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Research on Parameterized Design of Urban Furniture in Wuyi Overseas Chinese Hometown from the Perspective of Digitalization and Localization

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Abstract. "In the context of parametric design based on visual programming, this study explores an innovative approach combining digitization and localization. It applies a two-way progressive structural topology optimization algorithm to conduct research on innovative urban furniture design in the Wuyi Overseas Chinese Hometown. It utilizes digital media to connect with local cultural characteristics, taking the "qilou" architectural style in the Wuyi Overseas Chinese Hometown as a design prototype. Through the algorithm, the study progresses through initial design preparations, formative design, topology optimization design, and post-processing manufacturing to create urban furniture that embodies both local characteristics and aesthetically pleasing forms, as well as structurally sound and digitally ecological elements. It employs the power of design to address local and regional real-world issues, enhancing the daily experiences of local residents and out-of-town visitors. The design practice validates an innovative design pattern that combines parametric design with local cultural features, providing a novel generative tool and strategy for contemporary innovative furniture design in the Wuyi Overseas Chinese Hometown. Furthermore, it serves as a reference for applying this algorithmic model in other domains."

Keywords. Digitization, localization, Wuyi Overseas Chinese Hometown, urban furniture; Parametric

1. Existing Issues in Parametric Furniture Design

Compared to foreign counterparts, the development of parametric design in China started relatively late. The related research primarily concentrated in the field of architecture. In recent years, there has been a gradual increase in explorations within the field of furniture design. The main research direction focuses on investigating the feasibility of specific parametric software or design practices [1]. As an avant-garde

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design technology, parametric design possesses significant advantages, yet it still faces certain constraining factors [2].

"Through literature research and exhibition surveys, it has been observed that the application of parametric design in furniture design is continuously expanding. However, its primary practical application is somewhat weaker in the field of architectural design. Additionally, there are several issues identified:1) There is limited research on the theoretical basis of parametric design and the underlying logic in the formative stage.2) The majority of parametric design studies focus on algorithmic generation of complex furniture forms [3], lacking in-depth analysis of the relationship between parametric design, furniture products, and users.3) The core of parametric design lies in data analysis. Most designers primarily rely on their own experience or intuition to control and adjust parameters during the design process. Only parameters derived from objective data analysis experiments can lead to greater innovation on the functional and usage levels.4)In the practice of combining parametric technology with traditional culture, designers are more focused on how to transform traditional cultural symbols or elements for application in the appearance and surface decoration of furniture, thus downplaying critical factors in furniture design such as ergonomics, load-bearing forces, structural optimization, and material specifications. Based on the aforementioned issues, the following text will summarize the theoretical basis and development process of parametric design, distill existing parametric design method models, and utilize a bidirectional progressive structural optimization algorithm to generate urban furniture that embodies both local characteristics and digital ecology."

2.The scientific theoretical basis of parametric design

Parametric design does not refer to the limitation of using a specific software tool or modeling technique. It is a design thinking approach, a professional term widely applied in mathematics, design, and various fields [4]. The designer's design process no longer revolves around selecting a single final object, but rather, creating a group of designs that encompass all potential possibilities. This allows for an understanding of form through the analysis of the program's inherent logical patterns, and deliberate generation and modification of forms. This shift expands the designer's mindset from considering individual objects to contemplating a broad range of choices.

2.1. Theoretical Aspects of Parametric Design

Rivka Oxman considers parametric design as an entirely new 'design thinking' approach that has given rise to entirely new forms of design expression [5]. Philosopher Dennett refers to it as 'design Darwinism'. Complexity science theory provides the theoretical foundation for parametric design. The application of parametric design in product styling is influenced by the monad theory proposed by the German philosopher and mathematician Leibniz and the philosophical ideas put forth by the French postmodern philosopher Gilles Deleuze.

2.2. Complexity Science Theory

Chaos Theory: It is a method that combines qualitative thinking with quantitative analysis, and the 'butterfly effect' has become synonymous with chaos. The application of chaos theory in artistic form design began in the 1980s. The fractal theory in chaos theory proposes the beauty of fractals generated by self-similar forms, allowing for the existence of simple and orderly rules behind extremely complex phenomena [6]. Self-organization Theory: Originating from systems theory, it explores the forms of organizational evolution[7]. It is the process by which a system achieves ordered, complex structures through self-regulation within itself. In the practice of parametric design, the process involves the system self-adjusting to form ordered structures and complex forms of products. Nonlinear Theory: Since postmodernism, many architects have used computer-aided design as a tool to solve various issues of compound diversity. The techniques and concepts they employ, such as dislocation, twisting, confrontation, and mutation, have spontaneously incorporated the core ideas of nonlinear theory: architecture undergoes changes in a discontinuous and uneven state. Theoretically [8], it adheres to the principles of nonlinear complex scientific theory, and conceptually, it is based on the philosophy of nonlinearity in architecture.

2.3. Deleuzian Philosophical Theory

The philosophical ideas of the French postmodern philosopher Gilles Deleuze provide the conceptual foundation for parametric design. Deleuze's philosophical system is fundamentally based on the creation and generation of heterogeneous elements. His overarching philosophy emphasizes generativity and differentiation, gradually giving rise to concepts in post-structuralist philosophy aesthetics such as time crystals, folds, rhizomes, diagrams, and nomadism [9]. Deleuze's fold theory underscores an operation of 'more complex, supple, and heterogeneous forms', establishing a continuity of possibility [10]. Under the influence of fold theory, the development of nonlinear design has been propelled, leading designers to create many forms that challenge traditional concepts. Parametric design constructs parameter models through algorithms to generate designs encompassing all possibilities, and then refines specific models through the adjustment of relevant variables. This constitutes a dynamically generated design approach.

3.Visual Programming Parametric Design Method Model

3.1. Existing Parametric Design Methods

Common parametric design software includes CATIA, UGNX, Grasshopper, Pro/Engineer, SolidWorks, among others. Among them, Grasshopper is currently a popular and widely used parametric design software tool. Grasshopper is a plugin developed to address the drawbacks of difficult modeling, editing, and modification in Rhinoceros, as well as the need for remodelling for model adjustments. It possesses the following key features:

3.2. Furniture Visual Programming Parametric Design Method Model

In recent years, the most commonly used furniture visual programming parametric design in the field of design is based on the theory of parametric design. It employs parametric modeling generation technology to create a design by constructing a parameterized model group for furniture products. The matured 3D printing rapid prototyping technology is then utilized to materialize the product. The basic process can be summarized into four steps: Design Positioning: Analyze and summarize design requirements, extract defined parameters, and construct the system's physical architecture; System Architecture and Functional Design: Human-computer parameter adjustment subsystem, modeling parameter adjustment subsystem, generate a large number of basic design proposals using relevant algorithms; System Optimization: Optimize the design model structure and adjust the product form; Output Design Results: Conduct usability testing and subsequently manufacture, print, and assemble the actual product.

Throughout the entire process, there is a certain degree of disparity between the furniture model displayed in the Grasshopper plugin interface and the actual product model in terms of human-computer dimensions, perspective, and size proportions. Therefore, a rational and scientific parametric design for furniture necessitates the establishment of a personalized custom furniture design system physical architecture based on Rhino, Grasshopper, and Arduino. Initially, it is essential to employ a human-computer parameter acquisition device to gather relevant user anthropometric data in order to determine the pertinent dimensions of the seat. Subsequently, designers use the GH interface to adjust the seat's parametric model through relevant battery groups to meet aesthetic and mechanical elements. Then, the data is imported into sensors via Arduino, utilizing GH to construct an adjustable parametric model for the seat. Finally, the three-dimensional model is displayed and rendered in Rhinoceros.

Building upon the importation of sensor data, this method model requires further refinement of furniture functionality. Taking the seat as an example, the functional design primarily encompasses two adjustment subsystems: the human-computer parameter subsystem and the aesthetic parameter subsystem. Based on this, designers can fine-tune relevant parameters to generate a customized form of the seat that meets individualized requirements.

The aforementioned furniture visual programming parametric design method model is premised on personalized requirements. Utilizing anthropometric experimental data, it establishes a system for parametric furniture design, encompassing furniture shaping and functional parameter adjustments. This model is capable of generating furniture design proposals that align with ergonomic principles and individualized preferences. However, it also encounters challenges such as a complex process, user interface complexity, and variations in data testing. Additionally, factors related to furniture structure, load-bearing capacity, and materials are less emphasized.

The objective of this design project is to create urban furniture leisure chairs that embody both local cultural characteristics and digital ecology. In this process, particular attention is given to factors including furniture structure, load-bearing capacity, human-computer parameters, and material properties. Therefore, a bidirectional progressive structural optimization algorithm is chosen for the parametric design practice of the furniture.

4.Parametric Furniture Design Practice Based on Bidirectional Progressive Topological Optimization Algorithm in the Context of Digitalization and Localization Perspective

4.1. Bidirectional Progressive Structural Topology Optimization Algorithm

Today's designers, when using digital technology for form-finding, have shifted their focus from 'external form data' to 'structural data', prioritizing the safety and rationality of the form over its complex and diverse formative aspects. The Bidirectional Evolutionary Structural Optimization (BESO) algorithm possesses features that simulate natural forms and ensure sustainable performance. It was first proposed by Professor Yi-Min Xie in 1998 based on the foundation of the Evolutionary Structural Optimization (ESO) method. This algorithmic generation method represents a cutting-edge approach to structural optimization analysis and design. Its underlying principle follows a systematic design plan, providing multidimensional guided optimal structural outcomes, thus reducing costs and material waste. The main software packages capable of implementing progressive structural topology optimization currently include Abaqus, Karamba3D, and Ameba. Ameba, developed by Professor Yi-Min Xie's team in 2018, is a specialized plugin designed for the BESO algorithm. It boasts diverse grid processing capabilities and can handle data processing for both two-dimensional and three-dimensional topology optimization [11]. The design practice described in this paper is also based on Ameba for algorithmic generation experiments. The aim is to input data weights into the platform through this algorithm, allowing for form-finding. This process aims to achieve an optimization design result that is both aesthetically pleasing and rational, while also meeting the criteria of functional suitability, behavioral appropriateness, structural optimization, and material compatibility.

4.2. The Digitalization+Localization Integrated Parametric Furniture Algorithmic Generation Strategy

With the assistance of the Ameba software platform, the BESO algorithmic generation strategy can be implemented through a specific four-step process: Design Positioning, Initial Form Design, Topological Optimization Design, and Post-processing and Manufacturing. Firstly, Design Positioning requires clear definition of design objectives, design connotations, user requirements, and other considerations. Secondly, Initial Form Design primarily addresses the preliminary preset conditions of the model, which involves reading data on finite element grid division for the design area. The initial model can be categorized into target and non-target models. The target model involves constructing a geometric model for a real-world entity, while the non-target model utilizes the biomimetic modeling characteristic of the BESO algorithm to ensure structural rationality while achieving a design form rich in aesthetic features. Thirdly, Topological Optimization Design encompasses processes such as setting various load conditions, defining optimization parameters, material selection, preprocessing files before centralized data processing, and displaying iterative form-finding results. Fourthly, Post-processing and Manufacturing involves refining the serrated unit data results obtained from topological optimization to achieve a uniform and smooth effect. Finally, virtual results are interfaced with the equipment, and output data is read for size and material analysis, equipment operation analysis, and printing terminal analysis.

This is followed by actual operations using three-dimensional printing or data cutting on numerical control equipment, establishing an interconnected collaborative system (see Fig.1).

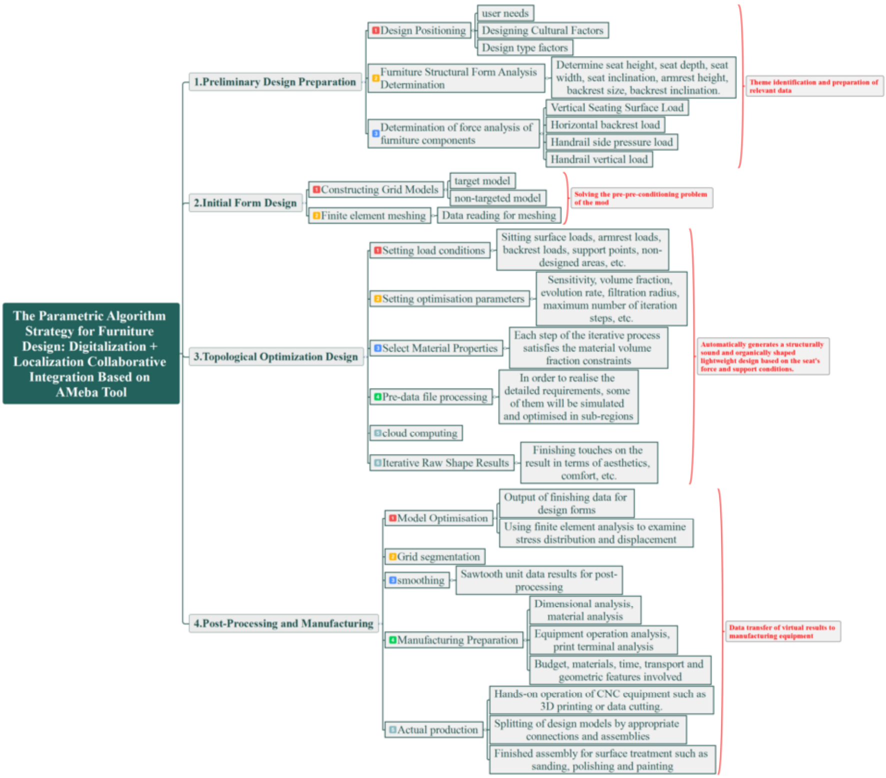


Figure 1. A strategy for generating parametric algorithms for furniture based on the Ameba tool for digital + in situ synergistic integration.

4.3. Parametric Design Practice of Urban Furniture in the context of Digitalization and Localization: A Case Study in Wuyi Overseas Chinese Hometown

4.3.1. Project Background

This design project aims to address the current issues in urban furniture in Jiangmen's Wuyi Overseas Chinese Hometown, which include a lack of diversity in furniture types, limited interactive experiences, weak spatial layout rationality, and a deficiency in showcasing the regional characteristics of the Overseas Chinese community. Starting from the perspective of 'Digitalization + Localization', we leverage the Ameba bidirectional progressive structural optimization algorithm to empower innovative and optimized design for urban furniture in the Overseas Chinese community. This involves integrating the local cultural characteristics of Wuyi Overseas Chinese Hometown with digital technology, resulting in a city furniture leisure chair that embodies both local features and digital ecological elements. This design endeavor aims to meet the urban development needs of Wuyi Overseas Chinese Hometown in the digital age, enhancing the daily experiences of local residents and out-of-town visitors.

4.3.2. Design Cultural Factor Positioning

The design takes the Jiangmen Xuding Street area's arcade-style buildings as its prototype, focusing on the theme of 'Digital Arcade'. Its aim is to conduct an experimental design collision between traditional culture and digital culture. From a design culture perspective, the Xuding Street area in Jiangmen is the birthplace of the city, with a history of over 700 years. An open market called 'Jiangmen Market' was established here by the ancestors of Jiangmen at the end of the Yuan Dynasty and the beginning of the Ming Dynasty. Due to its location at the highest point, it was named 'Xuding Street'. Additionally, because there are 33 levels of bluestone steps at Shuibu Head in the area, climbing them leads to Xuding Street, earning it the name 'Thirty-Three Market Street'.As an old commercial district of Jiangmen, the 'arcade' architecture here retains the charm of the past. The arcade is a type of corridor-style building, with a pedestrian walkway on the first floor facing the street, and the main building above the walkway, giving the appearance of the upper floors 'riding' on the first floor. This type of architecture was originally referred to locally as 'arcades with legs', later shortened to just 'arcades'. Chinese bas-reliefs and Manchu windows, along with Western elements like Roman columns and carvings, blend together, allowing cultural elements from different regions and eras to coexist harmoniously, forming a unique characteristic of the Overseas Chinese community. The top of the street is adorned with various types of decorative lights, while the exterior walls feature transformed European-style columns, window decorations, and Spanish-style balconies. At the same time, it is embellished with Chinese mountain flowers, Manchu windows, and stone inscriptions, making it akin to a 'Museum of International Architecture'.

Architectural decorative styles often bear a strong sense of their era. Against the backdrop of the modern fusion of Eastern and Western cultures in Jiangmen, arcades reflect a characteristic of cultural inclusivity. The decorative structures of arcades are diverse, with a particular emphasis on mountain flowers, windows and their frames, balcony railings, and columns [12]. Therefore, this design project inherits the open-mindedness, inclusiveness, and innovative spirit expressed by the arcades of Jiangmen in the context of cultural fusion between East and West in modern Jiangmen society. Taking the appearance of arcade architecture as the initial form, it integrates the wheat straw and persimmon vine patterns of the arcades. Utilizing the bidirectional progressive structural optimization algorithm, the project progresses through preliminary design preparations, initial form design, topological optimization design, and post-processing and manufacturing. This results in an urban furniture leisure chair that combines local characteristics with digital ecological elements. The design is then applied to actual street scenes.

4.3.3. Algorithm Generation Process

1. Initial Form Design: Constructing Geometric Entities and Grid Models
Taking the architectural appearance of the arcade as a prototype, the initial stage of form setting does not strictly require a replica simulation of the original arcade shape. Instead, it aims to simplify and refine, achieving a form that retains the charm of the arcade while also meeting the seating size requirements for easy topological optimization. In Rhino, the initial form of the leisure chair is established, and the initial model is linked to the 'Volume' battery. The AmebaMesh3D battery is selected to subdivide the model into 197,825 high-density meshes. The higher the mesh density,

the more refined the optimized model. Since the seating surface and backrest are the main force-bearing areas for armless leisure chairs, the 'Volume' is exploded using the battery command in GH. This extracts the surfaces that need to bear the load without affecting the geometric entity itself, determining that the seating surface and backrest surface are the key factors for load setting [13] (see Fig.2 and Fig.3).

Figure 2. Leisure chair model and size drawing.

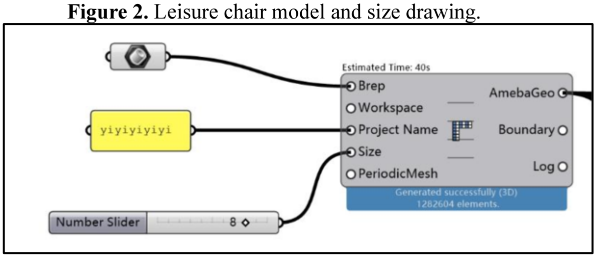


Figure 3. Build a grid model.

2. Topological Optimization Design

(1) Support Configuration

The typical load-bearing points of a regular seat are the four legs intersecting with the bottom surface. Therefore, in GH, the Support3D component is selected to import the seat support area, and the numerical value of support displacement is controlled. After multiple attempts, it was determined to control Ux and Uy within an absolute value range of 0.1, while Uz remains unchanged at 0, as shown in Fig. 4.

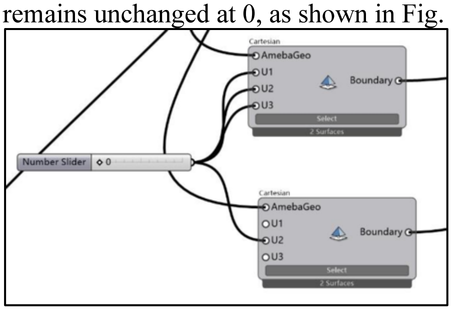
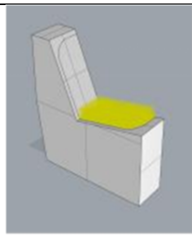
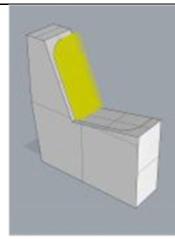
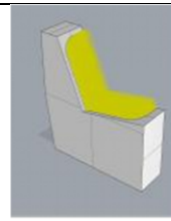


Figure 4. Support setting.

(2) Load Configuration

The stress on armless chairs primarily concentrates on the central and peripheral areas of the seat, the backrest, and the legs. With structural rationality as a premise, a uniformly distributed load is applied to the entire seat, as shown in Table 2. The corresponding load data is imported into the preprocessor through the NormallLoad3D component for logical editing, while simultaneously adjusting the slider to modify the area of force application, as shown in Fig. 5.

Tab 1. Leisure chair force analysis diagram.

Force Application Point	Center of the Seat	Backrest	Entire seat surface
Legend			

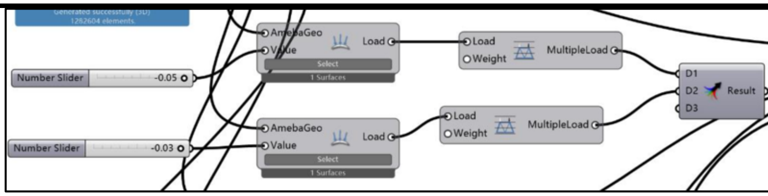


Figure 5. Load setting

(3) Material Specification

In the bidirectional progressive structural optimization algorithm, material specification is achieved by parameterizing key performance parameters of the material, combined with the system's default material library. This enables the algorithm to search for the optimal material combination during the design process, with the goal of optimizing the structure. The optimization method can optimize the distribution of material combinations within a specified range and generate models with minimized weight and maximized structural performance. The system's default isotropic materials include ABS plastic, nylon, steel, aluminum, etc. Additionally, users can set parameters such as material density, Poisson's ratio, and elastic modulus. In this practice, ABS plastic was selected, and three different types of seats were used to compare the different structures generated by the algorithm.

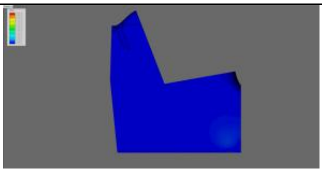
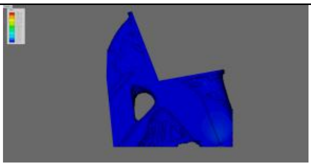
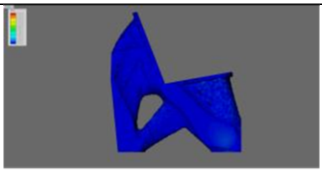
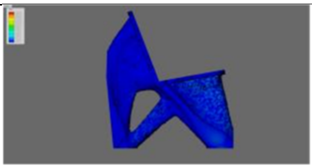
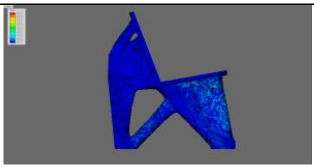
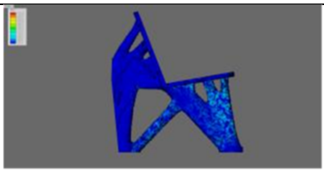
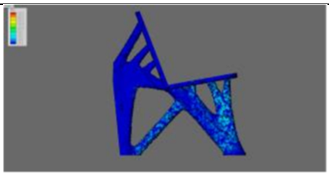
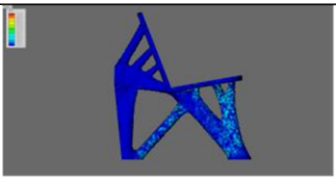
(4) Optimization Parameter Configuration

In Ameba, the optimization parameters are set using the BESO OptParameters operator. One of the objectives of topological optimization is to minimize the use of material. Through multiple experimental operations, it was determined that when the constraint volume is set to 0.01 (vf), a more suitable optimization objective can be generated. The lower the purge rate value, the more precise the mesh optimization, typically set to 0.02 (ert). Sensitivity 'S' represents the density of stress (default is 1). For a model with a mesh subdivision value of 1.28 million, the filter radius needs to be set to double (rmin) (delete units below double) in order to compute the generation. Additionally, the default maximum iteration steps are applied.

(5) Iterative Form Generation

As shown in the table below, the topological optimization process is displayed for iterations ranging from 2 to 142. The structural morphology changes occur at intervals of 20, with a target volume fraction of 0.05 (vf) and a purge rate of 0.02 (ert) (to increase optimization time and enhance optimization precision). Throughout the iteration process, while satisfying the constraint of material volume fraction, the total strain energy gradually changes, and the flexibility curve eventually stabilizes to achieve a visually pleasing, efficient, and reasonable convergent result.

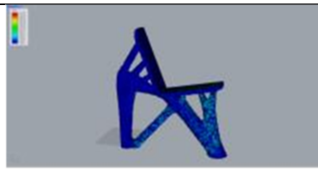
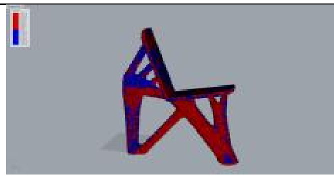
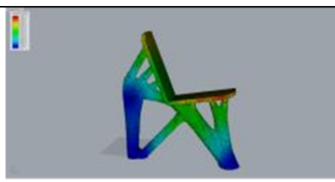
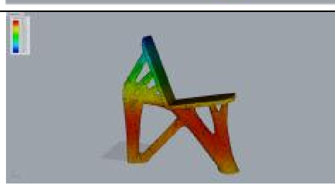
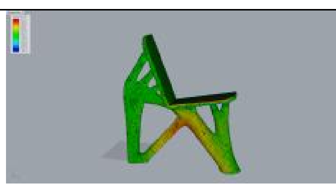
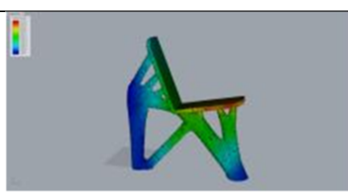
Tab 2. Stress cloud of evolutionary data and 3D topology optimisation results for leisure chairs

Number of Iterations	Illustration	Volume Fraction	Total Energy
2		0. 960402705	5. 899681
22		0. 641171668	6. 7355322
42		0. 428060814	8. 59480358
62		0. 285759485	11. 6855876
82		0. 190755767	16. 5284284
102		0. 127366737	23. 9552045
122		0. 09999677	31. 0344120
142		0. 100001546	31. 2132831

(6) Generated Form

The table below shows six different display modes of the optimized leisure chair. Based on the results below, it can be concluded that the maximum equivalent stress is 2.315 MPa, and the overall maximum displacement of the seat is 2.136 mm. The final algorithm-generated result shows a relatively uniform distribution of stress areas, meeting the requirements for the use of the leisure chair in terms of structural form.

Tab 3. Leisure chair optimization results display and illustration

Display Modes	Illustration	Maximum Value and Position
Mises		Maximum Equivalent Stress: 2.315MPA
Principal		Maximum Compression: 1.763MPA Minimum Tension: 1.763MPA
Displacement Uxyz		The maximum displacement of the entire seat is 2.136mm, located at the top and middle of the backrest.
Displacement Ux		The maximum displacement in the X-axis direction is 3.361mm, located at the top of the backrest.
Displacement Uy		The maximum displacement in the Y-axis direction is 1.157mm, located at the top of the backrest.
Displacement Uz		The maximum displacement in the Z-axis direction is 2.135mm, located at the top of the backrest.

3. Post-processing and Manufacturing

(1) Model Optimization

Because the bidirectional topology optimization method optimizes the seat by increasing or decreasing the mesh, the optimized model surface contains a large number of 'non-manifold edges,' also known as 'serrated' units. Therefore, post-processing is required to repair and smooth the model surface in order to obtain a smooth manifold surface, remove non-manifold edges, and meet the quality requirements of the product. The Mesh checker battery is used to detect the mesh. The original optimization result will have non-manifold edges. After adjusting the smoothness and reconstruction of the dangling edges and points, as shown in Fig. 6, the mesh model has been optimized. Finally, the QuadMesh battery is used to turn the mesh into a polygonal mesh. The model surface is more refined and can be directly placed in Rhino for rendering (see Fig. 7, 8, and 9 10).

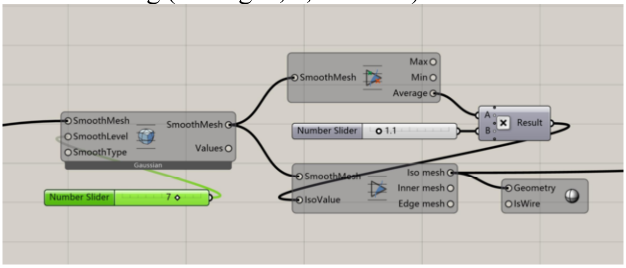


Figure 6. Mesh checker.

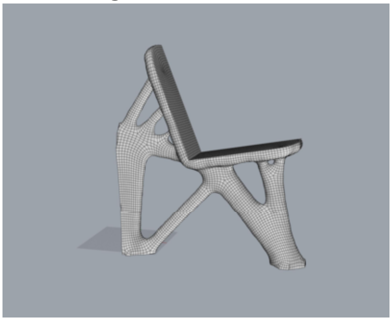


Figure 7. The model after the final reconstruction of the surface.

Figure 8. Render the renderings.

Utilizing the bidirectional topology optimization method, we altered the initial form and, considering functional usage, redefined the load and support parameters. Employing metallic materials, we generated two additional design proposals. To further validate the structural performance of the topology-optimized results, it is necessary to employ finite element analysis to examine the stress distribution and displacement of the seat, predict product performance, and identify potential weak points.

Figure 9. Scenario 2 Render the renderings.

(2) Scenario Simulation

Figure 10. Leisure chair use scene diagram.

(3) 3D Printed Physical Model

Utilizing additive manufacturing 3D printing technology, the mechanical structure of the seat is analyzed. Materials with sufficient strength and durability, such as nylon and engineering plastics like ABS, are chosen for the physical production of the seat. Throughout this process, considerations are made for budget, time, and geometric features involved in the design. The design model is divided and assembled using appropriate connecting methods. Finally, surface treatments such as polishing, painting, and coating are applied to showcase distinctive surface characteristics (see Fig.11).

Figure 11. 3D printing model.

The BESO algorithm is currently one of the advanced topology optimization algorithms. It has not only found effective practical applications in STEM fields but is also gradually being explored in multidimensional approaches in art and design disciplines. This paper, based on the elucidation of the fundamental connotation, developmental history, related theories, design process, and current issues of visual programming parametric design, summarizes the advantages of the Bidirectional Evolutionary Structural Optimization (BESO) algorithm. It clarifies the algorithm's generation strategy and optimization method in furniture design, explores how digital technology can empower the reactivation of local culture. Taking the 'qilou' architecture in the Jiangmen Old Street, a traditional arcade-style building, as the design prototype, it conducts a collaborative algorithmic generative design practice. This provides opportunities for diverse choices in generating urban furniture design outcomes. However, since the BESO algorithm requires relevant data support in various aspects such as form, structure, material, and energy conservation, it is necessary to further validate the versatility of its application with more new tools and new design method systems. This will create more opportunities for sustainable design and creation in empowering the local cultural industry through digital algorithmic generation.

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