# Parametric Design of Urban Furniture Based on the Analytic Hierarchy Process

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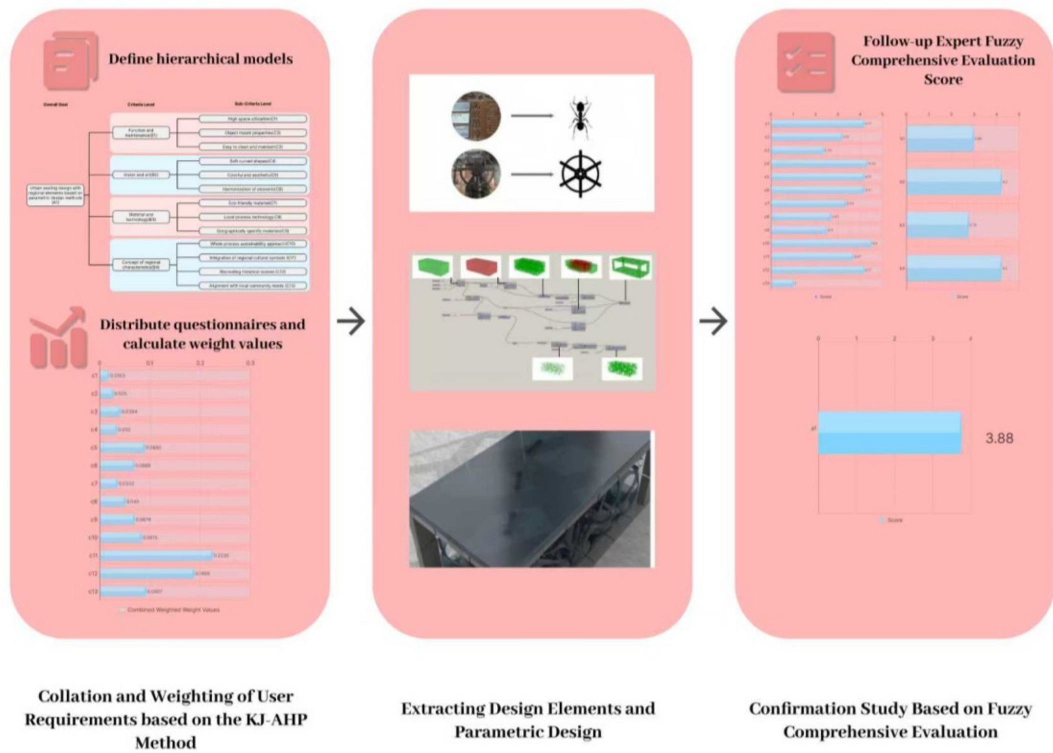
DOI: 10.15376/biores.20.4.10974-10991

## GRAPHICAL ABSTRACT



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As an important component of public spaces, urban furniture meets the daily needs and cultural expressions of residents. It also significantly influences the aesthetic and practical value of urban environments. The research used an integrated approach of affinity diagram method (KJ method), analytic hierarchy process (AHP), and fuzzy comprehensive evaluation to conduct a systematic qualitative and quantitative analysis of urban seating design, assessing the importance of function, form, materials and regional features. By analyzing the integration of urban furniture design with regional features, this paper offers a multidimensional perspective for modern design. Based on the survey results, integration of regional cultural symbols and recreating historical scenes are key requirements that guided the parametric design of Harbin Westred Square's seating furniture. It highlights the importance and potential of parametric design in innovating urban furniture and conveying the spirit of urban culture.

*DOI: 10.15376/biores.20.4.10974-10991*

*Keywords: Urban furniture; Parametric design; Regional elements; Analytic hierarchy process*

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## INTRODUCTION

The acceleration of urbanization has resulted in contemporary public spaces in urban areas taking on a variety of meanings. Public spaces are defined as gathering or meeting places outside of the home and workplace, including both indoor and outdoor venues. These venues are typically open to the public and promote resident interaction, providing opportunities for connection and engagement (Francis *et al.* 2012). As an indispensable component of public space, urban furniture serves the daily needs and cultural aspirations of city dwellers, and its design and innovation directly influence the aesthetic and practical value of the urban environment. Nonetheless, the realm of urban furniture design continues to grapple with numerous challenges in practice, particularly with regard to the exploration and transformation of regional cultural elements. Designers frequently depend on their subjective experience, lacking systematic analysis methods and quantitative evaluation mechanisms. In particular, when setting design priorities, factors such as function, form, materials, and culture are often treated ambiguously, resulting in design outcomes that struggle to balance practicality and cultural expression in actual use.

The present research uses an integrated approach, combining affinity diagram method (KJ Method), analytic hierarchy process (AHP) and fuzzy comprehensive evaluation (KJ-AHP-FCE) to undertake a systematic qualitative and quantitative analysis of the requirements of urban seating design. This process helps to clarify the relative importance of different dimensions, including function, form, materials, and regional elements. It also provides specific demand weights and directions for design practice. Parametric design is an emerging methodology that integrates design thinking with technical means through the use of adjustable design rules. This approach allows designers to rapidly explore a variety of design alternatives, thereby increasing the flexibility and efficiency of the design process. In urban furniture design, parametric design can effectively address diverse functional needs and regional cultural characteristics, ensuring that designs are both practical and culturally rich. When combined with 3D printing technology, parametric design offers greater creative freedom and material options for furniture manufacturing, allowing designers to achieve intricate geometric structures and personalized designs. This not only meets the market's demand for customization and innovation, but it also plays an important role in reducing material waste and improving sustainability.

The objective of this study was to establish a connection between the 'experience-based qualitative methods' of traditional design and 'parametric design solutions based on data and cultural logic' in the context of urban furniture design. The investigation employed a systematic, operational, and culturally profound approach to address this gap. It was hypothesized that this research will provide new reference points for urban public space design, promoting the aesthetic enhancement and cultural regeneration of the urban environment.

## Literature Review

*Parametric design*

Parametric design is a design methodology that relies on algorithms and mathematical models to define the attributes and behaviors of design objects through parameters and variables. In this design paradigm, design elements such as size, shape, and position are transformed into adjustable parameters, which are adjusted and evolved by computer programs to automate and optimize the design (Sun 2017; Gu *et al.* 2021). In the conventional furniture design process, design concepts frequently undergo a protracted cycle. Subsequent to the design's completion, comprehensive product drawings are developed, and manufacturing prototypes are constructed. Throughout this period, designers meticulously refine and modify the design until it is finally optimized. Parametric design enables designers to entirely digitize the design process by establishing a set of logical rules. The furniture shapes generated by the algorithms possess a high degree of adaptability. It provides designers with inspiration to develop diverse design solutions (Bai and Zhu 2023). Parametric design, with its flexible parameter adjustments and diverse random outputs—such as the application of morphologies like Voronoi polygons and slime mold algorithms—has become a vital tool for design innovation, providing designers with a rich wellspring of creative inspiration.

Furthermore, parametric design reduces the burden of repetitive tasks and facilitates continuous iteration in furniture design through generative design optimization (Bai and Zhu 2023). Parametric tools facilitate the modification of parameters, ensuring that any alterations made by the designer to the designed object or document component are automatically reflected in the associated component. Parametric changes resulting from the movement, deletion, and size modifications of components will consequently lead to corresponding changes in the parameters of the relevant components. Changes made in any view can be bidirectionally propagated to all related views in a parametric manner and ensures the consistency of all drawings, eliminating the need to check all drawings individually and guaranteeing uniformity across all drawings. This approach streamlines the design process by eliminating the need to modify all views individually, enhancing efficiency and quality (Schumacher and Han 2014).

Parametric design incorporates the 'relationship between human and nature' into the design process, allowing for the creation of unique scenarios. Parametric coding technology is employed to construct diverse spaces, such as bleachers and enclosures, thereby embracing a broad range of urban life possibilities. This approach encourages spontaneous and social interactions based on the fulfillment of people's needs for comfort and convenience, thereby facilitating the harmonious integration of urban furniture into the urban environment (Li 2017). Moreover, parametric design offers an effective method for incorporating regional elements, enabling the rapid iteration of modeling rules through techniques such as abstract refinement and morphological reconstruction. This allows for a more seamless integration of the design into the urban environment and a greater alignment with local cultural norms, thereby achieving a harmonious balance between two-dimensional and three-dimensional elements (Lu 2023). Furthermore, the modular seating form can simulate different arrangements according to the space of the venue and the possible communication patterns of the users when they use the seats. This embodies personalized humanization and care (Zhou and Zhang 2021).

*Urban furniture*

The term 'urban furniture' was used to describe all types of furniture located in urban environments (Bao and Shi 2019). In addition to fulfilling the functional requirements of specific activities, furniture also plays an important role in enhancing the aesthetic quality of streetscapes (Lesan and Gjerde 2021). Indeed, China's comprehension of urban furniture frequently becomes conflated with its understanding of outdoor furniture and landscape furniture. Urban furniture conceptualizes the city as a complex 'home,' thereby weakening the conventional notion of 'city' and emphasizing the fundamental essence of 'furniture.' The term 'outdoor furniture' is understood to be analogous to 'indoor furniture,' while the term 'landscape furniture' is used to denote facilities with landscape significance. In comparison to urban furniture, these concepts exhibit a comparatively limited scope and certain deviations in practical terms. With regard to implementation, urban furniture design must give due consideration to the positive impact on the environment and adopt the whole life cycle sustainable design method. It is essential to select environmentally friendly materials and to consider the management of economic costs, with the objective of emphasising the ecological, cyclical and economic aspects (Schindler and Mbiti 2011; Lu 2023).

By designing furniture to encourage specific behaviours, designers can create environments that promote community engagement and enhance the overall urban furniture experience (Pahlavani 2021). Therefore, it is important to pay more attention to the different behaviours and activities that occur in public spaces and to shape the spatial scene through human behaviours or needs, with the aim of accommodating and supporting more opportunities for city residents to have a richer form of public life (del Real *et al.* 2006; Fang 2022). In 2001, Jianqing Weng posited a prospective trajectory for the evolution of urban furniture, suggesting that it would increasingly align with popular art forms and undergo a process of conceptual diversification and dynamic development. The framework of 'one system, two characteristics, three concepts,' proposed by Shidu Bao, provides a three-dimensional theoretical structure for the basic construction concept and development characteristics of Chinese urban furniture.

The distinctive character of regional culture is shaped by its natural environment. The thoughtful incorporation of these regional elements into the design of urban furniture can showcase the identity of the city, perpetuate its historical legacy, safeguard the local ecosystem, and facilitate the sustainable growth of urban furniture (Li *et al.* 2022). Liang Chen conducted a study on an innovative model of digitising and localising based on parametric design with visual programming. They applied a two-way progressive structural topology optimisation algorithm to implement the city furniture design of the Wuyi overseas Chinese community. The building overhang on Wei Street in Wuyi Overseas Chinese Village is taken as a prototype, and combined with the local cultural characteristics. The design and manufacturing are carried out to create urban furniture with local characteristics and an aesthetic structure. This is then applied to the actual street to improve the daily experience of local residents and tourists (Chen *et al.* 2024). The selection and utilisation of materials is a key aspect. Local natural materials can be employed directly or incorporated into the design to create a regional cultural ambience through the manipulation of texture and material. To illustrate, Wang Shu's project in Wen village, Fuyang District, Hangzhou, the exterior plastering is composed of yellow clay sourced from the village, and the process is also the rammed earth technique employed by the local ancestors. Consequently, the design exhibits a natural coherence with the visual texture of the traditional village.

Furthermore, cultural symbols can be refined to symbolize and express local traditional culture using modern construction techniques and new materials, perpetuating these cultural elements in an innovative manner. Studio gt2p's Imaginary Geographies collection of furniture is a digital material reconstruction of the iconic geography of the Andes Mountains, where the designers use technology and digital fabrication techniques to create lines from sound and transform them into furniture objects.

In addition, modern technology, such as multimedia or AI, can be employed to recreate historical scenes in a manner that enables the public to experience and feel the history in a contemporary setting. This approach facilitates the fusion of technical and emotional, material and spiritual elements. The concept of Landscape-Feng Feng, located in Hong Kong and designed by Studio Kota, is abstracted from the natural elements of Hong Kong, such as waves, tides, and hills. The rhythm of waves and tides can be fused to create an infinite cycle, and its inherent connection and the energy it generates define the spirit of Hong Kong people's spirituality and dynamism.

By employing urban furniture as a conduit for the rational implementation of regional elements, it is possible to enhance the functionality and comfort of the furniture, thereby reflecting the cultural character of the city. This enables individuals to gain a deeper understanding and recognition of the local characteristics and culture through their utilisation of the furniture (Pahlavani 2021; Lu 2023). Furthermore, the aesthetic experience of the urban public space can be enriched, thus reinforcing the city's cultural image and infusing it with new vitality. This, in turn, serves to effectively promote the innovation and development of outstanding culture.

## EXPERIMENTAL

### An Integrated Research Method based on the KJ-AHP Approach

The KJ method, also known as the affinity diagram method, is a qualitative research method that can be used to quickly clarify complex information and form an effective information architecture. This method was proposed by the humanist Jiro Kawakita and facilitates the construction of a demand framework by the designer.

The analytic hierarchy process (AHP) is a qualitative and quantitative combination of a hierarchical weighting analysis method. The method involves solving the eigenvectors of the judgement matrix to determine the weight index of each layer element on the upper level of the target. Additionally, the consistency ratio is tested, the validity is determined, and the levels are obtained, which effectively improves the objectivity of decision–making.

This paper presents an innovative integration method, combining the KJ–AHP approach with the parametric design method, for conducting qualitative and quantitative analyses of the diverse requirements for urban seating design in regional elements. Firstly, the KJ method is employed to collect and arrange complex information, identify the logic and potential laws between the data, and group it. This is then combined with the AHP method to calculate the weight of the demand for urban seating design. The Parametric Design is then carried out according to the results, which can effectively improve user satisfaction.

## Collation and Weighting of User Requirements based on the KJ-AHP Method

The procedure for organizing and prioritizing user requirements based on the KJ-AHP method is illustrated in Fig. 1.

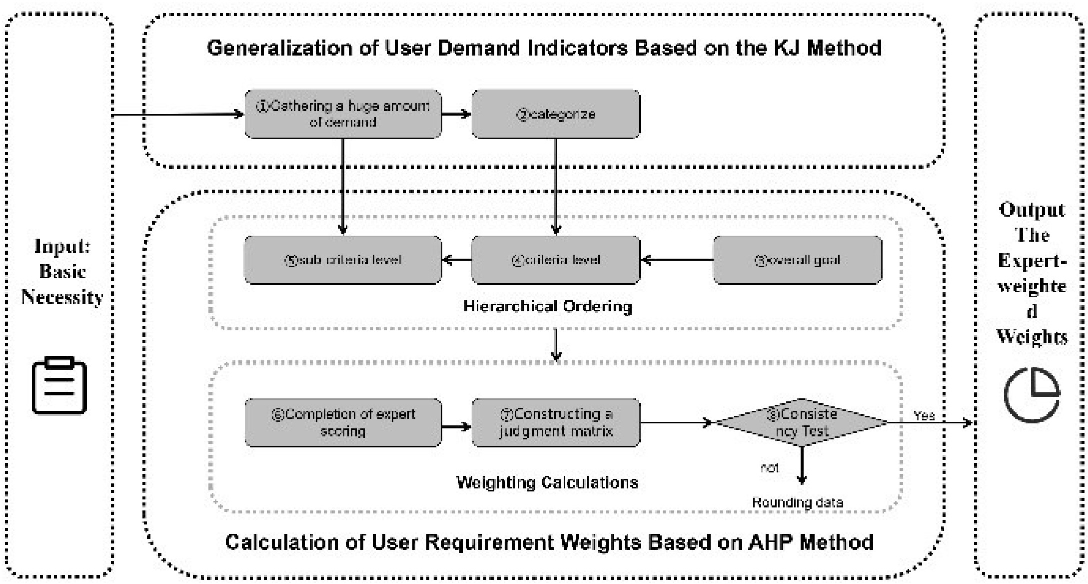



**Fig. 1.** Technology roadmap for the KJ–AHP method

First, user demand indicators are collated and categorized according to the KJ method in the semantic dimension, as illustrated in Fig. 2. The design team members collect and organise a substantial number of user requirements for urban seating devices. Following the processes of synonymous merging and simplification, 13 fundamental demand indicators are obtained after classification and organisation. The 13 sub-criteria level indicators were formed by naming and categorizing the requirements with relatively close logic. Subsequently, the sub-criteria level indicators were integrated to form four criteria level indicators, namely, function and maintenance, vision and art, material and technology, and concept of regional characteristics. Ultimately, the objective is to summarize the design requirements of urban sitting furniture with regional elements based on the parametric design method and to summarize and organize the hierarchical structure model.

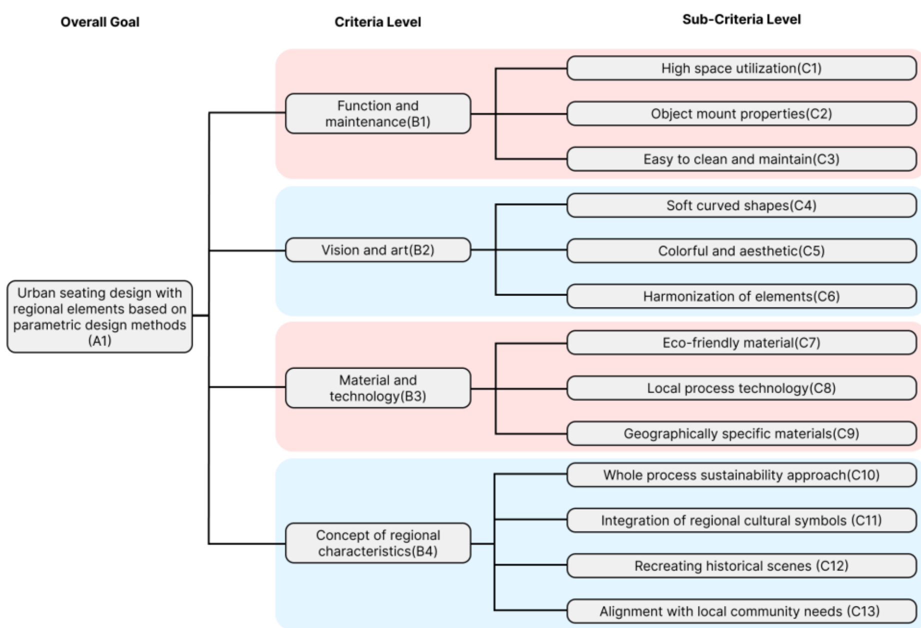



**Fig. 2.** Flowchart of the AHP hierarchical structure

In this study, six experts in the field of furniture design and engineering were invited to evaluate the items according to a nine-level scale method. The questionnaire was designed with six questions. The first five questions assessed the significance of the aforementioned criteria level and the associated needs of the sub-criteria level in comparison to the preceding indicator. This was done through a two-by-two matrix, where values were assigned based on the following xi/xj scale. The resulting scoring values are odd integers, situated midway on the scale. The scale is based on the item set A1= B1, B2, B3, B4, which is used as an illustrative example. The concepts of function and maintenance, vision and art, material and craftsmanship, and regional characteristics are compared two by two to determine the degree of importance to the overall goal. In other words, the importance of B1 to the overall goal is compared to that of B2, B1 to the overall goal is compared to that of B3, B1 to the overall goal is compared to that of B4, B2 to the overall goal is compared to that of B3, and B3 to the overall goal is compared to that of B4. This process is repeated for each sub-criteria level, resulting in the identification of item sets for each level. Question 6 entails the calculation of each expert weight subsequent to the scoring of experts based on their educational background, professional designation, and other pertinent indicators. Subsequently, the six experts on the criteria level and the sub-criteria level provided scores, which were used to construct a judgment matrix to obtain the weights of each indicator. After processing, the maximum eigenvalue was obtained, and then the consistency index (CI) was calculated. Finally, the consistency ratio (CR) was calculated. The matrix was found to pass the consistency test when CR < 0.1, and the failed samples were removed. The combined weights of the experts were then calculated, resulting in the expert-weighted weights of the criteria level and the sub-criteria level. The specific methods are as follows:

The ratings of the six experts on the criterion layer and each sub-criterion layer were aggregated to construct a judgment matrix, designated as Z. The weights were calculated for the matrix, and the raw data were normalized by columns to obtain the matrix A:

$$a_{ij} = \frac{Z_{ij}}{\sum_{i=1}^{n} Z_{ij}} (i,\ j = 1,2,\ldots,\ n) \quad (1)$$

The weights of the indicators were obtained by summing the matrix A by rows of items and dividing by n.

$$\omega_i = \frac{\sum_{j=1}^{n} a_{ij}}{n} (i = 1,2,\ldots,\ n) \quad (2)$$

The maximum eigenvalue, denoted by $\zeta_{max}$, is calculated by substituting the weight values into the following equation:

$$\lambda max = \sum_{i=1}^{n} \frac{[ZW]_i}{n\omega_i} (i = 1,2,\ldots,\ n) \quad (3)$$

In order to ascertain the consistency index (CI), the maximum eigenvalue ($\lambda_{max}$) is introduced into the formula.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (4)$$

The consistency indicator (CI) and the average random consistency indicator (RI) are incorporated into the following formula to obtain CR. The value of RI can be determined by referencing the table of standardized values of illumination.

$$CR = \frac{CI}{RI} \quad (5)$$

A value of CR < 0.1 indicates that the matrix passes the consistency test, and the data samples that pass the consistency test are retained for the subsequent calculation.

Ultimately, the calculation of the AHP comprehensive weighted average weights is conducted in the following manner: The resulting weights that pass the consistency test are assembled to create the weight matrix , wherein each column represents a vector of weights derived from an expert matrix and each row represents a vector of weights assigned to each expert for the same problem.

$$W_{wj} = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1n} \\ w_{21} & w_{22} & \cdots & w_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ w_{m1} & w_{m2} & \cdots & w_{mn} \end{bmatrix} \quad (6)$$

In this paper, the subjective assignment method was employed to evaluate the educational background, professional designation, tenure, and familiarity with the indicators of the experts, with the objective of normalizing the weight of each expert. The criteria for assessing the scores are presented in Table 1. The weights of the six experts were evaluated, and the results are shown in Table 2.

**Table 1.** Expert Scoring Criteria

| Educational Background | Score | Professional Designation | Score | Tenure | Score | Familiarity | Score |
|---|---|---|---|---|---|---|---|
| Bachelor's degree and below | 1 | Middle level | 1 | Less than 5 years | 1 | Unfamiliar | 1 |
| Bachelor's degree | 3 | Associate Senior | 3 | 5-10 years | 3 | Average | 3 |
| Doctoral degree | 6 | High ranking | 6 | More than 10 years | 6 | Very familiar | 6 |

**Table 2.** Table of Expert Weighting Results

| | Educational Background | Professional Designation | Tenure | Familiarity | Score | Weight |
|---|---|---|---|---|---|---|
| Expert 1 | 6 | 6 | 6 | 6 | 24 | 0.24 |
| Expert 2 | 6 | 1 | 6 | 3 | 16 | 0.16 |
| Expert 3 | 3 | 3 | 6 | 6 | 18 | 0.18 |
| Expert 4 | 3 | 3 | 6 | 3 | 15 | 0.15 |
| Expert 5 | 3 | 6 | 6 | 6 | 21 | 0.21 |
| Expert 6 | 1 | 1 | 1 | 3 | 6 | 0.06 |

The weighted expert weight matrix, denoted by W, is obtained by multiplying each column of the weight matrix by the weight assigned to the corresponding expert.

$$W_{zj} = [w_1, w_2, ..., w_m] \tag{7}$$

$$w_1 + w_2 + ... + w_m = 1 \tag{8}$$

$$W = W_{zj} \cdot W_{wj} = [W_1, W_2, \ldots, W_n] \tag{9}$$

The weight matrix is of the form m×n, and the weight vector of experts is of the form m×1. The matrix is multiplied pointwise, that is, m×1·m×n, in order to obtain the weighted vector of n×1 indicator weights. This is then divided by the number of experts, m, in order to obtain the weighted average vector, which is then normalized in order to obtain the expert-weighted AHP weight indicators for each criteria level, as well as for each sub－criteria level, as illustrated in Table 3.

The weighted average weight of the criterion layer is multiplied by the weighted average weight of each sub-criterion layer to obtain the combined weighted average weight of each indicator. Subsequently, the combined weights are sorted, and the three needs with relatively high weight values are identified. These are the integration of regional cultural symbols, the reproduction of historical scenes, and the precision of service targets. The elements associated with these needs are then highlighted as much as possible in the design strategy.

A review of extant literature revealed significant ‘contextual differences’ in the weighting of design elements in urban furniture design across different studies. For instance, Pahlavani (2021) underscores the pivotal role of functionality in user experience, Zhou and Zhang (2021) prioritize the structural logic of adapting seating to behavioral pathways, Li (2017) accentuates the integration of natural ecology into parametric modeling, and Lesan and Gjerde (2021) advocate for the cultural neutrality and multi-adaptive nature of design language.

**Table 3.** Table of Weights for Each Level and Combined Weighted Weights

| Criteria Level | Weighted Value | Sub-Criteria Level | Weighted Value | Combined Weighted Weight Values | Ranking |
|---|---|---|---|---|---|
| Function and maintenance (B1) | 0.0807 | High space utilization(C1) | 0.2016 | 0.0163 | 13 |
| | | Object mount properties (C2) | 0.3099 | 0.0250 | 12 |
| | | Easy to clean and maintain (C3) | 0.4885 | 0.0394 | 9 |
| Vision and art (B2) | 0.1868 | Soft curved shapes (C4) | 0.1711 | 0.0320 | 11 |
| | | Colorful and aesthetic (C5) | 0.4723 | 0.0882 | 4 |
| | | Harmonization of elements (C6) | 0.3566 | 0.0666 | 7 |
| Material and technology (B3) | 0.1499 | Eco-friendly material l(C7) | 0.2213 | 0.0332 | 10 |
| | | Local process technology (C8) | 0.3267 | 0.0490 | 8 |
| | | Geographically specific materials (C9) | 0.4521 | 0.0678 | 6 |
| Concept of regional characteristics (B4) | 0.5826 | Whole process sustainability approach (C10) | 0.1399 | 0.0815 | 5 |
| | | Integration of regional cultural symbols (C11) | 0.3836 | 0.2235 | 1 |
| | | Recreating historical scenes (C12) | 0.3208 | 0.1869 | 2 |
| | | Alignment with local community needs (C13) | 0.1558 | 0.0907 | 3 |

Note: Overall Goal: Urban seating design with regional elements based on parametric design methods (A1)

In contrast, this study places cultural expression at the core of the design weighting structure, but it places greater emphasis on the direct linkage between form and cultural symbols. This finding suggests that the weighting orientation of parametric design is not solely influenced by methodology but is also substantially constrained by research contexts, cultural backgrounds, and design objectives. In the context of urban renewal initiatives that prioritize 'cultural narratives' and 'local identity,' the indicator ranking in this study underscores a discernible trend toward the elevation of cultural value in public spaces within the Chinese context.

However, a notable constraint of this study is the limited number of participating experts. To address this shortcoming, the study incorporated expert-weighted scoring and consistency tests to enhance the reliability of the results. However, the AHP method itself is highly subjective, and its conclusions are contingent on the personal judgments of experts. To enhance the reliability of the method, future studies may consider expanding the sample size of experts to encompass a more diverse range of perspectives. It is important to note that the hierarchical structure developed in this study demonstrates excellent transferability. New cities or sites can directly reuse this framework when applying it by simply inviting local experts to reassign weight values based on the specific context. In the event that particular requirements emerge within the new context, the KJ method interview can be conducted once more to extract locally specific content and integrate it into the original structure. The contributions of the six experts in this study are not the final outcome, but rather the basis for a sustainable and adaptable 'methodological system.' In the future, any city has the potential to utilize this system to implement localized practices, thereby achieving the local expression and continuity of culture.

## Parametric Design Process

The parametric design process encompasses the full range of activities, from the initial integration of design requirements to the final product assembly, as illustrated in Fig.

3. Each phase is anchored in the tenets of parametric design, ensuring the flexibility and adaptability of the design. This methodology primarily revolves around the creation of parametric models and the modification of parameters.

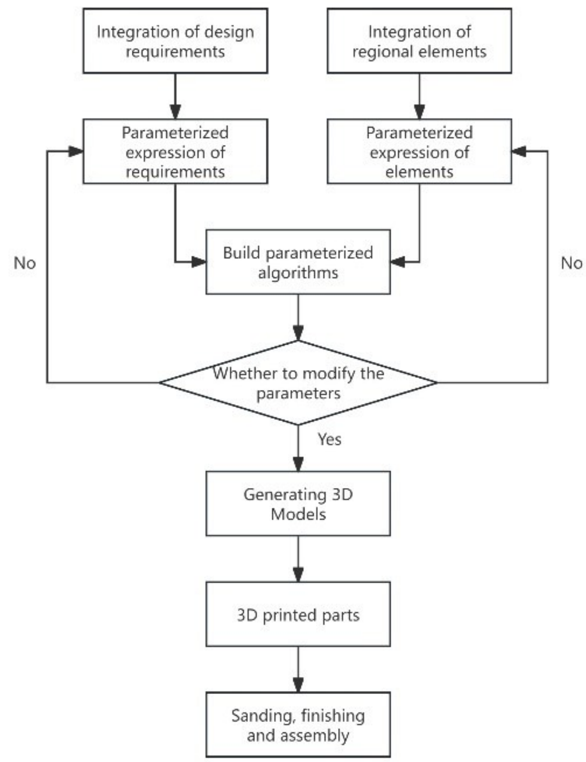



**Fig. 3.** Parametric design flowchart

## RESULTS AND DISCUSSION

### Element Extraction

This study is concerned with the design and optimization of urban commercial public space, with Harbin Westred Square serving as a case study. Harbin Westred Square, formerly known as Harbin Machinery Factory, was once an important location for industrial development, carrying Harbin's unique history and culture. The factory was famous for its spirit of 'ants gnawing on bones', reflecting the regional qualities of courage and perseverance. The integration of these cultural elements into the styling design of the furniture serves to enhance both the cultural expression of the furniture and its role as an important carrier for the dissemination of regional elements. This, in turn, enhances the aesthetic value of the public space and contributes to the inheritance and innovation of the city's culture.

In this historical context, the design of parametric urban furniture can be better combined with local culture, reflecting the spirit of industrial heritage. The extremely strong performance of parametric design in this space is based on its flexible use of form and function, not only to enhance the efficiency of the use of space, but also to enhance the aesthetic expression (Li *et al.* 2023). The study particularly draws upon the ant image of 'ants gnawing on bones' and the hand-wheel element of old machinery, integrating them into the design of the seating furniture in this area, as shown in Fig. 4. Through the furniture shape, color and material to convey the concept of ‘ants gnawing on bones’ to enhance the public’s sense of identity and sense of belonging to the local culture. The objective of this study is to establish a correlation between each high-weight sub-criterion and the design parameters and operational logic within the Grasshopper environment. For instance, Integration of regional cultural symbols (C11, weight = 0.2235) exerted a direct influence on the selection of visual symbols, such as the ‘ant motif’ and ‘industrial handwheel,’ in this design. These symbols were subsequently embedded into the Rhino model *via* an image sampler and Boolean operations. Recreating historical scenes (C12, weight = 0.1869) guided the authors in selecting materials with an old industrial feel and geometric patterns that convey a sense of era in the modeling process; while ‘color aesthetics’ (C5, weight = 0.0882) was realized through parameters such as gradient texture control and module subdivision density. These user requirement metrics are mapped to adjustable parameters in modeling, such as contour spacing, extrusion depth, hole density, and modulus distribution, forming a weight-driven geometric generation logic loop. By reconstructing these elements with regional elements and industrial aesthetics, the study employs parametric design techniques to establish a connection between history and modernity, infusing the public seating with a sense of cultural depth and historical gravity.

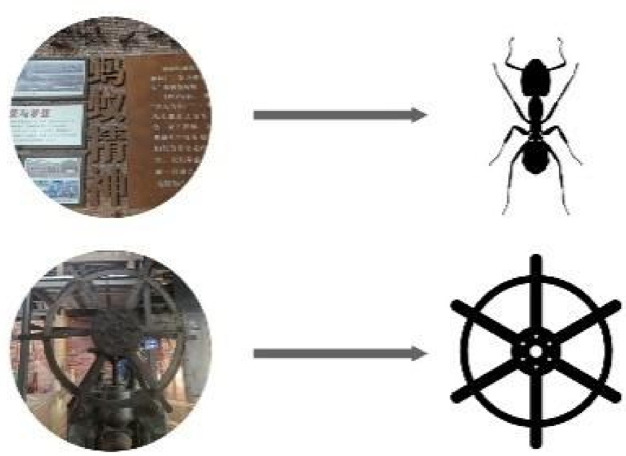


**Fig. 4.** Parametric design element extraction

## Parameterized Algorithm

*Application case 1:*

In this scenario, the height was set to 450 mm, the width to 600 mm, and the length to 1300 mm. Subsequently, the Tyson polygons were reconstructed using the Weavebird plugin, which is a set of topological mesh subdivision and conversion algorithms that can be used to gradually obtain smoother surfaces through iteration. In addition, Image Sampler was used to map parametric coordinates to images, and then pixels were sampled using interpolation to extract channel information. Finally, the output was used to control the model and flexibly generate flexible hole patterns on the seat surface.

In the Grasshopper plugin, a rectangle was defined on demand using the Center Box component, and a series of random points were generated within the rectangular volume using the Populate 3D component. The random points will subsequently serve as the basis for the generation of Tyson polygons using the Voronoi algorithm, which will produce multiple Tyson polygons to provide support for the complex morphology of the anthill. A solid difference set operation must then be performed on each poly-surface set in order to skeletonize the middle of the rectangular volume. This process enhances the spatiality of the design and the complexity of the structure. The Picture Frame tool of the Weave bird plug-in was employed to create openings at the center of each face of the generated Tyson polygon. This design not only enhances the visual presentation but also echoes the ecological characteristics of the ants. The Loop Subdivision algorithm converts the mesh around the holes into subdivided triangular faces, thus smoothing the shape and refining the structure. Finally, the Mesh Thicken component was used to thicken the subdivided mesh body to generate a solid structure. Figure 5 shows a diagram of the seat frame parameterization algorithm.

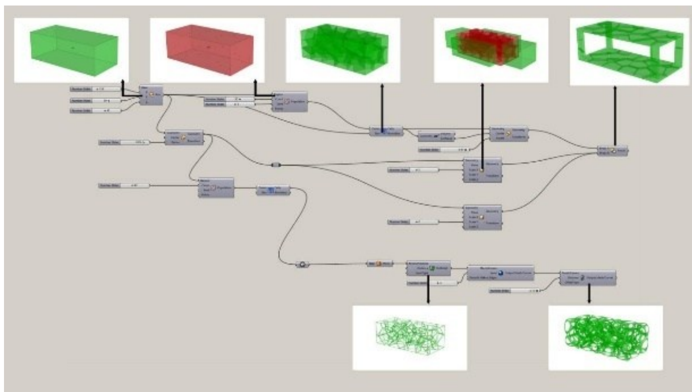


**Fig. 5.** Reconstructing Tyson polygons using the Weavebird plugin

Generating image interference: The procedure involved the generation of a dot matrix in the specified area, sampling of the image by Image Samper operator, extracting the grayscale value of the ant image, and using Remap Numbers operator to map the grayscale value to the interval. Adjustments were made to get the interval where the image is located by Construct Domain operator and map the dot matrix to the interval where the image is located. The procedure first maps the spatial coordinates of the dot matrix to the image domain (U,V ∈ [0 – 1]) for consistent sampling. Subsequently, grayscale values obtained from the Image Sampler are remapped to a user-defined geometric interval (via Construct Domain and Remap Numbers), which controls dot size/spacing and yields the interference dot-matrix pattern. Figure 6 shows a diagram of the interference image parameterization algorithm.

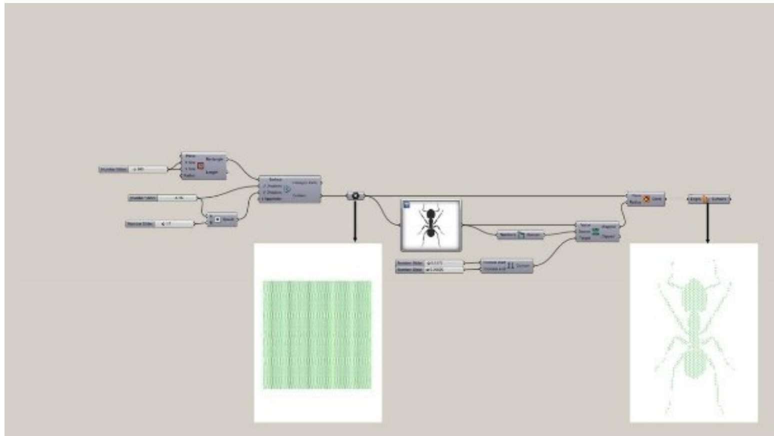
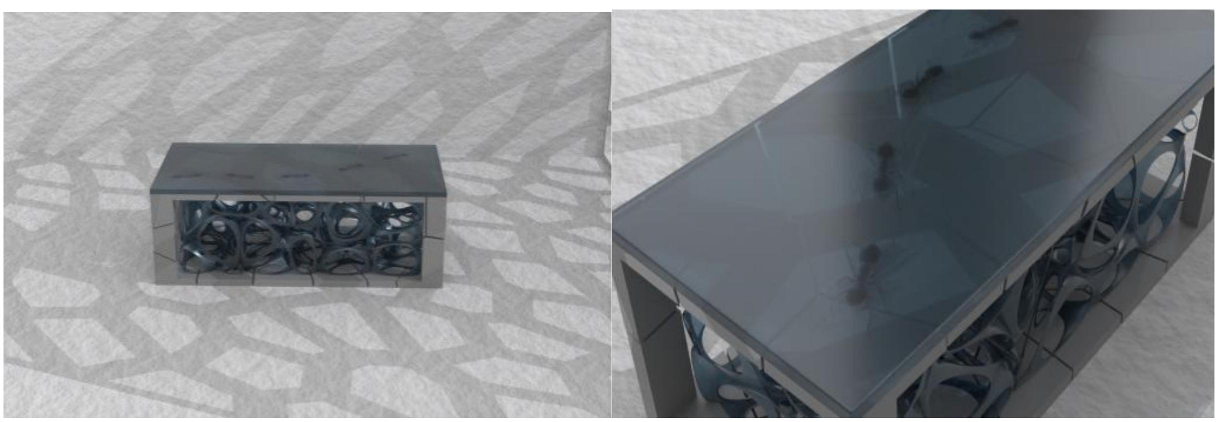


**Fig. 6.** Parameterization algorithm for disturbed images

Subsequently, a rectangle was created in Rhino software as the base part of the seat and an interference dot pattern, an ant pattern, was incorporated into the Rhino model. The appropriate thickness was then set, and Boolean operations were applied to create the surface of the seat with the interference dot pattern texture. Ultimately, the frame component of the preceding stages was integrated into the Rhino model, thereby concluding the design of the entire seat, as illustrated in Fig. 7.



**(a)** First rendering **(b)** Second rendering

**Fig. 7.** The rendering of application case 1

*Application case 2:*

Figure 8 shows another design scheme, in which the total length is set to 2540 mm, the total height is set to 870 mm, the highest point of the curved seat surface is 470 mm, and the maximum value of the seat depth is 460 mm. The seat was constructed using a modularized piecewise structure, which facilitates both production and transportation. The design is inspired by the industrial mechanical hand wheel at the Harbin Machine Union Machinery Factory. The parametric design is logical and easily adjustable, and the streamlined structure can be customized according to the specific shape of the site. Furthermore, by transforming the seating layout, it is possible to create diverse spatial functions and features that promote communication.

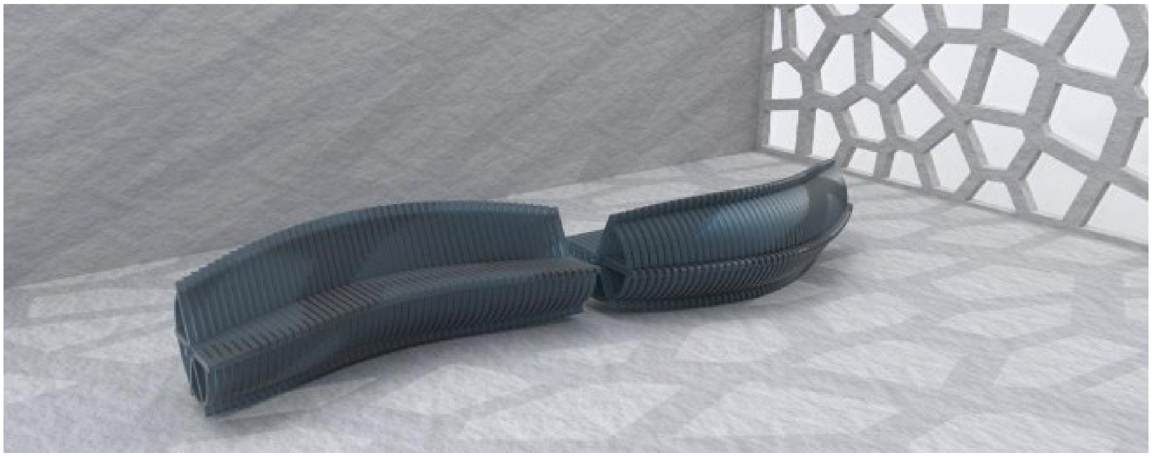


**Fig. 8.** Parametric flowchart mainly constructed by the series operator

The specific steps are shown in Fig. 9. First, the Series operator should be used to create an isotropic series with a step length of 50 mm and a step count of 6. Then, the Move and Scale functions should be applied to move and scale the generated data along the x–axis. Subsequently, the data structure is modified through the utilisation of the Flip Matrix operator. Ultimately, the Contour tool is employed to ascertain the direction and distance, thereby constructing the contours of a series of composite surfaces. Subsequently, the Boundary Surfaces command is applied to generate planes. Subsequently, the Extrude function is employed to extrude along the y–axis, thereby forming a three–dimensional structure.

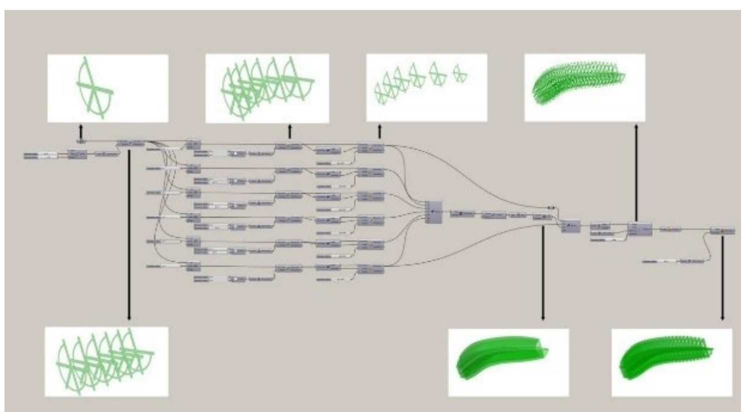


**Fig. 9.** Parameterized algorithm for application case 2

## Confirmation Study Based on Fuzzy Comprehensive Evaluation

Finally, six experts were invited to evaluate the results of the design practice using Fuzzy Comprehensive Evaluation (FCE). FCE is a comprehensive evaluation method based on fuzzy mathematics, which borrows the maximum membership principle and idea to combine multiple indicators into a single indicator, transforming qualitative evaluation into quantitative evaluation.

The method is as follows: First, create a fuzzy comprehensive evaluation questionnaire and distribute it. Ask experts to select the corresponding comments for each indicator in the table. Set five evaluation levels, including “very good, good, average, poor, and very poor.” For example, if you think A11 is average, check the box below “average.”

Note that the questionnaire only collects Sub-Criteria Level data.

The second step is to establish a set of FCE factors, a set of evaluation criteria, and a set of weights. U = {UA, UB, UC, UD} is defined as the set of criteria level weighted values, U1 = {UA1, UA2, UA3} is defined as the set of Sub-Criteria Level weighted values, and the evaluation set V = {Excellent, Good, Average, Pass, Fail} (with corresponding scores of 5, 4, 3, 2, 1) is defined; the weight set is defined as Wi = {a1, a2, a3, a4...}.

The FCE questionnaires distributed to six experts were collected, and the initial quantitative evaluation values shown in Table 4 were obtained.

After quantifying the indicators, the membership degree of the i-th factor for the j-th evaluation was obtained, where the membership degree F is the proportion of the number of people who gave the j-th evaluation for the i-th factor in the total number of people who participated in the evaluation.

**Table 4.** initial Quantitative Evaluation Values

| Sub-Criteria Level | Very good | Good | Average | Poor | Very poor |
|---|---|---|---|---|---|
| High space utilization(C1) | 2 | 3 | 1 | 0 | 0 |
| Object mount properties(C2) | 1 | 1 | 2 | 2 | 0 |
| Easy to clean and maintain(C3) | 0 | 1 | 2 | 1 | 2 |
| Soft curved shapes(C4) | 3 | 2 | 1 | 0 | 0 |
| Colorful and aesthetic(C5) | 2 | 3 | 1 | 0 | 0 |
| Harmonization of elements(C6) | 3 | 1 | 2 | 0 | 0 |
| Eco-friendly material(C7) | 1 | 1 | 3 | 1 | 0 |
| Local process technology(C8) | 1 | 0 | 2 | 2 | 1 |
| Geographically specific materials(C9) | 0 | 0 | 4 | 1 | 1 |
| Whole process sustainability approach(C10) | 2 | 1 | 2 | 1 | 0 |
| Integration of regional cultural symbols (C11) | 3 | 3 | 0 | 0 | 0 |
| Recreating historical scenes (C12) | 3 | 1 | 2 | 0 | 0 |
| alignment with local community needs (C13) | 1 | 4 | 1 | 0 | 0 |

This establishes a fuzzy relationship matrix:

$$F_{ij} = \begin{bmatrix} F_{i1}^{j1} & F_{i1}^{j2} & \cdots & F_{i1}^{j5} \\ F_{i2}^{j1} & F_{i2}^{j2} & \cdots & F_{i2}^{j5} \\ \cdots & \cdots & \cdots & \cdots \\ F_{in}^{j1} & F_{in}^{j2} & \cdots & F_{in}^{j5} \end{bmatrix} \tag{10}$$

Fuzzy operations were performed on the weight Wi and fuzzy matrix Fij to obtain the fuzzy evaluation results of the indicator layer row vector Ui.

$$U_i = W_i \times F_{ij} = [u_i^1 \ u_i^2 \ u_i^3 \ldots \ u_i^n] \tag{11}$$

The final fuzzy evaluation results for each level of indicators were obtained by multiplying the membership degrees of each indicator by the corresponding set of evaluation comments, thereby determining the final evaluation results for each level of indicators. The scoring formula is as follows:

$$Y_{ij} = [u_i^1 \; u_i^2 \; u_i^3 \ldots u_i^n] \times [\mathbf{5} \quad \mathbf{4} \quad \mathbf{3} \quad \mathbf{2} \quad \mathbf{1}]^T \tag{12}$$

The membership degrees of various indicators are summarized in Table 5.

Based on the FCE results, the evaluation scores for indicators with higher weights, such as C11, C12, C13, and C5, fell within the good range, reflecting significant achievements in visual language and cultural representation. However, the overall evaluation score was 3.8798, which fell within the average range, indicating that further improvements are needed in terms of feasibility and engineering details. Going forward, efforts should be made to strengthen functional optimization and integration with local technical resources to enhance overall sustainability and user experience.

**Table 5.** Summary of Membership Degrees

| Membership degree results | Very good | Good | Average | Poor | Very poor | Score |
|---|---|---|---|---|---|---|
| Value | 5 | 4 | 3 | 2 | 1 | |
| High space utilization(C1) | 0.333 | 0.5 | 0.167 | 0 | 0 | 4.17 |
| Object mount properties(C2) | 0.167 | 0.167 | 0.333 | 0.333 | 0 | 3.17 |
| Easy to clean and maintain(C3) | 0 | 0.167 | 0.333 | 0.167 | 0.333 | 2.33 |
| Soft curved shapes(C4) | 0.5 | 0.333 | 0.167 | 0 | 0 | 4.33 |
| Colorful and aesthetic(C5) | 0.333 | 0.5 | 0.167 | 0 | 0 | 4.17 |
| Harmonization of elements(C6) | 0.5 | 0.167 | 0.333 | 0 | 0 | 4.17 |
| Eco-friendly material(C7) | 0.167 | 0.167 | 0.5 | 0.167 | 0 | 3.33 |
| Local process technology(C8) | 0.167 | 0 | 0.333 | 0.333 | 0.167 | 2.67 |
| Geographically specific materials(C9) | 0 | 0 | 0.667 | 0.167 | 0.167 | 2.5 |
| Whole process sustainability approach(C10) | 0.333 | 0.167 | 0.333 | 0.167 | 0 | 3.67 |
| Integration of regional cultural symbols (C11) | 0.5 | 0.5 | 0 | 0 | 0 | 4.5 |
| Recreating historical scenes (C12) | 0.5 | 0.167 | 0.333 | 0 | 0 | 4.17 |
| Alignment with local community needs (C13) | 0.167 | 0.667 | 0.167 | 0 | 0 | 4 |
| Function and maintenance(B1) | 0.1189 | 0.2339 | 0.2997 | 0.1847 | 0.1628 | 2.96 |
| Vision and art(B2) | 0.4213 | 0.3526 | 0.2261 | 0 | 0 | 4.20 |
| Material and technology(B3) | 0.0913 | 0.0369 | 0.521 | 0.2211 | 0.1298 | 2.74 |
| Concept of regional characteristics(B4) | 0.4248 | 0.3725 | 0.1795 | 0.0233 | 0 | 4.20 |
| Urban seating design with regional elements based on parametric design methods (A1) | 0.3495 | 0.3073 | 0.2491 | 0.0616 | 0.0326 | 3.88 |

## CONCLUSIONS

The present study developed a comprehensive methodology for urban furniture design, integrating user needs analysis, parametric generative design, and fuzzy evaluation. The innovative application of the integrated KJ–AHP–FCE method enabled the study to achieve a closed-loop process, encompassing design weight analysis and effect evaluation. Utilizing the Harbin Industrial Heritage Space, designated as Harbin Westred Square as a case study, the research employs dual validation through expert weighting and fuzzy comprehensive evaluation. This approach not only establishes the priority sequence of each design dimension but also reveals the core value of 'thematic design' in urban furniture. By constructing a unified narrative thread through cultural imagery, the furniture transcends its basic functional attributes and is elevated to a spatial medium that carries collective memory and emotional resonance.

In the context of sustainability, parametric models facilitate the realization of structural lightweighting and precise material matching through geometric control. When employed in conjunction with digital manufacturing techniques, such as three-dimensional printing, this method facilitates on-demand production, personalized customization, and the reduction of material waste. Furthermore, parametric logic can be integrated into life cycle assessment (LCA) tools to optimize numerous parameters, including carbon emissions, usage cycles, and maintenance requirements, from the initial design phase.

It is imperative to acknowledge that the validation of the present method in the context of industrial heritage necessitates additional testing across a more extensive array of urban spatial types to refine its adaptability framework. In contexts that are not industrial or culturally neutral, it is important that the indicator structure and weighting logic be dynamically adjusted to account for heterogeneous spatial characteristics. This limitation elucidates the trajectory for future research endeavors, namely the development of a flexible evaluation system through multi-scenario validation.

The practical model proposed in this study combines theoretical innovation with practical value. At the methodological level, it establishes a replicable and adaptable integrated design-evaluation pathway. At the practical level, it provides a systematic solution for public space design that integrates cultural narratives, environmental responsiveness, and sustainable optimization. This offers a new paradigm for enhancing the quality of the human living environment in the context of smart cities.

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Article submitted: April 21, 2025; Peer review completed: June 13, 2025; Revised version received: July 21, 2025; Accepted: July 22, 2025; Published: October 30, 2025.
DOI: 10.15376/biores.20.4.10974-10991