# Creating novel furniture through topology optimization and advanced manufacturing

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**Abstract**

**Purpose** – Furniture plays a significant role in daily life. Advanced computational and manufacturing technologies provide new opportunities to create novel, high-performance and customized furniture. This paper aims to enhance furniture design and production by developing a new workflow in which computer graphics, topology optimization and advanced manufacturing are integrated to achieve innovative outcomes.

**Design/methodology/approach** – Workflow development is conducted by exploring state-of-the-art computational and manufacturing technologies to improve furniture design and production. Structural design and fabrication using the workflow are implemented.

**Findings** – An efficient transdisciplinary workflow is developed, in which computer graphics, topology optimization and advanced manufacturing are combined. The workflow consists of the initial design, the optimization of the initial design, the postprocessing of the optimized results and the manufacturing and surface treatment of the physical prototypes. Novel chairs and tables, including flat pack designs, are produced using this workflow. The design and fabrication processes are simple, efficient and low-cost. Both additive manufacturing and subtractive manufacturing are used.

**Practical implications** – The research outcomes are directly applicable to the creation of novel furniture, as well as many other structures and devices.

**Originality/value** – A new workflow is developed by taking advantage of the latest topology optimization methods and advanced manufacturing techniques for furniture design and fabrication. Several pieces of innovative furniture are designed and fabricated as examples of the presented workflow.

**Keywords** Topology optimization, Advanced manufacturing, Furniture, BESO

**Paper type** Research paper

## 1. Introduction

Furniture has existed since the very beginning of human civilization. Furniture can be made by using natural materials such as rocks and tree stumps (Smardzewski, 2015). The design of furniture reflects not only the culture and aesthetics (Fitzgerald, 2018) but also the design approach, materials science and manufacturing technology (Lawson, 2013). With the development of three-dimensional (3D) printing technology, innovative furniture designs have been developed using the latest advanced manufacturing methods (Bhooshan *et al.*, 2017).

Advanced manufacturing fabricates products with state-of-the-art technologies, which can be classified as additive manufacturing (AM) and subtractive manufacturing (SM) techniques. AM produces products by stacking materials with precise and digital control (Sachs *et al.*, 1993). Common materials used in AM are plastics, resins, ceramics, concrete, rubber and metals. The advantages of AM include rapid prototyping, low material waste, less design constraints and multi-material fabrication (Attaran, 2017). Different from AM, SM which represents controlled machining and material removal processes typically uses cutting, burrowing or milling for production. SM has considerable advantages in manufacturing large-scale structures such as building components. SM is much faster than AM for flat-pack product manufacturing. Besides, it supports a wider range of materials, such as wood, stone and metal (Bar-Cohen, 2018). Both AM and SM have been widely used in fabricating, e.g. furniture, mechanical products and architectural facade.

When producing 3D-printed chairs, designers may pay more attention to aesthetics or ideas than cost. Huang (2016) combined principal stress analysis, asymptotic stability, and ergonomics to design the Durotaxis Chair. The famous Zaha Hadid Architects designed the Rise Chair through fused filament fabrication (FFF) printing technology (Schumacher and Andia, 2018). However, the porous, free-form designs of these chairs lead to high cost and material waste.

Robots are used for fabricating furniture to lower the cost and improve material utilization. The Dark Satine Chair designed by Xuberance's designers was produced by the robotic AM (UPM Biocomposites, 2019). However, robots can only print structures with no supports and small overhang angles, which limits the structural design significantly. Meier (2011) made several expanded polystyrene chairs by hot wire cutting using a robotic arm. However, such a SM technique is not capable of fabricating chairs with complex geometries. Aouf (2017) tried to avoid this problem through globally continuous printed paths. He designed and manufactured the Voxel Chair

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through robotic AM. However, this technique results in a rough surface.

Structural topology optimization has been a powerful design tool for industry designs. Some of the most widely used topology optimization techniques are the solid isotropic material with penalization method (Bendsøe, 1995; Sigmund, 2001; Sigmund and Maute, 2013), the evolutionary structural optimization method (Xie and Steven, 1993; Xie and Steven, 1997), the bi-directional evolutionary structural optimization (BESO) method (Huang and Xie, 2009) and the level-set method (Wang *et al.*, 2003; Allaire *et al.*, 2002). The aim of topology optimization is to maximize the structural performance under certain conditions. Through optimization, the structural performance can be guaranteed and the material cost can be saved. The original intention of reducing low efficient materials are the same for both topology optimization and evolution of biological structures in nature. Topology optimization has not only been applied in engineering structural design but also for exploring the optimization mechanisms of biological materials (Zhao *et al.*, 2018; Zhao *et al.*, 2020a, 2020b). Apart from the advantages of achieving high structural performance and low material usage, beautiful structure appearance is also a by-product from topology optimization. Several buildings and landmarks have been applied with topology optimization for architecture design (Aage *et al.*, 2015; Donofrio, 2016). The BESO technique has been widely adopted due to its concise and easy-to-understand algorithm. It can produce 0–1 results where there is no transitional materials in the final design (Xia *et al.*, 2018; Huang and Xie, 2010). Recently, complex constraints on, e.g. the structural complexity/connectivity and the maximum principal stress have been successfully integrated into the BESO-based topology optimization (Zhao *et al.*, 2020a, 2020b; Xiong *et al.*, 2020; Chen *et al.*, 2021). Novel approaches have developed based on the BESO method for generating diverse and competitive designs (He *et al.*, 2020; Yang *et al.*, 2019; Xie *et al.*, 2019).

A combination of topology optimization and advanced manufacturing will provide an excellent platform for designing and fabricating high-performance and innovative furniture. The demand of customization and rapid prototyping for furniture will be more rigorous.

In this work, we propose a new workflow for furniture design and prototyping. Parametric modelling, custom optimization and fast prototyping are included in this workflow. The proposed workflow can be applied to other industrial designs.

## 2. Methodology

The workflow of the furniture design process is presented below.

### 2.1 Initial design

The initial design of a piece of furniture is performed before topology optimization. Various design factors should be taken into account in this stage, including the size, material, function, budget, quantity, manufacturing, storage and transportation. These factors can help determine the general feature of the furniture.

The initial model can be created through the following steps. As shown in Figure 1(a), we first create a low-poly mesh model using the hierarchical subdivision surface modelling technology (Bhooshan and El Sayed, 2011). This can be done by multiple computer-aided design (CAD) tools and Rhinoceros (Rhino 7) is adopted here. The quadrilateral meshes can realize simple and fast geometry modification. Catmull–Clark subdivision scheme (Stam, 1998) is then used to smooth the model by generating a high-poly mesh, as shown in Figure 1(b). The initial model should be simple and plain to allow more design freedoms for topology optimization to produce an efficient design.

### 2.2 Topology optimization

The BESO-based framework is adopted for topology optimization for furniture. The objective is to maximize the structural stiffness. The problem statement is to minimize the structural compliance under prescribed loading and boundary conditions. By discretizing the design domain into $n$ elements, the problem can be described as:

$$\min_{x} : \quad C(x) = \frac{1}{2}\mathbf{U}^{\mathrm{T}}\mathbf{K}\mathbf{U} \tag{1}$$

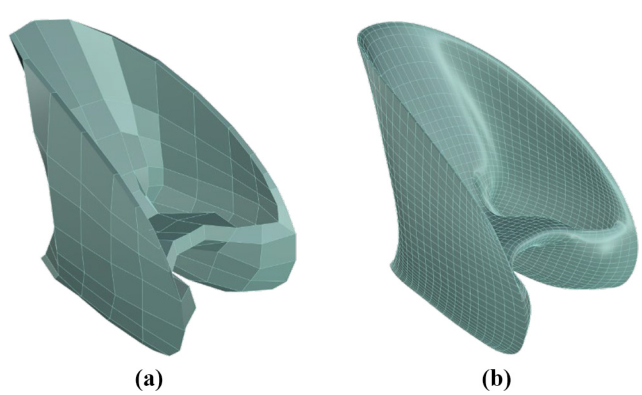
$$\begin{aligned} \text{s.t.} \ &: \mathbf{K}\mathbf{U} = \mathbf{F} \\ &\frac{\sum_{i=1}^{n} x_i v_i}{\sum_{i=1}^{n} v_i} = \hat{v}_{\mathrm{f}} \\ &x_i = x_{\min} \ or \ 1, \quad i = 1, 2, 3, \ldots, n \end{aligned} \tag{2}$$

where $C$ represents the structural compliance; **K, F** and **U** are the global stiffness matrix, the force vector and the displacement vector, respectively; $x_i$ and $v_i$ represent the design variable and volume of element $i$; $\hat{v}_{\mathrm{f}}$ is the target volume fraction. An element is solid if its design variable is equal to 1 and it is void if the design variable is equal to $x_{\min}$. Denote Young's modulus of the material as $E_0$. The Young's modulus of element $i$ is calculated as:

$$E_i = x_i^p E_0 \tag{3}$$

where $p$ is a penalization number.

**Figure 1** Meshes of the initial design: (a) low-resolution mesh, (b) high-resolution mesh



The optimization is implemented through an iterative process. The volume of material is set as 100% at the beginning. Denote the iteration number as $k$, the volume of material in the iteration $k+1$ is expressed as:

$$v_f^{k+1} = \max\left[v_f^k(1-\sigma),\ \hat{v}_f\right] \tag{4}$$

where $\sigma$ is the evolutionary rate.

The design variables are updated in each iteration according to the elemental sensitivities. The sensitivity numbers are derived from equations (1-3) and normalized by the elemental volumes. The sensitivity number of element $i$ is expressed as:

$$\alpha_i = -\frac{1}{pv_i}\frac{\partial C(x)}{\partial x_i} = \begin{cases} \frac{1}{2}\mathrm{u}_i^{\mathrm{T}}\mathrm{k}_0\mathrm{u}_i/v_i & \text{where } \mathrm{x}_i = 1 \\ \frac{1}{2}\mathrm{x}_{\min}^{p-1}\mathrm{u}_i^{\mathrm{T}}\mathrm{k}_0\mathrm{u}_i/v_i & \text{where } \mathrm{x}_i = x_{\min} \end{cases} \tag{5}$$

where $\mathrm{k}_0$ is the elemental stiffness matrix and $\mathrm{u}_i$ the nodal displacement vector of element $i$.

The following filtering technique is used to achieve mesh-independent solutions and to avoid checkerboard patterns:

$$\hat{\alpha}_i = \frac{\sum_{j=1}^{n}\omega_{ij}\alpha_i}{\sum_{j=1}^{n}\omega_{ij}} \tag{6}$$

where $\omega_{ij}$ are the weight factors. $\omega_{ij}$ is calculated as

$$\omega_{ij} = \max(r_{\min} - d_{ij}, 0) \tag{7}$$

where $r_{\min}$ is filter radius and $d_{ij}$ the distance between element $i$ and $j$.

To improve the convergence of the optimization, the sensitivity of each element is averaged with its value in the previous iteration:

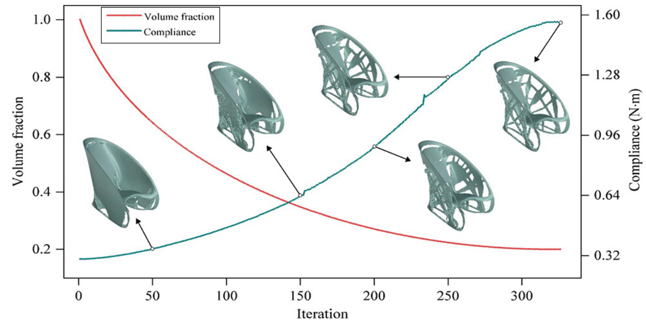
$$\overline{\alpha}_i = \frac{\hat{\alpha}_i^k + \hat{\alpha}_i^{k-1}}{2},\ k \geq 2 \tag{8}$$

Once the following convergence criterion is satisfied, the optimization will be terminated:

$$\frac{\left|\sum_{t=1}^{N}\left(C^{(k-t+1)} - C^{(k-N-t+1)}\right)\right|}{\sum_{t=1}^{N}C^{(k-t+1)}} \leq \delta_{err} \tag{9}$$

where the integral number $t$ is here set to be 5, $C^{(k-t+1)}$ is the compliance in the $(k-t+1)_{th}$ iteration, and $\delta_{err}$ is an allowable convergence error. Figure 2 shows the history curves of an optimization process for the armchair. The red curve shows the variation of the volume fraction of material and the blue curve shows the variation of the structural compliance. Both curves become stable at the end of the form-finding process.

**Figure 2** Evolution histories of mean compliance and volume fraction when BESO starts from initial design




### 2.3 Multiple load cases

The loading conditions of a piece of furniture are not always the same. More than one loading conditions need to be considered. Multiple load cases optimization can be realized by adjusting the objective function, which is modified to be the average of the compliances for all load cases (Huang and Xie, 2010). The objective function and sensitivity function can be rewritten as:

$$\min_x : \quad C(x) = \sum_{z=1}^{m}\lambda_z C_z \tag{10}$$

$$\alpha_i = -\frac{1}{pv_i}\frac{\partial C(x)}{\partial x_i} = \begin{cases} \frac{1}{2}\sum_{z=1}^{m}\lambda_z\left(\mathrm{u}_i^{\mathrm{T}}\mathrm{k}_0\mathrm{u}_i/v_i\right)_z & \text{where } \mathrm{x}_i = 1 \\ \frac{1}{2}\mathrm{x}_{\min}^{p-1}\sum_{z=1}^{m}\lambda_z\left(\mathrm{u}_i^{\mathrm{T}}\mathrm{k}_0\mathrm{u}_i/v_i\right)_z & \text{where } \mathrm{x}_i = x_{\min} \end{cases} \tag{11}$$

where $m$ is the number of load cases and $\lambda_z$ is the weight factor for each load cases.

### 2.4 Postprocessing

The result of topology optimization, shown in Figure 3(a), consists of a large number of irregular tetrahedral elements and a serrated surface. Such elements can produce many non-manifold edges and vertices, which are not suitable for manufacturing directly. Postprocessing is required to obtain a smooth solution to meet the surface quality requirement of products. Firstly, we create a voxel-based signed distance field from tetrahedral elements (Osher and Fedkiw, 2003). Next, an isosurface extraction method, Marching Cubes, is used for surface reconstruction to gain a manifold model [Figure 3(b)] (Lorensen and Cline, 1987). The above surface reconstruction may result in many irregular triangular facets and disorder vertex distribution. Further, functional and/or aesthetic improvements are made by using a pure quadrilateral mesh model, as shown in Figure 3(c). This is realized by using the QuadRemesh function in Rhinoceros (Rhino 7). Then, the model can be easily customized with common CAD software. It

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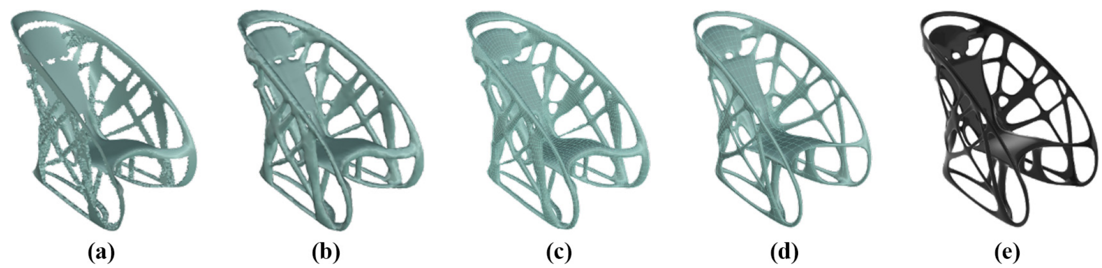
**Figure 3** Postprocessing of the optimized result: (a) optimized result, (b) isosurface extraction, (c) quad remeshing, (d) re-modelling and (e) rendering




is recommended that finite element analysis is performed to check the structural performance after the above design modifications. A satisfactory design should achieve an excellent balance among structural performance, functional requirements and aesthetics. Figures 3(d, e) shows an example of the final design.

### 2.5 Manufacturing

The physical prototype of the digital design model is fabricated. Firstly, either AM or SM will be chosen as the manufacturing technique according to the topology and material of the design. AM is able to rapidly produce complex 3D structures and very little material will be wasted during the manufacturing process. However, AM usually has limitations such as small operating range, slow manufacturing process for large scale printing, costly for mass production and limited material selection. By contrast, SM has superiority in mass production, especially for flat-pack design. SM also has a broader range than AM. Nevertheless, SM usually leads to more material wastes than AM and has many fabrication constraints in making 3D hollow structures. When selecting the manufacturing method, we need to consider the budgets, materials, time, accessibility and geometry features of the designed furniture. The designed model can be split up accordingly with a suitable connection and assembling scheme. Once the raw furniture is fabricated and assembled, surface treatments such as sanding, polishing and painting can be applied to enhance the surface quality and provide special surface features.

To clearly demonstrate the proposed workflow, a diagram is presented in Figure 4.

New furniture can be designed and fabricated through the following steps:

- Generate a coarse initial furniture model using a common 3D modelling software.
- Import the initial model to a topology optimization platform (Ameba on Grasshopper is used here) and apply loading and boundary conditions. With the optimized result obtained from topology optimization, smooth the model via Laplacian smoothing.
- For a two-dimensional (2D) planar design, extract boundary curves and conduct the detailed design directly for functional or aesthetic improvement. For a 3D design, extract isosurface to gain a manifold model. Then, change the manifold model to a pure quadrilateral mesh one. Next, conduct detailed design directly on the 3D quadrilateral mesh model for functional or aesthetic improvement.
- Choose the split and connection scheme of the model according to manufacturing, transportation and storage factors.
- Choose an AM/SM technique according to the manufacturability, time, material, accessibility and costs. Then, fabricate the furniture.
- Finalize the furniture by sanding, assembly and painting.

**Figure 4** The overall workflow for design and manufacturing

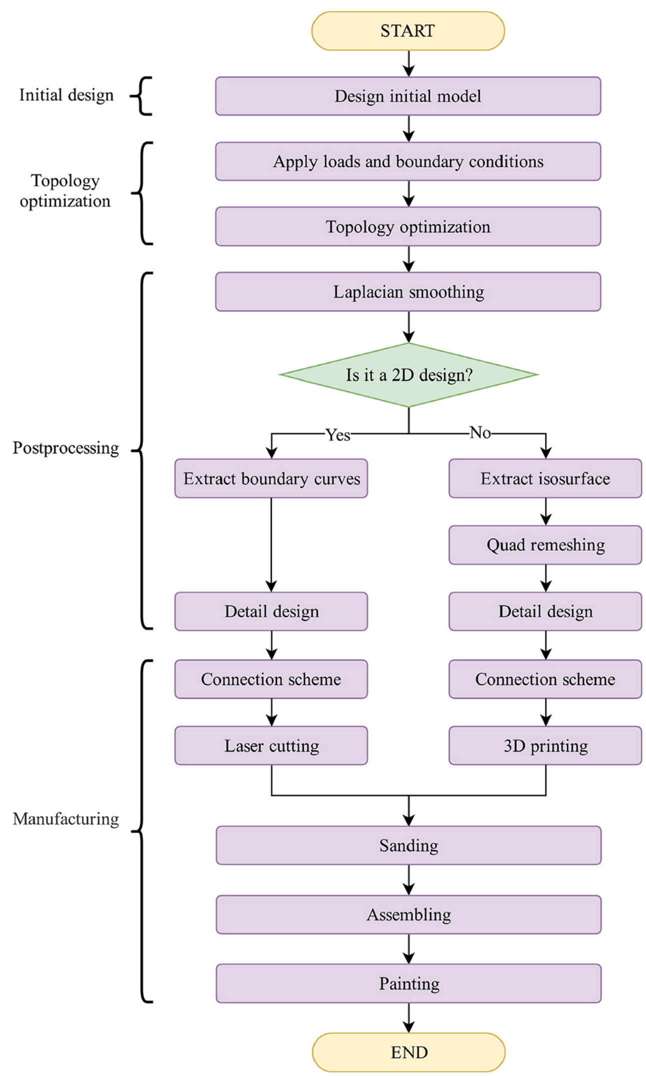
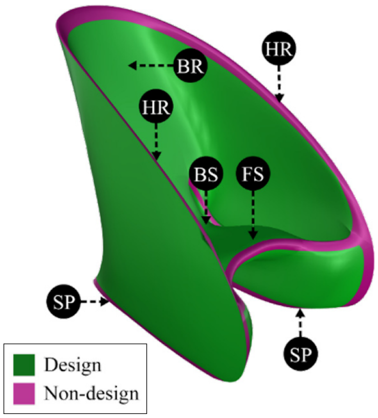


**Figure 5** Loading and boundary conditions for the Jue chair




## 3. Results

In this research, several prototypes are fabricated. A detailed description of the utilization of the workflow are provided.

### 3.1 Jue chair

An armchair is proposed inspired by a Chinese ancient vessel Jue (Childs-Johnson, 1987). AM renders more freedom for the design of such a chair using topology optimization. Refer to the geometry of Jue, an initial design model is generated, as shown in Figures 1(a, b). Considering scenarios (Zhu, 2013) of an 80 kg human sitting on it, the chair is featured as back-rest (BR), hand-rest (HR), front-seat (FS), back-seat (BS) and support (SP) for applying loading and boundary conditions as in Figure 5. The green region is designable, whilst the purple region is non-designable. Three load cases are analysed and the relative force densities in different regions are given in Table 1.

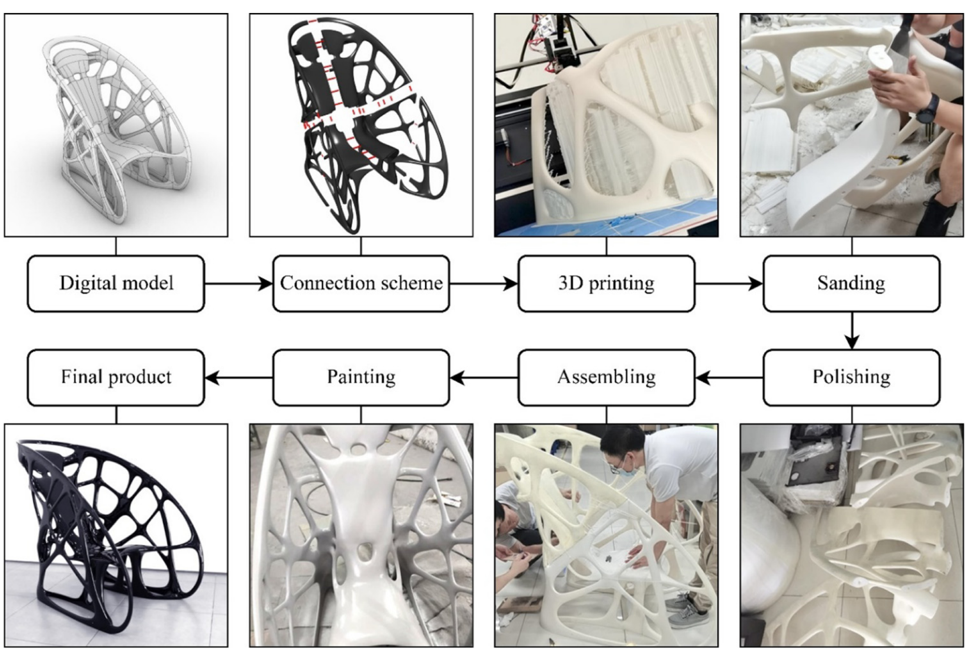
**Table 1** Relative force densities in different regions

| Load case | Relative force densities in different regions | | | |
|---|---|---|---|---|
| | BR | HR | FS | BS |
| 1 | 0 | 1 | 0 | 0 |
| 2 | 2 | 0 | 3 | 1 |
| 3 | 20 | 1 | 30 | 10 |

The target volume faction is set as 20% and the optimized result is shown in Figure 3(a). After postprocessing, a CAD model for the Jue Chair is obtained, as shown in Figure 3(e).

The size of the Jue chair is 1,310 × 796 × 1,134 mm. It is time-consuming and costly to print the whole chair in one piece. Therefore, the design model is divided into several parts and these parts are printed separately and simultaneously. Dowel and glue are used to assemble these parts. The FFF technique is here adopted for manufacturing because it is cheap and suitable for large scale printing. Stack traces will be generated on the product surface when using the FFF technique. Sanding, polishing and painting are thus carried out to promote the surface quality of the chair. The finalized chair has a smooth and shining surface. The whole manufacturing workflow for the chair is illustrated in Figure 6. In the conventional method, the design of free-form and complex structures such as the Jue chair will usually take several days and it is very likely to generate inefficient structural topologies. By contrast, the proposed workflow enables the designer to produce a complex, efficient structural design in few hours. In comparison to SM, the FFF AM technique reduces material wastes and imposes almost no constraints on the design complexity. Besides, a chair produced by 3D printing technique without material usage control and splitting can cost tens of thousands of dollars. By contrast, the Jue chair produced through our workflow costs only approximately 2,000 dollars.

**Figure 6** Manufacturing workflow for the Jue chair



### 3.2 Flat pack chair and tables

Flat pack furniture is easy to be transported and stored and thus is suitable for mass production. Firstly, we design a flat-pack chair through topology optimization. By integrating the arm rest and chair leg into the same surface, the initial 2D design domain is shown in Figure 7(a). The non-design domain is highlighted in purple, including the leg profile, arm rest profile, back profile and seat profile. The loadings on the back rest and seat are marked as BR and S. The two corners at the bottom are fixed. Figures 7(b, c) shows the optimized and the postprocessed results, respectively.

A customized back and seat can be mounted on the main structure using angle brackets. The chair is a flat-pack design and we adopt SM. Plywood and computer numerical control (CNC) cutting are chosen, respectively, as the material and manufacturing methods to achieve a low-cost and fast fabrication combination. Wood putty is used to isolate the painting and cut faces. Sanding and painting are conducted to produce smooth and glossy surfaces. The manufacturing process for the flat-pack chair is shown in Figure 8.

Two flat-pack tables are then designed and fabricated using the SM. The first table has four identical parts in a cross arrangement and hence only a quarter of the structure is analysed. Vertical loads from the top of the table and horizontal perturbation are considered, as shown in Figure 9(a). The optimized design is shown in Figure 9(b) and the smoothened design is shown in Figure 9(c).

Laser cutting is used for fabrication. Four $800 \times 500 \times 15$ mm acrylic sheets are used, which have an outstanding surface appearance. It takes about 1 h to cut each part (Figure 10), which is much faster than using the AM. Epoxy is used for assembling. To prevent the table from torsion-induced failure, each corner at the connection regions is reinforced by a small right angle, as shown in Figure 10. Only the connection area requires sanding and polishing. A 20 kg circular glass is used as the table surface.

Further, a flat-pack triangle table with an interlocking assembling scheme is developed to keep the appearance neat and clean and simplify the assembling process. The initial model has a triangle arrangement, which has a greater resistance to torsion than the cross arrangement. Vertical loads, horizontal perturbation and torsional force are analysed. The conception and the optimized result are shown in Figures 11(a, b). Grooves were added to the design for interlocking, as shown in Figure 11(d) and Figure 12.

**Figure 7** Optimization of a flat pack chair: (a) loading and boundary condition, (b) optimized result, (c) smoothed design

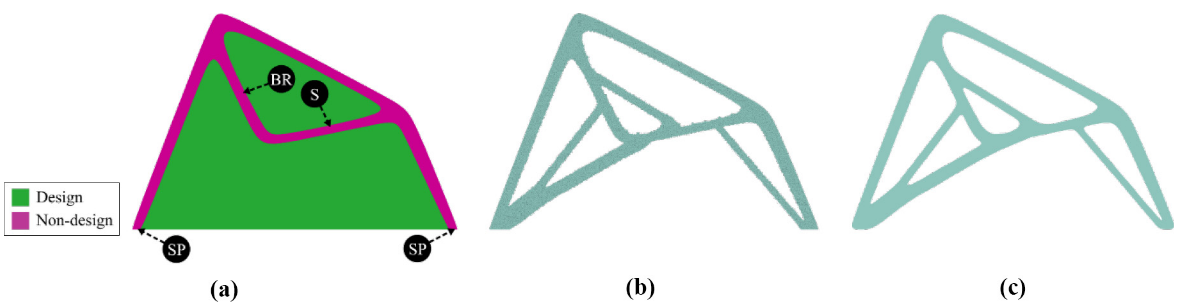



**Figure 8** Manufacturing workflow for the flat pack chair

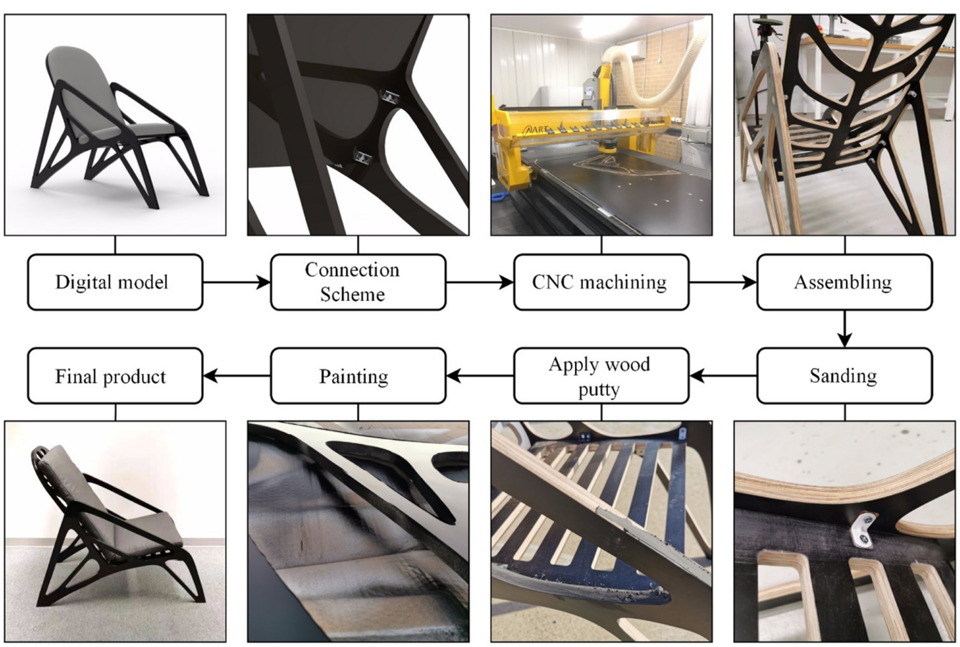


**Figure 9** Optimization of a table: (a) loading and boundary condition, (b) the optimized result, (c) the smoothed design after postprocessing

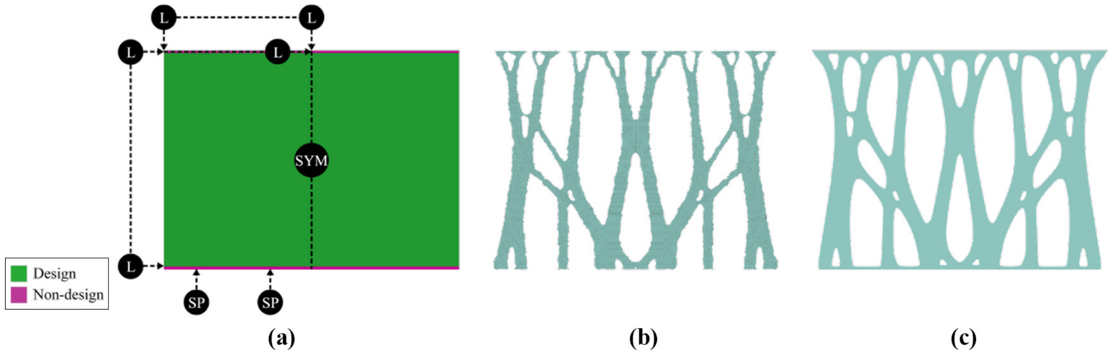
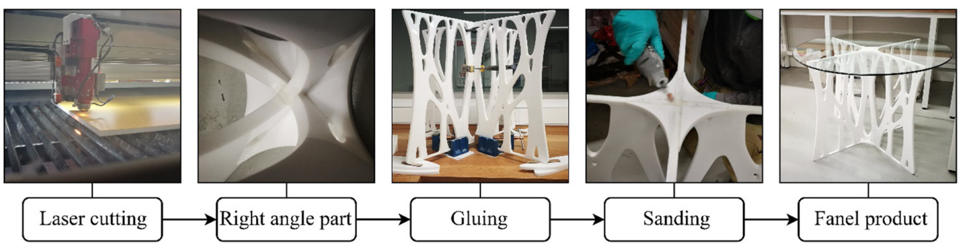



**Figure 10** Manufacturing workflow for the cross table




Because the final structure is in a triangular arrangement, the surface of grooves requires beveling. This is done by milling via a CNC machine. Figure 12 shows the manufacturing process and the final assembled table. These cases demonstrate that the proposed workflow is valid for producing flat-pack furniture. In contrast to the common sense of cheap and tedious design for flat-pack furniture, topology optimization under the proposed workflow can enhance the appearance and structural complexity of the furniture and the material usage can be reduced at the same time. Compared with conventional methods, the proposed workflow can add aesthetic value to the design and increase the material efficiency of flat-pack furniture.

## 4. Discussion

The proposed workflow combines topology optimization with advanced manufacturing, which opens up new avenues for furniture design through fast initial design conception, convenient geometry adjustment and less cost. We demonstrate that both AM and SM work effectively in this workflow.

Our results show that AM has fewer restrictions on the topology of the design and can produce 3D structures with more complex geometries. SM is suitable for producing flat-pack furniture because it has a much faster prototyping speed than AM. Besides, SM can be used for mass production.

The FFF is a well-developed AM technology which is cheap and suitable for large-scale printing. Although the FFF leads to deposit lines on the surface, the fabricated structure can meet the requirements of furniture after surface treatment. The polylactic acid material used in this research has advantages of low cost, excellent mechanical properties and low environmental impact. It should be mentioned that emerging AM technologies would render much faster speed for prototyping.

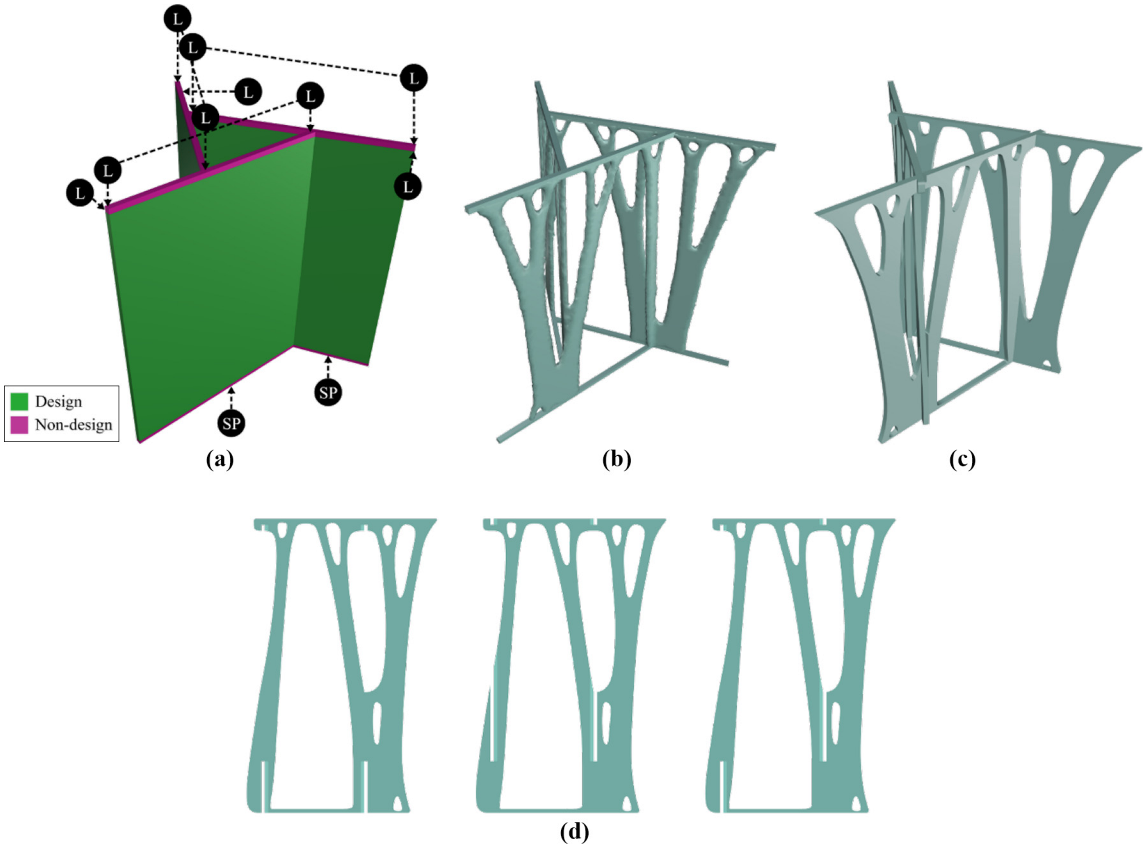
This research has proposed effective ways of connection and assembling, to lower the costs of manufacturing. A large-size product can be divided into multiple pieces, which can be fabricated separately and simultaneously. The usage of dowel, glue and interlocking connection can provide sufficient strength, which will not affect the aesthetics of the products.

In conventional workflows, the usage amount of material, structural performance, aesthetics and manufacturing cost of the furniture are considered. In the proposed workflow, we combine topology optimization and advanced manufacturing to balance these factors effectively. Compared with conventional workflow, our workflow has the following advantages. Firstly, advanced manufacturing techniques enable the designers to fabricate geometrically complex structures. Secondly, designers can quantitatively control the usage amount of material and the structural performance of products with the help of topology optimization. Thirdly, a flat-pack design is feasible by using the proposed workflow.

## 5. Conclusion

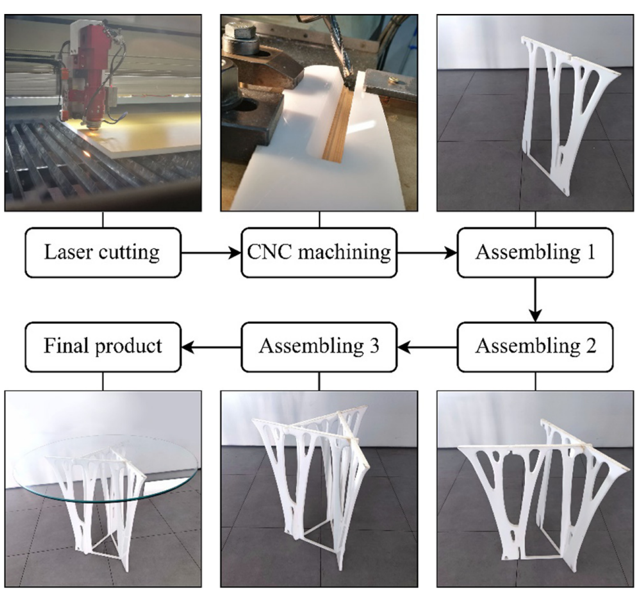
In this study, an innovative workflow has been presented for creating novel and elegant furniture. Multidisciplinary approaches including computer graphics, topology optimization and advanced manufacturing are combined effectively in this workflow. Several innovative products, including chairs and tables, have been designed and fabricated using different manufacturing techniques. The design constraints and time and cost of producing furniture can be significantly reduced using the presented workflow, in comparison to conventional

**Figure 11** Optimization of a triangle table: (a) loading and boundary condition, (b) optimized result, (c) smoothed design after postprocessing and (d) disassembled design




techniques. This research paves a way for using state-of-the-art technologies in designing and fabricating advanced furniture. The developed workflow can be easily extended to the creation of other industrial products.

**Figure 12** Manufacturing workflow for the triangle table

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