design guidelines. We demonstrate the effectiveness of our system through various multi-function furniture designed with different sets of reference inputs and various movement constraints. We also evaluate the design results through several experiments including comparative and user studies.

Index Terms—Multi-function design, shape reconfiguration, assembly-based modeling.

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1 INTRODUCTION

In recent years, mainly due to the space-saving advantage, multi-function or function-convertible furniture objects are getting more and more popular, especially in modern cities with limited land supply, such as Tokyo and Hong Kong. Several attempts have been made to help design the structures of reconfigurable or multi-function furniture in the past decade (e.g., [1], [2]). However, the designs of furniture objects with multiple functions often require creative ideas of human designers, even with the assistance of the aforementioned methods. Since furniture reconfiguration can be applied in a rich variety of ways, how to determine the part-level correspondence between different function-related shapes is challenging.

Even though some potential solutions have been proposed via shape segmentation and recombination (e.g., [3]), the resulting designs often involve a complicated reconfiguration process. Therefore, the designs of furniture objects with easy-to-reconfigure structures are still individualized case by case even for experienced designers. This explains why the products of multi-function furniture in the market still have limited variations. Then a question arises: does there exist a common design paradigm for multi-function assembly? Namely, such an approach does not rely on particular groups of furniture categories, but mainly focuses on the functions reflected by the furniture shapes and structures. If so, the same design process that combines one group of furniture categories (e.g., a bed and a couch), can be used to combine another group (e.g., a TV cabinet and a bookshelf).

Fig. 1. Examples of furniture designs with reconfigurable structures. Reconfigurable shapes with respect to different functionalities lead to space-saving designs. Note that in the bottom case, pushing down the table could reconfigure the furniture into a bed.

Motivated by the design of Swiss army knives, which follow a design paradigm illustrating the concept of a single object that changes configurations to address a number of problems, the design paradigm for multi-function assembly of furniture could also have reconfigurable components. When forming a certain function-related shape, the associated components are unfolded and the others are folded. For example, in the top two cases of Figure 1, the smaller function-related shapes can be folded and fitted into larger shapes for space-saving purposes. Following this paradigm,

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Fig. 2. An example of the multi-function assembly designed by our *Magic Furniture* system. **Left:** the 2D projection of such a design with movable boards and movement mechanisms. **Right:** the input reference shapes (Top) and the associated reconfiguration (Bottom), which consists of certain movable boards (highlighted in blue), to support multiple functions with a space-saving design.

methods like [4] are proposed to design multi-function assembly. However, since such a paradigm largely relies on the geometry compatibility of the inputs, the quality of the multi-function assembly depends on a case-by-case basis.

On the other hand, a certain part of the multi-function furniture can be reused and participate in more than one function-related shape (e.g., Figure 1-Bottom). If we regard all function-related shapes as independent furniture objects, aligning these objects could be a proper way to obtain the parts shared by more than one associated object. For instance, when we align a couch and a bed, the couch's seat might match the bed's mattress but the couch's armsets and back might not. This motivates us to separate the mismatched areas from the matched areas, thus dividing a certain plan of an object into pieces. In this manner, the problem of how to design multi-function assembly is converted to the problem of how to reconfigure the geometry shapes of the mismatched areas. Inspired by the computational design methods of rigid part assembly (e.g., [5]), we expect to propose a computational design paradigm for modular multi-function assembly. Even though such a paradigm might break a part of furniture into multiple pieces (similar to [1]), proper seams and support mechanisms would ensure little harm to the functionalities of the designed furniture. Besides, the pieces could be movable driven by movement mechanisms, to form various shape-related shapes across different categories of furniture. Ideally, the designed multi-function assembly should be stable, efficient and flexible to operate, and easy to manufacture.

In this paper, we study a novel problem of the design paradigm for multi-function assembly given several reference furniture objects, each providing certain functions (Figure 2), and develop the *Magic Furniture* system to tackle this problem. Our goal is to achieve an easy-to-reconfigure assembly, which has a minimum number of movable parts and can approximate the reference objects through different reconfigurations in terms of both shape and function. To achieve this, we first roughly align the input furniture objects to obtain a compact shape of the combination. We observe that in many cases the main function of a furniture object is provided by its horizontal or vertical surfaces. We thus project the aligned objects either horizontally or vertically (depending on their main functions) and use the resulting 2D projections to construct a new 3D model as the assembled multi-function furniture. We employ an evolutionary-based algorithm to reduce the number of required movable parts but still enable the functionality of each type of configuration available. To enable easy reconfiguration, we drive the movement of movable parts using properly chosen movement mechanisms with well-planned positions, including telescopic bases, folding supports, drawer rails, and hinges. This ensures the resulting design to have proper thickness when folded and adequate areas for certain boards such as a desktop. For example, in Figure 2, the left shows the top-view projection of a designed multi-function furniture with our system. The movement mechanisms (red) can drive the movable boards not only with vertical movement (grey boards), but also with horizontal movement (green boards) and flipping movement (yellow boards). In this manner, the designed furniture has multiple kinds of folding mechanisms and thus can generate various shapes and functions similar to the reference objects.

This paper makes two main contributions: 1) a computational framework to design assembly-based multi-function furniture, which can be reconfigured to different shapes and functions similar to the input reference furniture; 2) an evolutionary-based algorithm that adjusts the number and shapes of movable parts to achieve the functions of the input reference furniture while keeping the structures simple. We demonstrate the effectiveness of our method through various multi-function design results and evaluations based on user studies.

2 RELATED WORK

We first briefly review the approaches on assembly-based furniture fabrication, and discuss the trend of research on the problem of reconfiguration and the associated mechanisms. Then we review the functionality analysis and hybrid methods, especially for the design of multi-function objects, which are motivated by design and manufacturing applications.

Assembly-based Furniture Fabrication. Assembly-based modeling has been well developed with a number of approaches and systems available in recent years. Most of the proposed methods are data-driven and rely on component datasets (e.g., [6], [7], [8], [9]). Besides, the validity of assembly such as interlocking [10], [11], [12], structure [13], and stable support [14], has also been considered. As one subset of such techniques, designing fabricatable furniture is also a hot topic in the field of computer graphics. For example, Saul et al. [15] proposed to decompose a furniture object into fabricatable pieces and determine the proper placement of connectors for assembly. Umetani et al. [16] developed an interactive system to assist the exploration and design of geometrically and physically valid plank-based furniture. Schulz et al. [17] presented an interactive design-by-example system for designing 3D models that can be fabricated.

For most of the above works, reducing human efforts by automatically suggesting proper parts and structures is a key motivation, which is in the same spirit as our work from an application perspective. However, instead of relying on component datasets or structure priors for certain objects, our system creates multi-function furniture by computationally designing various boards that can be assembled to form certain function-related shapes similar to the references.

Reconfiguration Mechanisms. Lots of reconfiguration mechanisms have been investigated for the space-saving design of collapsible tools and furniture, including cutting and packing [18], stacking [19], and folding [1]. As a fundamental problem, revealing the typical part movement of man-made objects and their transmission mechanisms has attracted attention in computer graphics and computer-aided design communities. For example, Mitra et al. [20] proposed an approach for mechanical assembly visualization that incorporates motion arrows, frame sequences, and animations to convey the causal chain of motions and mechanical interactions between parts. Hu et al. [21] presented a learning-based method to model the mobility of parts in 3D objects. These efforts also encourage the design of man-made objects and indoor scenes with movable parts or objects. For example, Garg et al. [2] presented an interactive system for computational design of reconfiguration, aiming at supporting an object or a collection of objects which can be transformed between various states. Xiong et al. [22] presented an automatic method to program the layout conversion process of indoor scenes with movable objects. There are also some works that focus on objects with interactive parts, such as movable cabinet doors and drawers [23], [24].

In our work, since the movable parts of the designed furniture are assumed to be horizontally or vertically moving boards, we utilize various movement mechanisms as the constraints to ensure that the resulting assembly is easy to reconfigure and easy to fabricate. This is somewhat similar to [25], in which some modular inflatable actuators are employed to drive an array of collapsible enclosures, in order to construct various shapes. Our system adopts this concept but focuses more on multi-function furniture. Namely, we use movable boards with different shapes, instead of a standardized unit array, to ensure the simple and effective reconfiguration process. Moreover, our system also considers flipping movements besides vertical and horizontal movements for multi-function furniture design.

Functionality Analysis and Hybrid. The functionality of man-made objects are always associated with their shape, structure, and relations to other objects and humans. Some works have attempted to let the computer understand and analyze the functionality of man-made objects (e.g., [26], [27]). These works also inspire the synthesis of objects across different categories for functionality hybrid. For example, Su et al. [28] presented a method leveraging a reference shape with a complex structure to guide cross-class shape synthesis. Hu et al. [29] proposed to use functionality models for functional hybrid creation. Fu et al. [30] presented a system that leverages human poses to inspire the assembly of parts from different object categories. Song et al. [3] presented computational methods to assist the design and construction of reconfigurable assemblies for furniture.

With a similar motivation to these approaches, our work aims to design reconfigurable furniture with hybrid functionalities. In other words, we do not intend to generate a fixed shape whose parts can support different functions like [29], [30]. Instead, we prefer to employ dynamic reconfiguration processes to change the shape of the furniture for multiple functions. Our goal is thus more similar to that in [3], but we expect that the reconfiguration processes of the designs by our system could be easier to operate. Therefore, we choose the movable boards driven by the movement mechanisms for shape reconfiguration in our system, rather than the complex re-assembly approach of [3], which involves rigid transformations for individual components.

3 SYSTEM OVERVIEW

As illustrated in Figure 3, following the proposed design guidelines (last part of this section), the design process with our method consists of three stages: furniture alignment, board merging, and determining the required mechanisms (Section 4). For the given reference furniture objects, we first rank them based on their sizes from the largest to the smallest, in terms of their 2D projection areas. In the alignment stage, we intend to explore proper positions and directions for the given furniture to ensure the maximum space-saving effect. The aligned references lead to a hybrid plane combined by their 2D projections. Although the hybrid plane has been segmented into some parts with assorted shapes, the current granularity of segmentation is insufficient to merge into proper boards to fit the shapes of the references. Hence the plane is then further segmented into rectangular pieces that form the movable boards of the assembled furniture. In the board merging stage, our system merges certain boards, aiming at reducing the number of movable parts of the designed furniture, and meanwhile preserving the possibility of being reconfigured to similar shapes as the references. Finally, the system chooses the proper mechanism for each board based on its movement type, thus ensuring the functionality available and reconfigurable for the designed furniture.

Motion Mechanisms. We employ four kinds of mechanisms to tackle three types of movements. In Figure 4-(Top), we provide a CAD model to show how the mechanisms are installed on the movable boards to construct multi-function furniture (a). It illustrates that the boards with horizontal movement are driven by drawer rails (b), while the boards with vertical movement can be driven by either telescopic bases (c) or folding supports (d). Moreover, we can use hinges to expand the area of a certain board (d), thus improving the affordance of a certain reconfiguration shape, and ensuring the shape similarity to its reference furniture. This is useful when multiple function-related shapes have

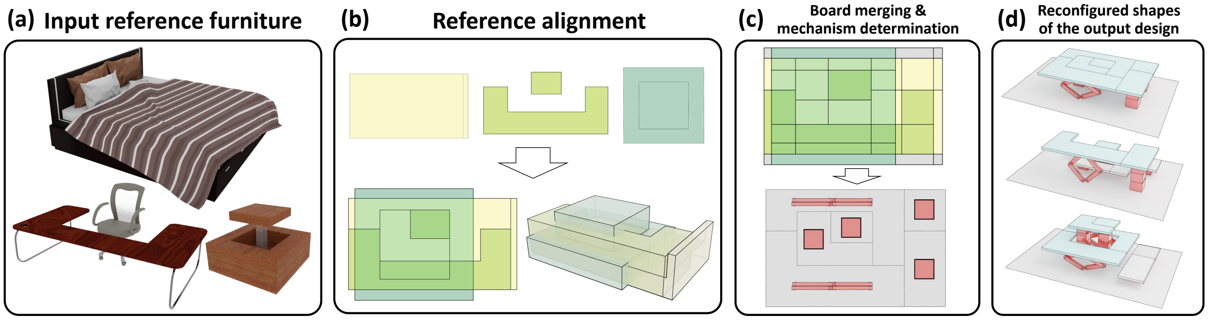

Fig. 3. Our system pipeline. Given multiple reference furniture objects (a), our *Magic Furniture* system first projects them to 2D projections ((b)-Top) and aligns them for maximum space-saving ((b)-Bottom). The aligned projections are combined with segmented boards ((c)-Top). The system then merges certain boards for simpler furniture fabrication and adds movement mechanisms on the boards for reconfiguration ((c)-Bottom). The output multi-function furniture can thus be reconfigured to different shapes and functions similar to the given references (d).

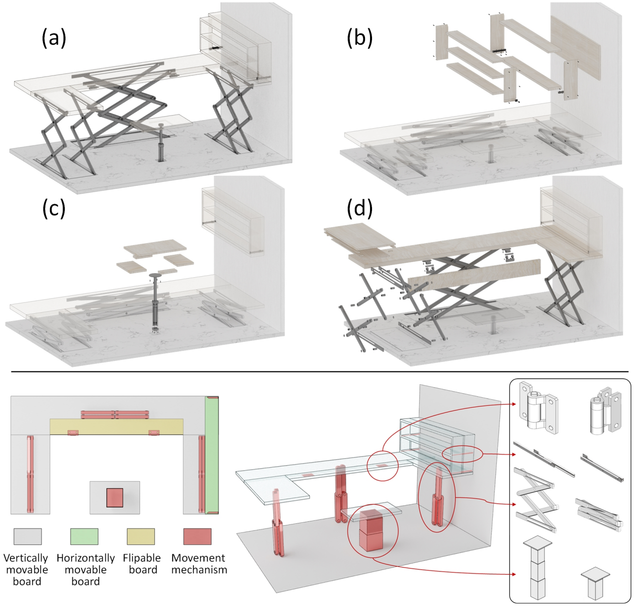

Fig. 4. **Top:** an example of a multi-function CAD model (a), and its three major parts (b-d), which have been detailed down to the level of individual screws, to demonstrate its fabricability. **Bottom:** to simplify the representation, we use such a coarse model and the associated 2D projection as an alternative in this article.

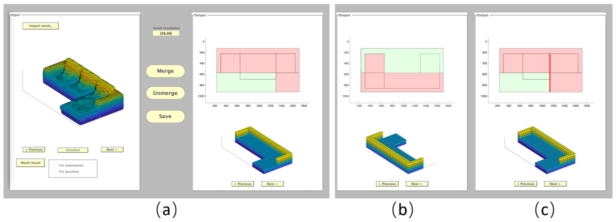

Fig. 5. Our system user interface (a) allows users to turn round the reference (b) or move certain edges (red line in (c)), thus modifying the design results.

an overlapped region that could be assigned to only one of them. We provide the item catalog of the mechanisms and the movable boards in these CAD models to demonstrate our design results are fabricable. In Figure 4-(Bottom), we simplify the representations of both the 2D projection and 3D model of the designed multi-function furniture. Such simplified representations have also been applied to the other figures in this article.

For the mechanisms we adopted, both telescopic bases and folding supports can be fixed at an arbitrary height by using a bolt to block the movement. The main difference is, a folding support can have a higher folding ratio (i.e., the ratio of the height before and after folding) than a telescopic base if the board has enough width. For boards with horizontal movement, the associated parts of the reference objects are projected in the side view. We will give more details about how to determine a proper mechanism for a board in Section 4. In addition, after the assembly configuration design, our system can also give guidelines about how to control the mechanisms to reconfigure the functionality of the designed furniture.

User Interface. We also develop a user interface to assist users in completing their designs. As illustrated in Figure 5-(a), the system UI consists of an input panel (Left) to assign the reference furniture, and an output panel (Right) to display the 2D projection of the assigned reference or the designed multi-function furniture. The output panel also shows the simplified shape of a certain reconfiguration state, and highlights the associated boards on the 2D projection as well. Besides, our system allows users to control the design process, e.g., users can disable the turn operation (i.e., rotating a projection with 180°) to impact the direction of certain function-related shapes (Figure 5-(b)). This intervention could change the structure of the design result. Users can also modify certain edges (e.g., the red line in Figure 5-(c)) on the 2D projection. This intervention would not change the final structure, but only resize certain function-related shapes.

Design Guidelines. As aforementioned, our design paradigm is to use certain movable boards to approximately construct the geometry shapes of the top-view (or side-view for components like drawers) projections of the reference furniture. Considering the space-saving purpose of the designed assembly, which needs the shapes of the given reference furniture objects to be well aligned and compact enough, the initial alignment of the given references is required. Besides, the combination of certain groups of movable boards should have shapes that are similar to the associated reference furniture. Only in this way the designed furniture can support the main functions of the reference furniture objects via reconfiguration.

On the other hand, aiming at ensuring the designed furniture to be easy-to-reconfigure and easy-to-fabricate, the number of movable boards should be as small as possible. Since each movable board should have at least one associated movement mechanism, reducing the number of boards will lead to fewer required mechanisms and thus decrease the assembly complexity of the designed furniture. We also encourage the design furniture to have more rectangular boards, which are easier to manufacture. Besides, considering the stability and load-bearing capacity of the boards, the usage of narrow boards or boards involving narrow regions should be limited. In addition, aiming at obtaining a higher folding ratio, the boards that have adequate widths should be suggested to have folding supports rather than telescopic bases. For some furniture categories including the cabinet, shelf, and backrest of couch or bed, we prefer to use sideboards with horizontal movement to construct the shapes of these furniture categories. Note that one designed furniture can have both vertically moved boards and horizontally moved sideboards. We will show several examples in Section 5.

Based on the above considerations, we propose the following design guidelines for multi-function assembly design:

- The relevant positions and directions of the given furniture objects should be determined via alignment, thus providing top- or side-view projections to generate a preliminary set of movable boards.
- The separated pieces that are created by the aligned references should be merged to form a smaller set of boards, which ensures that similar function-related shapes of the references can be constructed by these boards via reconfiguration.
- Proper mechanisms for the boards should be chosen, so that the multi-function furniture could have a high folding ratio, adequate stability, and be functionally and ergonomically correct as well.

4 METHODOLOGY

Following the design guidelines, our design flow consists of three stages, to create a new furniture object assembled by movable boards, which can be reconfigured to shapes similar to the input references.

Reference Alignment. As shown in Figure 6, our system first applies reference alignment to determine the relevant positions and directions of the given furniture objects to obtain a compact combination. Considering that multiple references could lead to too many potential combinations, for simplicity, we adopt a greedy approach by determining their positions one by one from the largest to the smallest, which leads to multiple rounds of placement. Since the directions of the input reference furniture always impact their affordance, e.g., the front direction of a couch could not face a nearby wall to ensure its affordance, we expect that the front directions of the references can be aligned by users, but our system can still turn round the 2D projections of certain references when determining their positions to obtain better board segmentation.

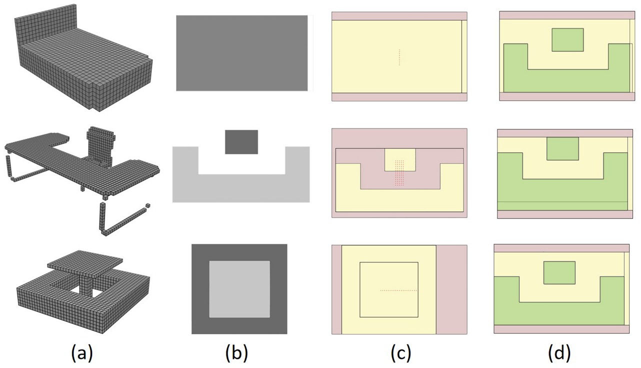

Fig. 6. By projecting the volumetric grids (a) of the input reference furniture objects to 2D planes (b) discriminated by their heights, we slid through all available sample positions (red dots in (c)) for the center of each object projection, within a range (pink background rectangle in (c & d)) of the largest length and width of all object projections' bounding boxes. The projection overlapping yields segmented pieces which can be then merged to form movable boards (green boards in (d)).

Without loss of generality, in the following discussion we assume that the user-specified movement direction of the designed furniture is vertical. We first capture the top-view projections of the input reference furniture objects, and then rank these projections by their sizes. Let $\{p_i\}$ be the set of central positions of these projections based on their bounding boxes. We expect that these projections are arranged within the range (L, W), where L and W are the largest length and width of the bounding boxes of these projections, respectively. For two or more furniture projections with different shapes, the combination would yield intersection regions, thus leading the region within the range (L, W) to be segmented into pieces (e.g., Figure 6-(d)).

Based on the design guidelines, we expect a minimum but a sufficient number of segmented pieces to form the function-related shapes of all references. However, such a goal is challenging since the impacts of reducing the number of segmented pieces on the shapes they can form are hard to formalize. For the alignment results, even though we can further segment these pieces into small rectangles which can be flexibly merged into boards with similar shapes as their reference projections, the number of segmented pieces still impacts the final merged boards. Namely, the alignment with more segmented pieces could generate more small rectangles, thus increasing the probability of shape changes. For example, in Figure 6-(d), the green boards are the merging results for certain alignments, while the bottom one has fewer shape changes compared to the other two cases. Therefore, we expect the placement of each reference projection should lead to as fewer segmented pieces as possible.

More specifically, we first uniformly sample positions on the range (L, W). For each projection, only part of these sample positions are available to ensure that the projection would be within the range (L, W) (e.g., the red dots in Figure 6-(c)). We set p_1 as $(\frac{L}{2}, \frac{W}{2})$, to denote that the central position of the largest projection is placed in the center of the range (L, W). In each round of placement, the largest projection of the rest ones is picked to traverse all its available

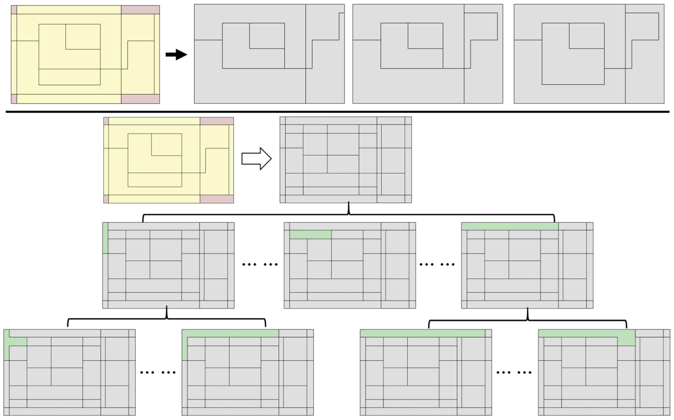

Fig. 7. **Top:** Directly merging the segmented pieces (Left) might generate boards (Right) that can hardly form shapes similar to the references. **Bottom:** So we first segment the alignment result into a plan only with rectangular boards (Top row). Then an evolutionary-based board merging (see each green board) can be performed.

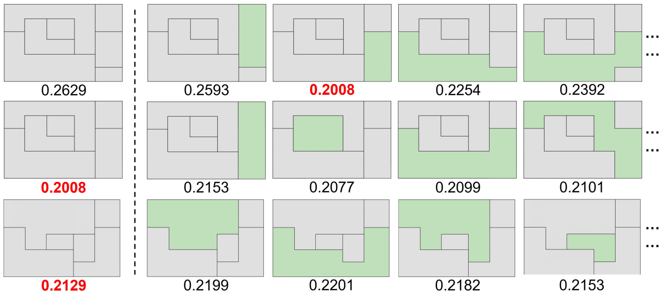

Fig. 8. Three rows of examples show the relation between an instance (Left) and its next generation with green merged boards (Right). We give the fitness energy by Equation 1 below each plan and highlight the minimum ones in red.

sampled positions. We count the number of the segmented pieces created by the intersection between such a projection and the previously combined projections. The position with the minimal number of pieces would be chosen. Then the placed projection will be combined with previously placed projections as a combination to attend the next round. We will repeat this process until all the references are aligned. Besides, we also flip all the projections except the first one during the alignment process, to determine the directions of the references as well. Note that when counting the number of the segmented pieces, we ignore tiny pieces whose area ratios relative to the largest reference are below a threshold ($\gamma_a = 5\%$ in our implementation), since such pieces can be easily merged into their adjacent large piece. For performance reasons, we adopt a greedy strategy to align the input reference furniture even though it might fail to find the globally best alignment solution.

Board Merging. After the reference alignment, we then intend to merge the segmented pieces into a small number of movable boards. However, as shown in Figure 7-Top, directly merging these pieces might easily fail to obtain proper boards that can be used to form the associated function-related shapes. To address this problem, we first further subdivide the pieces into smaller rectangular boards, and then perform board merging. This is because the subdivided rectangular boards can have more merging options, thus easily approximating the function-related shapes. Besides, in this stage, we can also consider the board shapes to ensure stability and ease of fabrication for the designed furniture. We show such an example in Figure 7-Bottom. After the subdivision of the reference alignment result (top row), we get an initial plan which can be used to generate multiple generations of instances (e.g., middle and bottom rows) through evolutionary-based board merging. Benefiting from the high segmentation granularity, such merging results can fit the reference projections better and avoid issues existing in the directly merging results.

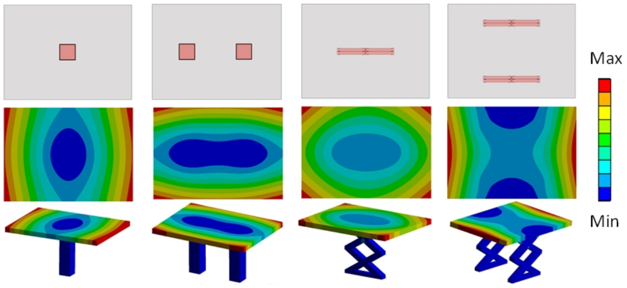

Fig. 9. Examples of improving the stability of the designed furniture by adding more folding supports or telescopic bases. We show their 2D and 3D finite element analysis results to illustrate the strains.

To explore the boards that could be merged, we employ an evolutionary algorithm in this stage. More specifically, the subdivision result that only has the rectangular boards is treated as an individual of the first generation. Since each instance of the filial generation only has a single parent generation, the evolution process only involves mutation, i.e., merging one pair of adjacent boards. Let's assume a parent generation has K segmented boards and its filial generation is a group of instances with $K - 1$ segmented boards. For each instance of the filial generation, a pair of adjacent boards in its parent are merged (see an illustration in Figure 7-Bottom). We define a fitness function to evaluate the merging results and use a threshold to eliminate undesired instances of the filial generation. For each evolution, if all filial instances of a parent are eliminated, this parent is picked up to the candidate set. Note that only the instances of the filial generation that are not eliminated could participate in the next evolution. The pseudo-code of the evolutionary algorithm is summarized below.

The fitness function is defined to encourage the instance to have as few segmented parts as possible, and preserve their functionality-related shapes similar to the reference furniture objects. In the meanwhile, we also encourage the design to have more rectangular boards and fewer thin boards or boards with thin regions, for the purpose of stability and ease of fabrication. To this end, we define the fitness function as follows:

$$\begin{aligned} Fitness(\rho) = \frac{1}{T}\sum_{t}(1 - \mathrm{IoU}(\varphi(\rho, t), \tilde{\rho}_t)) + \omega_1 K + \\ \omega_2 \frac{1}{K}\sum_{k}(-\log(\mathrm{IoU}(\tilde{\varphi}(\rho, k), b_\rho^k)) + S(b_\rho^k)), \end{aligned} \tag{1}$$

where T is the number of reference furniture objects. $\varphi(\rho, t)$ is a region combined by the boards of ρ constituting the functionality-related shape similar to the projection $\tilde{\rho}_t$ of

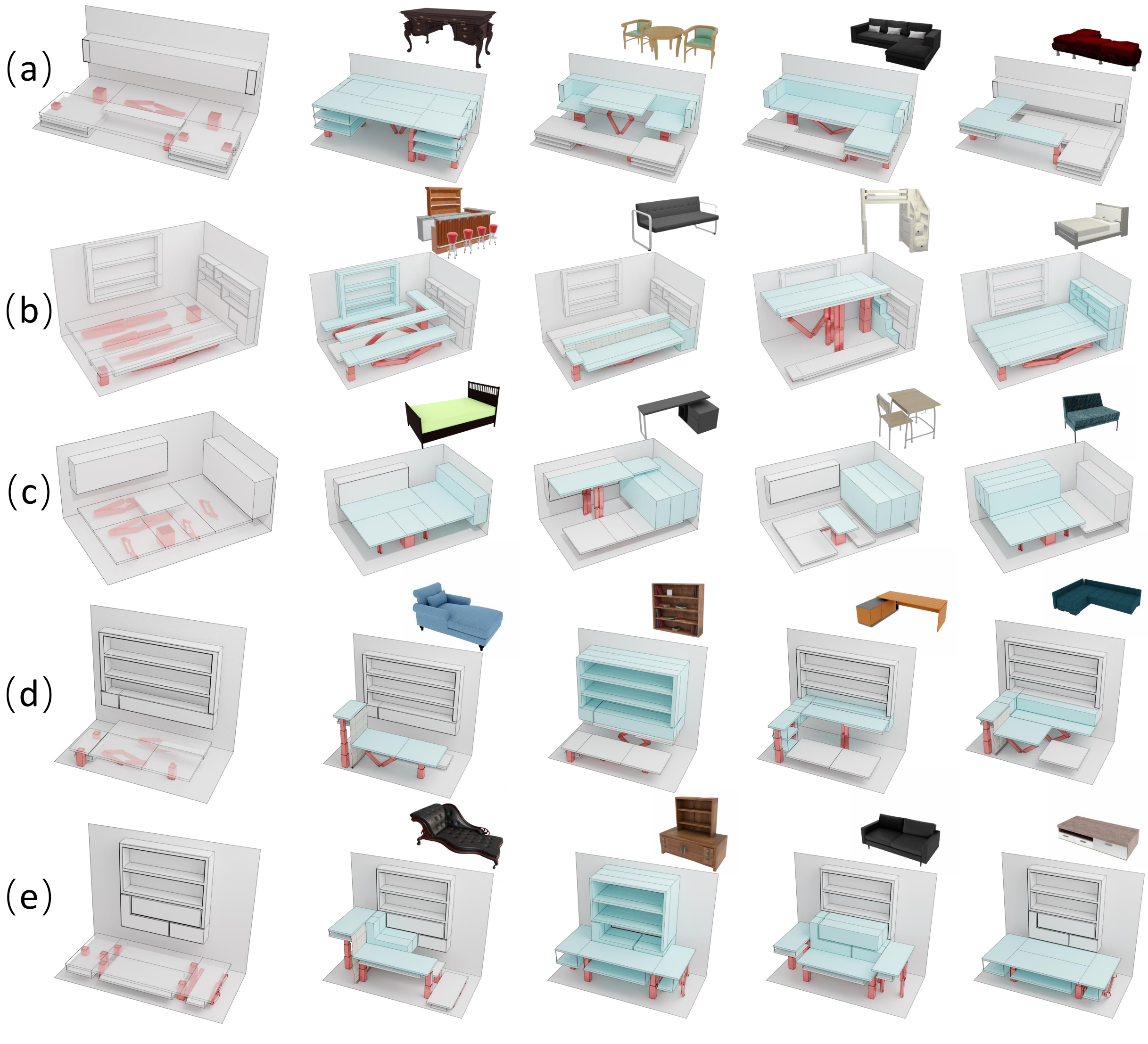

Fig. 10. Galleries of the designed multi-function furniture objects by our system. In each row, we show the folded state of the furniture (Left), four reconfigurations, and their associated reference furniture. The parts that participate in the reconfiguration are highlighted in blue.

the associated reference object. We adopt IoU (Intersection over Union) to compare the shape similarity after aligning two regions ($\varphi(\rho, t)$ and $\tilde{\rho}_t$)). We directly use the average IoU values of all pairs of the combined regions and the associated given reference furniture objects as the first term. In the second term, we set weight $\omega_1 = 0.004$ to encourage the instance to have as few boards as possible. The last term is to limit the board shape, namely, we adopt the IoU of the k-th board of ρ with respect to its bounding box b_ρ^k, and the length ratio between the short and long sides of its bounding box $S(b_\rho^k)$. The former enforces the board to approximate a rectangular shape and meanwhile avoids the board to have thin parts, while the latter penalizes thin boards. We set weight $\omega_2 = 0.1$ in our experiments. For each instance, after performing the evolutionary-based board merging algorithm to generate its filial generation, we use Equation 1 to evaluate all these filial instances. If no filial instance has lower fitness energy than its parent generation, the parent instance is then picked to the candidate set. Otherwise, the filial instances whose fitness energies are less or equal to their parent's energy can participate in the next evolution. In Figure 8, we show three examples of instances with their next generations. Based on their fitness energy, the instances in the second and third rows would be picked into the candidate sets, since they have lower fitness energy than all of the individuals in their next generations.

Mechanism Determination. Multi-function furniture could have both boards with vertical movement and boards with horizontal movement. These two types of boards can be first separately created by the aforementioned two steps, and then combined together. Since the relations between the movable boards and the furniture references are known, we can obtain all reconfigured shapes of the designed furniture. That means, the movement distances of all movable boards can be determined based on the associated surfaces on the reference furniture objects. Note that one movable board might have more than one movement distance when being reconfigured to different reference shapes. If some of its movement distances are similar, we use a single movement distance value for the board to present the associated sur-

Algorithm 1: Evolutionary-based board merging

```
Input: Evolution set $E = \rho_1^1$
Output: Candidate set $C = \emptyset$
/* $\rho_n^i$ denotes the $i$-th instance in the
   $n$-th generation                              */
$n = 1$;
$E' = \emptyset$;
while $E \neq \emptyset$ do
    for all $\rho_n^i$ in $E$ do
        $\forall$ adjacent boards $\alpha$ and $\beta$ of $\rho_n^i$, merge them
          to generate instances $\rho_{n+1}^j, j = 1, 2, \cdots, J$;
        $\gamma = Fitness(\rho_n^i)$;
        if $\forall j, \exists Fitness(\rho_{n+1}^j) \leq \gamma$ then
            $E' = E' \cup \rho_{n+1}^j$;
        end
        if $\forall j, \nexists \rho_{n+1}^j \in E'$ then
            $C = C \cup \rho_n^i$;
        end
    end
    $E = E'$;
    $E' = \emptyset$;
    $n = n + 1$;
end
return $C$;
```

faces of these reference furniture objects. This could reduce the required operations for reconfiguration.

For a board with horizontal movement, we use pairs of drawer rails on its two bottom edges. For a board with vertical movement, we first calculate the ratio between its movement distance and the maximum value of its length and width. If the ratio is below a threshold (2 in our implementation), meaning that the board has enough space to accommodate the folding supports in a folded state, we prefer to choose folding supports for this board. Otherwise, we will choose the telescopic base as the vertical movement mechanism for the board. Moreover, we also compare the reconfigured shapes to their associated reference furniture objects. If the length error of certain edges between a board and its corresponding surface on the reference is larger than a threshold (20% in our implementation), we expand the size of such a board by adding an extra board with a hinge for connection. The added board would have flipping movement, so that it could be folded if needed and thus not impact the other reconfigured shapes.

In addition, aiming at improving the stability of the designs, we increase the number of movement mechanisms for boards designed for bearing heavy loads. In Figure 9, we perform finite element analysis on the same board but with different types and numbers of movement mechanisms. In these cases, we choose wood boards (910mm × 680mm × 46mm) and steel movement mechanisms with a cube cell size of 20mm. The results show that the more movement mechanisms a board has, the less strain (blue regions) the board will have. These cases show that for larger boards, using two movement mechanisms on the sides could increase the stability, and the folding supports lead the board strains to be more uniform than the telescopic bases.

5 EXPERIMENTAL RESULTS

In this section, we first show a series of multi-function furniture designed by our system. Then, we validate the effectiveness of our algorithm with an ablation study, in which we compare the design results with and without our board merging optimization. We also conducted two user studies to demonstrate the efficiency of our system and the quality of the design results, and conducted a quantitative analysis to evaluate the functionalities of the designs. Besides, we discuss how to improve the efficiency of reconfiguration for the designed multi-function furniture.

Design Results. In Figure 10, we show five examples of the designed multi-function furniture. Each example contains both vertical and horizontal movements to ensure a space-saving folded state (Left column). In each case, we show the reconfiguration results according to the input references. It demonstrates that the functions of the references are inherited by the multi-function designs through certain function-related shapes. Note that some tiny parts of the references (e.g., armrests and backrests of chairs or couches) could be manually reserved or abandoned in their 2D projections based on the design difficulty. Besides, we add some extra components in some cases (a, d, & e) to improve the practicality of these designs. More specifically, a board with vertical movement driven by telescopic bases could have more multilayer boards to construct a shelf under a desk. We also show that elastic cloth can be used as the side boards. These refinement approaches ensure the usability of the multi-function furniture designed by our system, by considering the real-world demands in our daily life. Besides, we pick the design results from (b & e) and use the same inputs but force the system only to use vertical movements to generate the multi-function furniture. The comparisons are shown in Figure 11. We can see that using boards with vertical movements only to form the cabinets would increase the thickness of the furniture in the folded state. Such boards are not suitable to implement the function of the cabinet as well.

We test our system by inputting different numbers of furniture references. In Figure 12, we choose 8 groups of references from 1 to 4 furniture objects as the inputs to generate two series of multi-function designs. We can see that given fewer reference objects, the designed multi-function assembly would have a simpler structure. Our system can still handle more reference inputs and hybridize their functions together as a whole with a more complex structure and more components. Typically, it takes about 40s to design one multi-function furniture by our system, including 30s for user operations (e.g., import references) and 10s for system runtime. All the experiments were tested on a PC with Intel's Core i5-9400 CPU, 8GB RAM, NVIDIA 1660ti GPU, and Matlab 2020a platform.

Evaluation. In Figure 13, we compare the structures of the designed multi-function furniture with and without our evolutionary-based board merging algorithm. We can see that this stage ensures the simplification of the furniture structure to support easy reconfiguration. Furthermore, we also provide the artificial designs by a designer who has a major background in industrial design and rich experience in product design, given the same reference furniture in

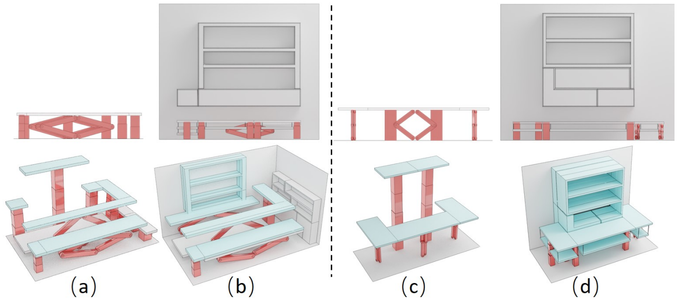

Fig. 11. Two pairs of examples to compare the designs with vertical movements only (a & c) and hybrid designs with both vertical and horizontal movements (b & d). Note that two cases in each pair have the same input references (see Figure 10-(b&e)).

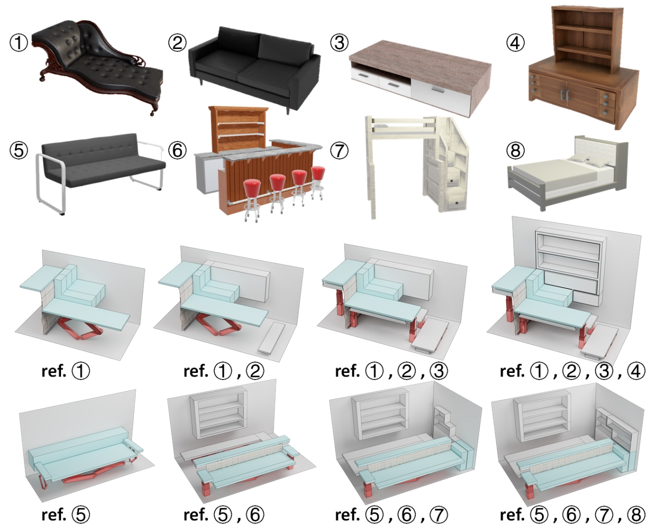

Fig. 12. From some reference furniture with indices (Top two rows), we show two series of design results (Bottom two rows) given different combinations of references (1 to 4 references from left to right). Note we show the function-related shapes of the designs about the same reference in each series.

this comparison (Figure 13-Bottom). To allow a comparison between our results and the results of a human designer, we told the designer about the idea of using composable boards and movement mechanisms to reconfigure the shapes of the furniture for different functions. We also showed the designer several examples created with our system. The designer was asked to manually move the 2D projections of the references, and adjust their configurations to create the 2D projection of the multi-function furniture. The results show that, under the design concept of using movable parts for reconfiguration, our system can create multi-function furniture competitive with the designs of the designer.

We further evaluate the necessity that our system considers boards with vertical, horizontal, and flipping movements, by conducting a user study. We invited 13 graduate students (9 females and 4 males) who majored in digital media technology and had basic industrial design backgrounds. The participants were told the idea of multi-function assembly, and then asked to review pairs of designs (i.e., 3D models of the designed furniture and their reconfigurations) by choosing the better one from each pair. Both two designs in each pair are created by our system, the

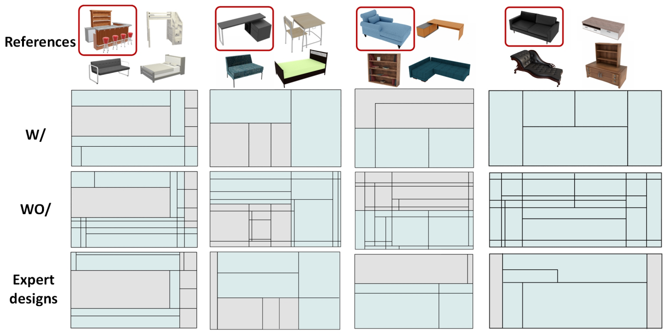

Fig. 13. Comparisons of the 2D projections between our designs with (W/) and without (WO/) board merging, and expert-designed results, with respect to the same group of references (top of each row). In each case, we show one function-related shape formed by boards highlighted in blue, according to the reference object (inside the red box).

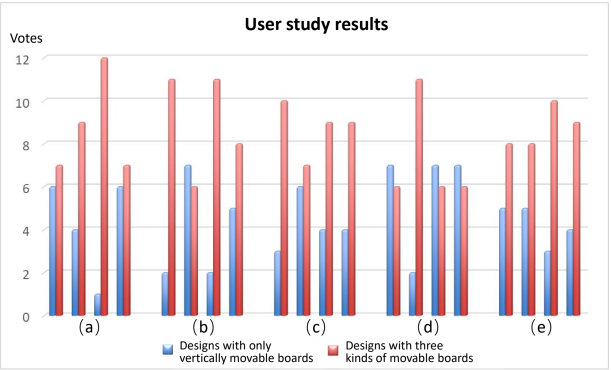

Fig. 14. Voting results of all pair-wise designs with only vertically movable boards and with three kinds of movable boards. Note that the indices from (a) to (e) denote the corresponding designs in Figure 10 and the four pairs of comparisons in each group correspond to the reference shapes from left to right of Figure 10.

difference is, we use boards with only vertical movement to generate one design, while using boards with vertical, horizontal, and flipping movements to generate the other one. Note that the orders of the furniture designs in the pairs were random. We summarized the results in Figure 14, in which we can see that designs with three kinds of movable boards got 170 votes comparing to 90 votes got by the results with only vertical movable boards. This validates the necessity of adopting three different kinds of boards in our system, and demonstrate that the more kinds of movable boards are adopted, the higher quality the designed furniture could be.

Functionality. We assume the functionality of furniture depends on its shape. To demonstrate the functionality of the multi-function furniture designed by our system, we calculate the shape similarities between the reconfiguration of a certain design result and the associated references, by using the examples in Figure 2. Specifically, we align a certain reconfiguration shape constructed by the blue boards and the reference shape, and then calculate the IOU between their per-component Oriented Bounding Boxes (OBBs). The IOU results are 0.89, 0.89, 0.74, 0.96, and 0.90 from left to right in Figure 2-Right. Note we ignore the chair's back and armrests and bed's head for the per-component OBBs of the reference shape in the second and last cases, respectively.

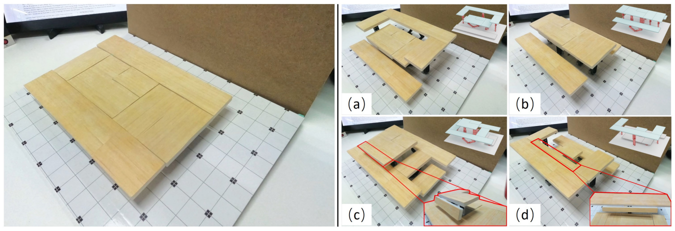

Fig. 15. A prototype of one designed multi-function furniture. We show its initial folded state (Left), and four reconfiguration results (Right). Note that in (c & d), the boards with hinges are zoomed in with red boundaries, to highlight the flipping process.

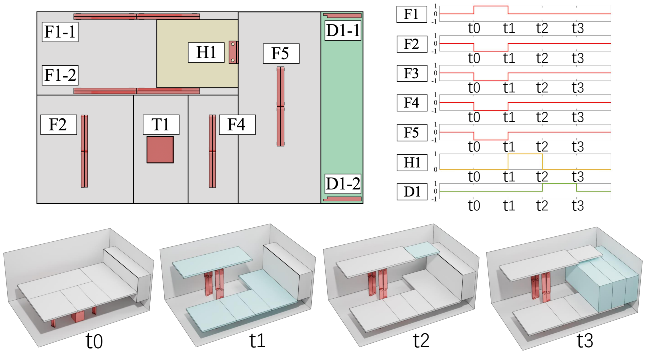

Fig. 16. **Top:** The 2D projection of a multi-function design (Left), and its mechanical control sequence diagrams (Right) including move forward/back and stop (1/-1 and 0, respectively) for telescopic bases (T), folding supports (F), and drawer rails (D), as well as the open (1) and close (0) states of hinges (H). **Bottom:** we show its reconfiguration at the time of t0, t1, t2, and t3. Note the moving boards in each reconfiguration state are highlighted in blue.

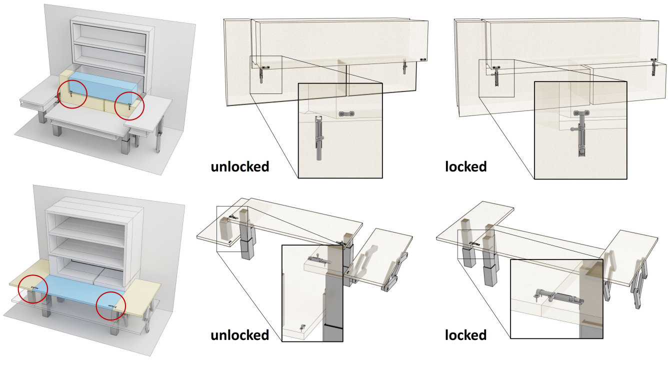

Fig. 17. Two examples show the usage of locking mechanisms that connect boards with consistent movements. Note that the latches in the red circles connect the blue and yellow boards, thus making them move together.

The results show that the multi-function furniture can reconfigure to a very similar shape as the reference furniture, thus preserving functionality. In Figure 15, we show a prototype of multi-function furniture. Based on the structure of the designed furniture by our system, we fabricate miniatures of the boards and movement mechanisms with plastics. Such a prototype validates the reconfiguration of the designed multi-function furniture in the real world and ensures our results are fabricable.

Mechanism Deployment Sequence. After determining the movement mechanisms, the mechanism deployment sequence can be obtained based on the reconfiguration of the designed furniture. For example, in Figure 16, we show a mechanism deployment sequence that drives the designed furniture to reconfigure from a bed (in t0) to a desk (in t1), and then to a desk with a side cabinet (in t3) through an intermediate state (in t2). From the chart of the sequence (Top-Right), we can see how the states of the mechanisms impact the shape and functionality of the designed furniture (Bottom). To improve the reconfiguration efficiency, the mechanism deployment sequence should perform efficiently, like letting more boards move simultaneously. Mechanisms that support cooperative movements like locking and linkage mechanisms, could be helpful. Locking mechanisms can be used for adjacent boards with movements in the same directions and have the same start and stop positions. For such boards, locking mechanisms can be installed between their common sides. Once locked, two boards can move together; otherwise, the boards move independently. On the other hand, linkage mechanisms can be used between adjacent boards that only have movements in opposite directions. In this manner, the movement of one board could lead the other board to move in the opposite direction. For example, in Figure 17, by using the locking mechanisms to connect two adjacent boards, moving one board can also drive the movement of the connected board. In Figure 18, we show how to use linkage mechanisms to drive a pair of boards in opposite directions. These movements have been validated through simulation with Solidworks software.

6 CONCLUSION

In this paper, we have developed a novel system for a design paradigm of assembly-based multi-function furniture. The proposed system leverages multiple given furniture 3D models as the references to create a new 3D model assembled by composable and movable boards. By setting telescopic bases, folding supports, drawer rails, and hinges on the shape, the designed furniture can be reconfigured similarly to the given references in terms of both shape and function. We present an optimization algorithm to determine the number and sizes of the required boards to make the structure of the designed furniture as simple as possible, able to support the reconfiguration for functionality conversion, and guarantee the structural stability of the function-related shapes. We have conducted various experiments to evaluate the efficiency of our system, as well as the quality of the designed multi-function furniture.

Limitations. Our current system still has several limitations. First, for simplicity, we have focused on three types of movements (i.e., vertical, horizontal, and flipping movements), and each board could have only one movement type. Even though this ensures the design to be easy-to-reconfigure and easy-to-fabricate, the structural variations of the designed furniture are thus limited. Extending the structure of our results with more reconfiguration modes would be helpful. Besides, the movable boards can also have more complex mechanisms that support multiple types of movements for more artful designs. On the other hand, in our current results, reconfiguration of boards with vertical movements might block the sideboards with horizontal

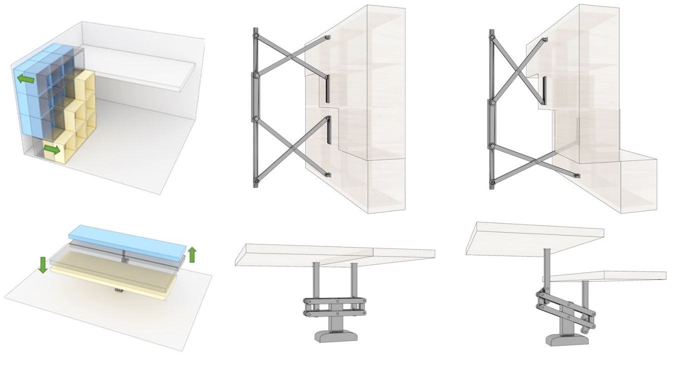

Fig. 18. Two examples show the usage of linkage mechanisms that drive a pair of boards in opposite directions simultaneously.

movements when belonging to the same furniture. This needs users to adjust the shape of horizontal movement sideboards or movement sequences to avoid collisions. Systems like [2] are helpful to tackle this problem.

Second, the current system cannot tackle internal and side structures beyond the movable boards. Additional user intervention is required if we want to determine the internal and side structures of the designed furniture. As we previously discussed in Figure 10, some approaches might be useful to address this problem, like combining our results with multilayer boards driven by the same telescopic base, and using elastic cloth as the side boards. Establishing the relations between the semantic labels of certain parts and required boards could relieve these user interventions. Moreover, for some boards with supporting functions, e.g., chair seats and bed mattresses, more movement mechanisms or extra components such as legs might be required on certain shapes to enhance the stability of the furniture.

To sum up, our method mainly focuses on shape-related functionality. However, in real industrial fabrication, the problem of functional assembly design is much more complex. Factors such as stability, mechanical complexity, and material would influence the practicality and comfort of the designed furniture. In the future, we plan to extend our system with more kinds of folding mechanisms, and enable movable boards to have more than one movement type for reconfiguration. We are also interested in exploring proper 3D shapes from a large-scale furniture database to reveal potential combinations for multi-function assembly, rather than directly giving the reference furniture as input. Besides, leveraging industrial design knowledge to address the problem of material suggestion or stability analysis is also worth studying. We believe that the design paradigm of multi-function furniture would yield more and more useful industrial products for our daily life.

ACKNOWLEDGEMENTS

We thank the anonymous reviewers for their constructive comments. This work was supported by a grant from the NSFC (No.61902032).

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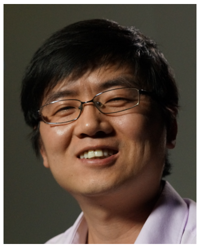

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