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An Innovative Design and Application Method for Song Yun Culture Based on Cultural Genes: Integration of Analytic Hierarchy Process and Shape Grammar

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Article

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ABSTRACT

This study integrates the Analytic Hierarchy Process (AHP) with Shape Grammar to translate cultural sources into garment structure. An expert panel of 15 raters (Round-1) was refined to 5 domain experts (Round-2). The AHP hierarchy comprises three levels (goal–criterion–alternative) with four criterion dimensions (B1–B4). Consistency metrics were audit-ready: Round-1 matrices showed CI ≈ 0.03–0.12 and CR ≈ 0.07–0.18 (two alternative-layer matrices >0.10); after expert screening, Round-2 matrices achieved CI ≈ 0.02–0.08 and CR ≈ 0.03–0.09 (CR < 0.10 for all). Headline global weights included C7 Literature & Arts = 0.233 and C4 Craft Products = 0.186. Shape-grammar rules then operationalised the prioritised criteria into 2D feature-line rewrites and 3D realisation, forming a reproducible pipeline. Numerical reporting follows three-decimal precision with decimal-point alignment, and matrices/scripts are supplied for reproduction. These results demonstrate a compact, data-forward bridge from cultural genes to controllable garment morphology.

KEYWORDS

cultural genes, analytic hierarchy process (AHP), shape grammar, Song Yun culture, washing hands and viewing flowers (painting theme), garment morphology, clo3d 7.2 (3d virtual fitting)

INTRODUCTION

In cultural-heritage design, the target constructs (e.g., symbolism, ritual salience, morphological distinctiveness) are multi-criteria and partly intangible. The Analytic Hierarchy Process (AHP) accommodates expert judgment through pairwise comparisons, quantifies priorities, and – critically - tests internal consistency (CI/CR), thus reducing arbitrariness while retaining interpretability. Compared with consensus-only procedures such as Delphi (rich in discussion yet lacking explicit global weights), data-driven dimensionality reduction (e.g., PCA; efficient but requires large-N metric data and sacrifices semantic transparency), or scoring schemes that still depend on exogenous weights (e.g., TOPSIS/entropy methods), AHP offers a transparent, auditable bridge between qualitative expertise and quantitative ranking that is well suited to small expert panels typical of heritage appraisal. Prior studies in design-gene extraction likewise use AHP to stabilise importance ordering and to control evaluator subjectivity, which is consistent with our two-round expert screening and CR<0.10 requirement reported in this manuscript [1,2].

Shape Grammar provides a formal generative system that encodes operations (substitution, addition/deletion, scaling, rotation, translation, etc.) and permits step-wise traceability from precedent to variant [3]. This study fixes bilingual terminology at first use and adheres to it thereafter: Shape Grammar (形状文法), cultural genes (文化基因), and positive mutation(s) (正向变异). This study situates the contribution against international work at the intersection of cultural-heritage digitisation and generative design. In garment and pattern design, grammar-based pipelines have been used to formalise silhouette and block transformations, panel/trim layout, and pattern rewrites that remain traceable under cultural or technical constraints (e.g., rule-controlled 2D→3D pipelines with virtual fitting) [4]. In contrast, data-driven approaches emphasise motif extraction and style transfer—for example, clustering or deep models that learn recurring contours and textures from corpora, as in recent AIGC-assisted pipelines [5]—but may trade off explainability or constraintability. This study contributes a hybrid yet rule-explicit path: criteria are prioritised analytically and then transformed under an operational grammar, yielding a reproducible bridge from cultural sources to garment structure. In fashion and adjacent domains, grammar-based pipelines have been used to formalise silhouette/pattern transformations and accessory morphologies; when linked with 3D garment modelling/virtual fitting, they lift 2D representations into controllable 3D configurations. Relative to direct motif pastiche or purely parametric editing (limited cultural constraint encoding), and relative to opaque data-driven synthesis (e.g., black-box image generation with authenticity risks), Shape Grammar offers constraintable, explainable derivations that preserve cultural semantics while enabling creative variation [4].

The literature supports coupling evaluation frameworks with generative systems to both select-what (scientifically prioritised features) and transform-how (rule-controlled morphology). In our setting, AHP provides defensible weights to filter high-value cultural genes (mitigating bias and documenting consensus), while Shape Grammar operationalises their transformation under explicit rules. This pairing is particularly appropriate for Song Yun garment morphology, where etiquette-bound structures must be respected even as forms are adapted to modern functions; it also aligns with virtual-fitting workflows documented in computational fashion studies [4]. The integrated path, therefore, offers a reproducible and auditable pipeline from cultural-gene extraction to 3D design generation, minimising negative mutations and ensuring cultural fidelity.

Literature Review

Amid globalisation and plural aesthetics, traditional heritage had to preserve its essence while adapting to contemporary design contexts to sustain vitality [6-9]. A cultural gene (i.e., meme) is the unit of cultural transmission or imitation [10]. Related notions such as 'design DNA' operationalise heritable, extractable features in product-family design [11].

From a methodological perspective, the Analytic Hierarchy Process (AHP) was employed to provide a systematic approach for evaluating the relative importance of cultural elements under multi-criteria conditions. A hierarchical structure model was constructed, pairwise comparison matrices were developed, and consistency checks were performed. Through this process, qualitative judgments were combined with quantitative analysis, subjective bias was reduced, and the reliability of decision-making was improved [1]. At the same time, Shape Grammar was applied to provide a formalised framework for morphological generation and transformation. A set of generative and transformative rules — such as substitution, addition/deletion, scaling, rotation, and translation - was defined, and existing forms were systematically evolved into new forms [4]. By integrating AHP with Shape Grammar, a complete methodological chain was established, in which the extraction of cultural genes was followed by their transformation into contemporary designs. In this chain, the scientific selection of features was ensured, and morphological generation was controlled effectively.

International applications of Shape Grammar have extended beyond architecture. Song Yun Culture, as the concentrated embodiment of the artistic essence and intellectual achievements of the Song Dynasty, was taken as the main object of this study. Definition and Conceptual Boundaries of Song Yun Culture. In this study, "Song Yun" (宋韵) is defined as the integrated aesthetic-ideational complex that crystallised during the Northern and Southern Song dynasties (960–1279), with its spatial core shifting from Bianjing/Kaifeng to Lin'an/Hangzhou and radiating across the Jiangnan cultural network. It encompasses literati taste and moral-intellectual ideals (refinement, moderation, clarity), visual languages in painting and calligraphy (e.g., restrained palettes, baimiao linework), courtly and urban etiquette, and material craftsmanship (porcelain, silk brocade, lacquer, furniture) that embed everyday-use aesthetics. For operational clarity, this study delimits the concept to material/visual domains that are directly mappable to garment morphology and structural features; specifically excluded are 1) post-Song revivals and retrospective "Song-style" reinterpretations of later dynasties and the modern era, when their lineage cannot be traced to Song sources; and 2) regional folk forms lacking demonstrable Song-period transmission. This boundary ensures that the cultural genes extracted in the present work derive from verifiable Song-period strata and remain translatable into rule-controlled morphological design in contemporary contexts [5,12-14]. Although abundant achievements had been obtained in the fields of clothing, architecture, painting, and opera, systematic research from the perspective of cultural gene extraction and generative morphological transformation was still relatively scarce [5,12-14]. Internationally, related studies have included the theory of gene-culture coevolution and cultural transmission analyses focusing on both tangible and intangible cultural heritage [15]. In China, the research scope has been continuously expanded, and methods such as AHP, fuzzy evaluation, and morphological modelling have been applied to the design of cultural heritage products, and practical results have been achieved in ceramics, fashion design, handicrafts, furniture, and folk arts [2,16-20].

This study was aimed at constructing and validating a cultural gene-oriented design method that integrated AHP and Shape Grammar, which was used for the systematic extraction, priority ranking, and morphological transformation of cultural elements. Within this research framework, AHP was employed to evaluate and screen the weights of cultural genes, and Shape Grammar was applied to realise the translation from two-dimensional feature forms into three-dimensional contemporary design forms. Taking the garment morphology in the Chinese historical painting Washing Hands and Viewing Flowers (盥手观花图) as a case study, the entire process from cultural gene extraction to the generation of modern three-dimensional designs was demonstrated. The objectives of this study included: 1) establishing a replicable and systematic cultural gene design process; 2) providing a scientific pathway for guiding the positive mutations of cultural genes; 3) promoting the sustainable innovation and inheritance of traditional culture in modern contexts.

By establishing these objectives, the foundation was laid for the methodological framework that followed. Therefore, in the next section, the overall structure of the proposed research method and its specific procedures were described in detail. Building on the literature-grounded rationale above, this study next presents the methodology configured for Song Yun cultural-gene extraction and grammar-based transformation.

Methodology for Cross-Reference

Step 1 – AHP extraction & ranking. Build goal/criteria/alternative hierarchy; construct judgment matrices; compute weights via geometric mean; check CI/CR (target CR<0.10); perform leave-one-out sensitivity. Construction logic: a mixed approach (top-down literature/expert synthesis for B-level; bottom-up open coding for (Ci)). Terminology is kept consistent across objectives and methods: Shape Grammar (形状文法), cultural genes (文化基因), positive mutation(s) (正向变异). This study cites each Figure and Table in prose before it appears; numeric columns in matrices and weight tables are aligned by decimal point with uniform three-decimal precision.

Step 2 – AHP→Carrier→Operation mapping. Map the top-weighted cultural gene(s) to dominant visual–material carriers that directly encode morphology; define morphological operation objects for each carrier type (e.g., paintings → garment contour system).

Step 3 – Shape Grammar derivation. Apply rule set {R1 substitution, R2 addition/deletion, R3 scaling, R4 rotation, R5 shearing, R6 translation, R7 duplication, R8 stretching} to operate on the defined objects; elevate 2D features to 3D garment models (virtual fitting). To make the pipeline audit-ready, this study discloses software/version, mesh, fabric, mannequin, and simulation settings.

For reproducibility of the 2D–to–3D pipeline, the implementation-critical details are documented as follows.

Software and Environment

All 2D–to–3D modeling and fitting were performed in CLO3D 7.2 (build 7.2.176); Blender 4.0.2 was used only for format conversion and scale sanity checks. The workstation ran Windows 11 (23H2) on an Intel Core i7-12700, 32 GB RAM, and NVIDIA GeForce RTX 4070 (driver 552.22). Projects used millimetres (mm) and the CLO default garment coordinate convention. Stochastic procedures (e.g., cloth solver initialisation) fixed a random seed = 12345 for reproducibility.

Meshes and Fabric Parameters

2D panels were triangulated with target edge length 3.0 mm (≈ 25 triangles/cm^2) using constrained Delaunay + Lloyd relaxation (edge-length equalisation). Self-collision was enabled with a collision thickness of 2.0 mm. Fabric used the “Cotton Shirting – Medium” preset as a base with the following parameters: areal density 130 g/m^2, thickness 0.35 mm, bending stiffness B_{warp} = 0.80 N·mm, B_{weft} = 0.70 N·mm, stretch stiffness k_{warp} = 12 N/mm, k_{weft} = 10 N/mm, shear stiffness k_{shear} = 5 N/mm, Rayleigh-type damping 0.02, friction (static/dynamic) μ_s = 0.45 / μ_d = 0.35, Poisson's ratio ν = 0.30.

Mannequin Sizing and Fitting

This study used a female avatar (CLO default v7) with height 168 cm, bust 88 cm, waist 68 cm, hip 94 cm in A-pose. Pattern-to-avatar fitting followed seam alignment → pinning at anchors (shoulders, CF/CB neckline, side waist) → iterative relaxation (50 iterations). Standard ease allowances were +4 cm bust, +2 cm waist, +3 cm hip, unless otherwise specified.

Simulation Settings and Boundary Conditions

Gravity 9.81 m/s^2; integrator implicit Euler, time step Δt = 1/60 s, 5 sub-steps; air damping 0.02; collision continuous collision detection (CCD); cloth self-collision threshold 2.0 mm; garment–avatar friction μ = 0.45. Boundary conditions included pins at shoulders, CF/CB neckline, side waist, sewing constraints on all seam groups, seam stiffness 5 N/mm, and no wind unless noted. Simulations ran for up to 2400 steps or until the kinetic-energy change fell below 1×10^{-6} J for 20 consecutive steps.

To enable later verification, each objective was aligned with a concrete check: a minimal reproducibility input set for Objective (i), robustness tests of AHP weights for Objective (ii), and a quantitative morphology similarity metric for 3D forms for Objective (iii).

Expert Inclusion and Exclusion Rules

This study recruited domain experts using purposive sampling.

Inclusion criteria were: 1) ≥5 years of research or professional experience relevant to the topic; 2) current affiliation with an academic, governmental, or industry institution; 3) familiarity with pairwise judgment or willingness to complete a brief AHP training; 4) availability to complete two rounds of judgments; and 5) absence of conflicts of interest regarding the evaluated alternatives.

Exclusion criteria were: 1) incomplete or internally inconsistent responses after a clarification request (e.g., failing attention checks or not completing the second round); 2) declared conflicts of interest; or 3) withdrawal of consent at any time. To reduce individual bias, this study used group aggregation and conducted a leave-one-expert-out sensitivity analysis (see “Robustness & Sensitivity Analysis”).

Consent and Privacy

All participants received an information sheet describing study aims, procedures, risks, and data use, and provided informed consent before participation. No personally identifiable information beyond professional background was collected. Data were de-identified, stored on encrypted drives with access restricted to the research team, and are reported only in aggregate (e.g., group weights). Where required, ethics approval or exemption was obtained/confirmed by the authors' institution.

METHODOLOGY

Overall Framework

Guided by the above review and methodological rationale, in this study, a systematic framework for cultural gene-oriented design was constructed, in which three core stages were included: cultural gene extraction, morphological transformation, and innovative design application. First, the AHP was employed to systematically identify and quantitatively evaluate multiple elements of Song Yun Culture, and representative cultural genes of high value were screened [1,2]. Based on these results, Shape Grammar was then applied to conduct rule-based analysis and morphological derivation for the cultural genes with higher weights, and the translation from two-dimensional feature forms to three-dimensional design forms was realised [4]. Finally, while the core characteristics of cultural genes were preserved, the generated forms were integrated with modern design concepts and functional requirements, and the innovative redesign of cultural elements was completed [6-8].

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The overall workflow of this method was illustrated in Figure 1, which started from data collection and preliminary classification of cultural genes, proceeded through AHP-based hierarchical analysis and Shape Grammar derivation, and concluded with the realisation of three-dimensional design. To ensure reproducibility of the 2D-to-3D transition, this study specifies the software and version, mesh resolution and collision settings, fabric physical parameters (bending, stretching, thickness), and the mannequin sizing standard, and this study provides an exemplar project file/parameter table for independent replication. The first step of the workflow was carried out by organising and categorising the constituent elements of Song Yun Culture through literature review and expert interviews. A compact overview of the entire pipeline is provided in Figure 1 before the detailed steps. Following the classification principles of tangible cultural heritage and intangible cultural heritage, Song Yun Culture was divided into four categories: costume culture, productive culture, spiritual culture, and folk culture. This classification system, shown in Figure 2, provided the foundation for the subsequent construction of the hierarchical analysis model and ensured both the comprehensiveness and the systematic nature of cultural gene extraction [8,21].

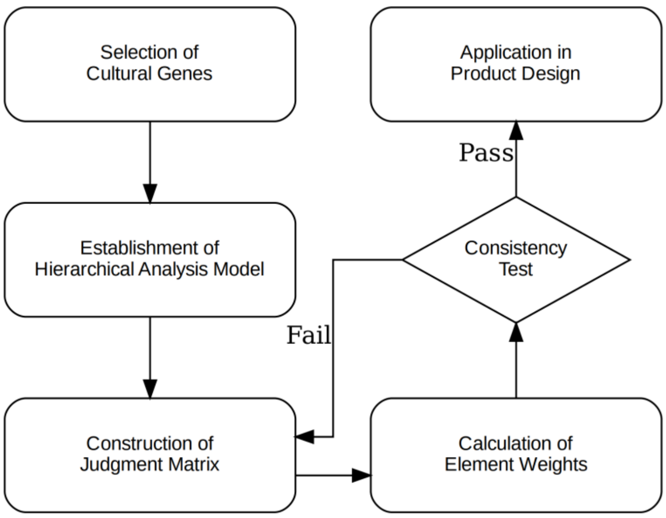

Figure 1. Selection and Analysis Process of Song Yun Cultural Genes (Self-drawn)

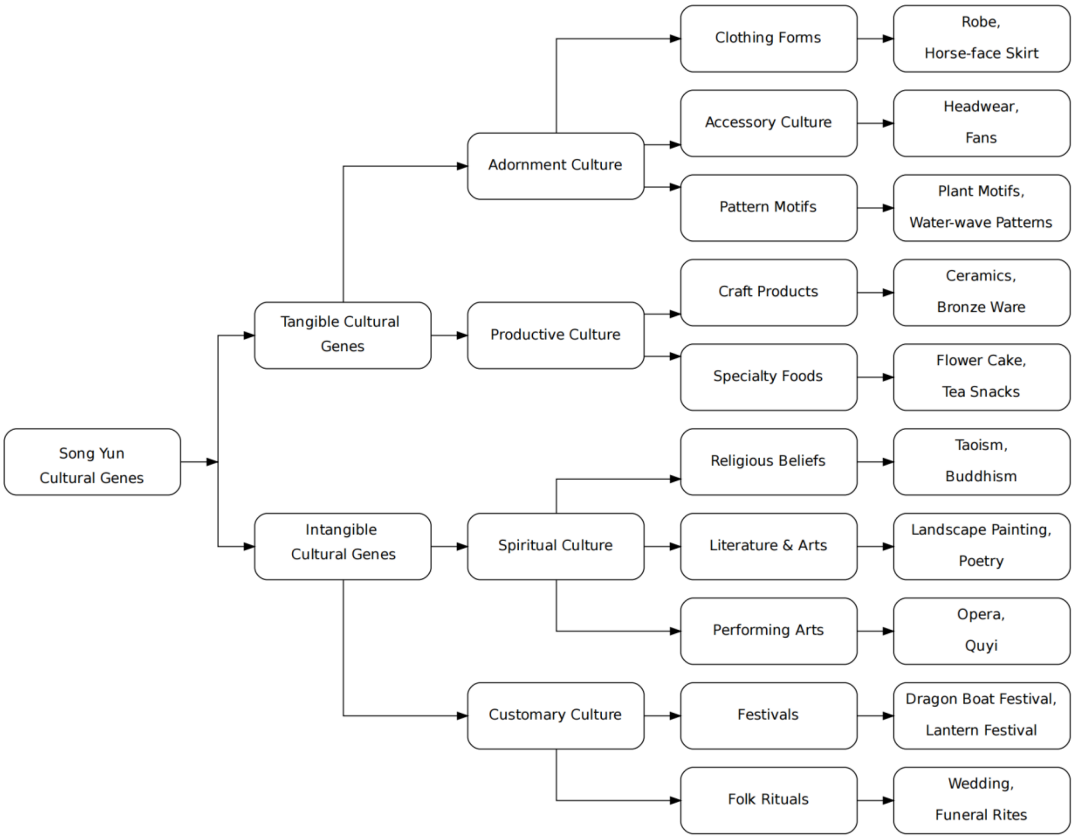

Figure 2. Classification of Cultural Heritage Genes (Self-drawn)

Cultural Gene Extraction Based on AHP

At the stage of cultural gene extraction, the **AHP** was employed to conduct a systematic quantitative evaluation of the importance of multidimensional elements of Song Yun Culture [1,2]. First, a hierarchical structure model of Song Yun cultural genes is shown in Figure 3 and is cited here before the figure is placed. In what follows, cultural genes (文化基因) are used consistently to denote encoded, heritable cultural factors in design translation.

This study adopts a mixed construction strategy for the AHP hierarchy. Top–down theory from the cultural-gene literature and expert synthesis defines the B-level dimensions, while bottom-up open coding of raw sources (texts, images, artefacts) inductively generates candidate criteria (Ci). The pipeline is: sources → initial codes → axial themes → candidate criteria → operational definitions (name, evidence, inclusion/exclusion) → final hierarchy used for AHP.

The model was divided into three levels: the goal layer (A), which was defined as "extracting representative Song Yun cultural genes"; the criterion layer (B), which included four categories — Costume Culture (B1), Productive Culture (B2), Spiritual Culture (B3), and Folk Culture (B4); and the **alternative layer (C)**, which was further subdivided into ten specific elements: Clothing Forms, Accessory Culture, Pattern Motifs, Craft Products, Specialty Foods, Religious Beliefs, Literature & Arts, Performing Arts, Festivals & Celebrations, and Folk Customs & Rituals (C1-C10).

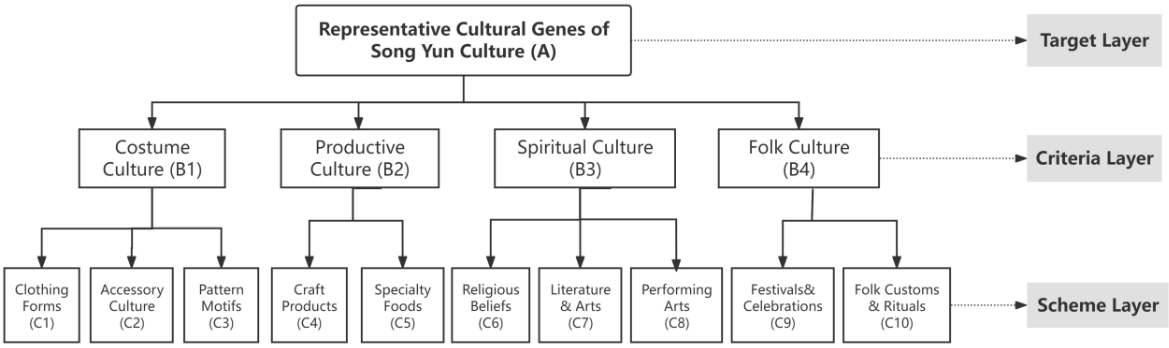

Figure 3. Hierarchical Structure Model of Song Yun Cultural Genes (Self-drawn).

After the model was constructed, pairwise comparison matrices were established.

Each element a_{ij} represented the relative importance of element i compared with element j , with the conditions$a_{ii} = 1$ and $a_{ij} = 1/a_{ji}$:

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1 \end{bmatrix} \tag{1}$$

The eigenvalue equation of the judgment matrix was given as:

$$A\ \omega = \lambda_{\max}\omega \tag{2}$$

Where $\omega = (\omega_1, \omega_2, \dots, \omega_n)^T$was the weight vector and $\lambda_{\max}$ Was the maximum eigenvalue.

The weights were calculated using the geometric mean method:

$$\omega_i = \frac{\left(\prod_{j=1}^{n} a_{ij}\right)^{1/n}}{\sum_{k=1}^{n}\left(\prod_{j=1}^{n} a_{kj}\right)^{1/n}}, i = 1,2, \dots, n \tag{3}$$

Subsequently, the maximum eigenvalue was approximated using the weight vector:

$$\lambda_{\max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(A\ \omega)_i}{\omega_i} \tag{4}$$

The consistency index (CI) and the consistency ratio (CR) were then calculated:

$$CI = \frac{\lambda_{max}-n}{n-1}, CR = \frac{CI}{RI} \tag{5,6}$$

Where RI was the random index, the values of which were determined by the matrix order n (according to Saaty's empirical table). When $CR < 0.1$, the judgment matrix was considered consistent; otherwise, the matrix values needed to be adjusted until the requirement was met [1,2].

In practical implementation, the judgment matrices were initially constructed based on the evaluation results of 15 respondents, including cultural heritage experts and members of the general public. However, during the consistency check, some matrices - such as those concerning costume culture and spiritual culture - failed to pass the test, mainly because the scores provided by the general public varied greatly and showed strong subjectivity. To improve the reliability of the data, a second round of calculation was conducted, in which only the evaluations of five experts with backgrounds in cultural heritage research or design practice were retained. The matrices were reconstructed and recalculated, and all CR values were less than 0.1, thus satisfying the consistency requirement.

Although the second-round evaluation relied on only five experts, the panel was deliberately restricted to ensure high authority and domain expertise. This practice is consistent with previous AHP applications in cultural heritage and design studies, where small but highly specialised panels (typically 4–7 members) are often adopted to guarantee data quality and consistency [1,2]. To strengthen credibility, this study additionally conducted a sensitivity analysis: removing one expert at a time did not change the top three priority elements, confirming the robustness of the results. Future studies will further expand the expert pool and, where possible, incorporate hybrid approaches (e.g., combining expert panels with broader stakeholder surveys) to triangulate findings.

The final weight calculation results for the criterion and alternative layers are presented in Tables 1**–**12**.** Among them, Table 1 shows the 1-9 scale definition of the AHP judgment matrix, which provides a standardised quantitative reference for expert scoring and pairwise comparisons.

Table 1. AHP Judgment Matrix Scale

Comparison of Factor 1 vs. Factor 2	Scale
Equal importance	1
Slightly more important	3
Strongly more important	5
Significantly more important	7
Absolutely more important	9
Intermediate values	2, 4, 6, 8
Factor 2 compared with Factor 1	Reciprocal

This study used the Saaty 1–9 fundamental scale (Table 1) with reciprocal entries enforced. Before rating, a brief calibration was provided: raters reviewed anchor descriptions for {1, 3, 5, 7, 9} with concrete garment examples and completed a toy 3×3 matrix to align interpretations; inconsistent entries were corrected before submission. Beyond per-matrix CR, inter-rater agreement was assessed using Kendall's W on the pooled judgments at each level, and an interquartile range (IQR) screen was applied (pairs with IQR > two scale points were flagged for re-check or winsorised to quartiles). All AHP numbers follow a uniform three-decimal precision with decimal-point alignment. This study reports, for every pairwise matrix, the numerical λmax, CI, RI, and CR. RI follows Saaty's reference values; CR = CI/RI. All AHP numbers use a uniform three-decimal precision and decimal-point alignment across tables. An audit-ready bundle (Appendix S6) provides the raw CSV matrices and a short script/spreadsheet that reproduces the weights from scratch.

Table 2. First-round Criterion Layer Judgment Matrix and Weights

A	B1	B2	B3	B4	*ωa*	λmax
B1	1.000	0.271	1.069	1.707	0.713	4.113
B2	3.694	1.000	2.038	3.547	1.915	
B3	0.936	0.491	1.000	3.391	0.969	
B4	0.586	0.282	0.295	1.000	0.403	

Table 3. First-round Alternative Layer for Costume Culture (B1)

B1	C1	C2	C3	ωa	λmax
C1	1.000	1.440	3.267	1.476	3.005
C2	0.695	1.000	2.832	1.104	
C3	0.306	0.353	1.000	0.420	

Table 4. First-round Alternative Layer for Productive Culture (B2)

B2	C4	C5	ωa	λmax
C4	1.000	3.273	1.532	2.000
C5	0.306	1.000	0.468	

Table 5. First-round Alternative Layer for Spiritual Culture (B3)

B3	C6	C7	C8	ωa	λmax
C6	1.000	0.801	2.769	1.116	3.007
C7	1.248	1.000	4.422	1.512	
C8	0.361	0.226	1.000	0.372	

Table 6. First-round Alternative Layer for Folk Culture (B4)

B4	C9	C10	ωa	λmax
C9	1.000	1.212	1.096	2.000
C10	0.825	1.000	0.904	

Tables 2-6 summarised the results of the first-round calculation, which covered both the criterion layer and the four alternative layers (costume culture, productive culture, spiritual culture, and folk culture). The results indicated that although significant weight differences were observed among several elements, the CR values of the costume culture and spiritual culture alternative layers exceeded 0.1 and thus failed the consistency test. This finding suggested that the professionalism of the evaluators had a critical impact on the stability of AHP calculations.

Sensitivity analyses indicate that the group weights are robust to expert composition; detailed metrics for the five-expert subset vs. full panel and the leave-one-expert-out runs are summarised in Supplementary S4.

Table 7. Second-round Criterion Layer Judgment Matrix and Weights

A	B1	B2	B3	B4	ωa	λmax
B1	1.000	0.547	0.236	2.467	0.652	3.118
B2	1.829	1.000	0.973	2.840	1.254	
B3	4.245	1.027	1.000	4.200	1.727	
B4	0.405	0.352	0.238	1.000	0.367	

Table 8. Second-round Alternative Layer for Costume Culture (B1)

B1	C1	C2	C3	ωa	λmax
C1	1.000	0.733	1.800	1.076	3.049
C2	1.364	1.000	1.267	1.175	
C3	0.556	0.789	1.000	0.749	

Table 9. Second-round Alternative Layer for Productive Culture (B2)

B2	C4	C5	ωa	λmax
C4	1.000	1.451	1.184	2.000
C5	0.689	1.000	0.816	

Table 10. Second-round Alternative Layer for Spiritual Culture (B3)

B3	C6	C7	C8	ωa	λmax
C6	1.000	0.547	3.800	1.052	3.028
C7	1.829	1.000	4.200	1.618	
C8	0.263	0.238	1.000	0.330	

Table 11. Second-round Alternative Layer for Folk Culture (B4)

B4	C9	C10	ωa	λmax
C9	1.000	0.973	0.986	2.000
C10	1.027	1.000	1.014	

Based on the above issues, the second-round calculation (Tables 7-11) was carried out by retaining only the scoring results of five experts with extensive experience in cultural heritage research and design practice. Under the same hierarchical structure, the judgment matrices were reconstructed.

The results showed that the CR values of all matrices were less than 0.1, indicating a significant improvement in consistency. It was noteworthy that after data screening and matrix reconstruction, the weight distributions became more concentrated and stable than those of the first round, and the ranking consistency of high-weight elements across layers was enhanced. This reflected a stronger consensus among experts in evaluating cultural values.

Table 12. Comprehensive Weights of Alternative Layer Elements

Element	B1	B2	B3	B4	Global Weight	Rank
C1	0.3586				0.0584	6
C2	0.3917				0.0638	5
C3	0.2497				0.0406	10
C4		0.592			0.1860	2
C5		0.408			0.1279	4
C6			0.3506		0.1513	3
C7			0.5395		0.2329	1
C8			0.1099		0.0474	7
C9				0.4932	0.0452	9
C10				0.5068	0.0465	8
Sum of global weights = 1.000						

Table 12 summarised the global weights of the alternative layer elements, presenting the final ranking results obtained after two rounds of consistency checks. The highest comprehensive weight was assigned to Literature & Arts (C7, 0.2329)**,** followed by Craft Products (C4, 0.1860) and Religious Beliefs (C6, 0.1513)**.** This study makes explicit the chain from art motifs → painted garment features → clothing structure. Painterly cues emphasised by C7 - such as long S-curves, crossed stroke rhythm, and vertical–horizontal cadence - are first read on the painted garment (cross-collar overlap, shawl drape, sleeve span, panel boundaries). These features are then carried by garment morphology: panels (front wrap, shoulder–yoke) and seams (princess and centre-front) that preserve the S-curve guidance and crossed rhythm. Garment morphology is prioritised as the preferred carrier because it stably translates motif grammar into silhouette and construction, supports sizing/fitting, and remains reproducible under pattern constraints; by contrast, ornaments operate mainly at the surface with high context variance, and utensils are extra-apparel artefacts not intrinsic to clothing structure. These three elements represented the core connotations of spiritual expression, material craftsmanship, and value systems within the overall structure of Song Yun Culture, and the results were highly consistent with its historical characteristics.

Elements with middle-level rankings, such as Accessory Culture (C2, 0.0638) and Clothing Forms (C1, 0.0584), had relatively lower weights but still held important aesthetic and symbolic significance within the category of costume culture. By contrast, the elements ranked at the lower end, Folk Customs & Rituals (C10, 0.0465) and Festivals & Celebrations (C9, 0.0452)**,** belonged to the external expressive layer of culture. Their lower weights reflected that, in expert evaluations, these elements were considered to have lower priority in morphological generation and design applications.

Robustness & Sensitivity Analysis

To assess the stability of group weights, this study 1) compared the full panel (all 15 raters) with the expert subset (5 raters used in the second round) and 2) performed a leave-one-expert-out (LOEO) analysis on the full panel. For group aggregation, individual pairwise matrices were combined by the geometric mean (AHP group decision-making). For each level (criteria and B1–B4), this study recomputed weights and compared them against the full-panel baseline using: Spearman ρ and Kendall τ (rank agreement), mean absolute error (MAE) and maximum absolute change (MaxΔ) in weights, and Top-1/Top-3 rank agreement flags. Numeric results are provided in Supplementary S4; the fully reproducible scripts and file structure are provided in Supplementary S5. As a practical interpretation rule, this study considers ρ or $\tau \geq 0.90$, MAE ≤ 0.05, and preserved Top-1 ranking as indicating high stability.

Uncertainty Estimation for Global Weights.

To formally quantify uncertainty in the global weights, this study reports mean ± standard deviation (SD) and 95% confidence intervals (CIs) based on nonparametric bootstrap over experts and leave-one-expert-out (LOEO) sensitivity. For each bootstrap replicate, experts are resampled with replacement, individual pairwise matrices are aggregated via the geometric mean, and local/criteria weights are re-estimated to obtain a replicated global-weight vector; 95% CIs are the 2.5^{th} - 97.5th percentiles across replicates. LOEO re-computes global weights after dropping each expert in turn to provide an additional robustness check. All outputs are rounded to three decimals to match the rest of the AHP reporting. The script and instructions are provided in Supplementary S6.

Linking AHP Weight Ranking to Morphological Operation Targets

To establish a causal link between what is prioritised by AHP and where/how Shape Grammar operates, this study defines an explicit mapping from cultural genes to their visual–material carriers and then to morphological operation objects.

1) For each cultural gene (Ci), this study identifies Song-period carriers that i) satisfy our temporal–spatial boundaries for Song Yun, ii) present directly observable morphology (lines, profiles, seams, structural layers), and iii) have reliable provenance.

2) Let C denote the highest-weighted gene. This study selects the dominant carrier(s) of C that most directly encode morphological evidence; when C belongs to the Literature & Arts (C7) domain, the dominant carriers are paintings/calligraphy that depict garments and etiquette in situ.

3) For each carrier type, this study defines the corresponding operation object for Shape Grammar: paintings → garment contour lines and structural partitions; textiles → weave lattices/pattern cells; ceramics → profile curves/sectional silhouettes; furniture → frame members and joint schemas.

4) Because C7 leads the AHP ranking in this study, this study instantiates R by selecting a Southern Song court painting with well-documented provenance in which garment structure is salient and continuous. Washing Hands and Viewing Flowers satisfies these criteria; therefore, the morphological operation object for Shape Grammar is defined as the garment contour system (primary outlines, seam-like divisions, proportion lines) extracted from the painting. This rule-based instantiation yields a transparent causal chain: AHP priority (C7) → dominant carrier (court painting) → operation object (garment contours) → grammar rules (substitution/addition, scaling, rotation, translation) → 3D elevation.

Morphological Transformation Based on Shape Grammar

As detailed in the Methodology Summary and Linking AHP Weight Ranking to Morphological Operation Targets, this study operates on the garment contour system defined by the AHP→carrier→operation mapping. Following the AHP-driven mapping, this study operates on the garment contour system extracted from the dominant carrier of C7 (the court painting). After the quantitative extraction and priority ranking of cultural genes had been completed, the study proceeded to the stage of morphological transformation, in which Shape Grammar was adopted as the rule framework for morphological generation and variation. Shape Grammar was first proposed by Stiny and Gips in 1972 [3], and it was capable of decomposing, recombining, and evolving existing forms through a set of formalised generative rules, thereby producing new morphological configurations. This method has demonstrated high flexibility and scalability in architectural design, industrial design, and the digital transformation of cultural heritage.

The study proceeded to the stage of morphological transformation, in which Shape Grammar was adopted as the rule framework for morphological generation and variation [4]. Shape Grammar was first proposed by Stiny and Gips in 1972 [3], and it was capable of decomposing, recombining, and evolving existing forms through a set of formalised generative rules, thereby producing new morphological configurations. This method has demonstrated high flexibility and scalability in architectural design, industrial design, and the digital transformation of cultural heritage.

To ensure that the morphological derivation both preserved the core characteristics of cultural genes and generated new forms adapted to modern design requirements, this study combined the theory of positive mutations of cultural genes [2,19.20] and defined a set of Shape Grammar rules specifically applicable to Song Yun cultural design, as shown in Table 13**.** The rules were classified into generative rules (e.g., R1 substitution, R2 addition/deletion) and modification rules (e.g., R3 scaling, R4 rotation, R5 shearing, R6 translation, R7 duplication, R8 stretching). The generative rules focused on retaining the genetic characteristics of cultural products to enable design innovation, while the modification rules introduced morphological variations under the premise of maintaining cultural consistency, to adapt the forms to new design contexts.

Table 13. Rules of Shape Grammar Derivation

Rule Type	Rule Description	Rules
Generative rules	Retain cultural genetic traits for innovation	R1 = Substitution; R2 = Addition/Deletion
Modification rules	Introduce morphological variations to generate new forms	R3 = Scaling; R4 = Rotation; R5 = Shearing; R6 = Translation; R7 = Duplication; R8 = Stretching

For each step, grammar rules were chosen to satisfy Song-Yun constraints on structure and etiquette while ensuring operability:

R1 (Substitution): replace ornamental micro-curves with archetypal seamlines of Song cross-collar robes to remove painterly noise and recover canonical structure.

R2 (Addition/Deletion): delete occluded/duplicated folds lacking structural semantics; add minimal partition lines only where they carry construction meaning.

R3 (Scaling): normalise key proportion indices (collar depth, shawl drop, sleeve width: length) to documented ranges for dignified silhouette.

R4 (Rotation): used sparingly to correct axis misalignment introduced by pictorial perspective so that contours align with the body's anatomical axes.

R5 (Shearing): intentionally not applied in the base case to avoid ritual asymmetry and distortion of garment hang; reserved for variant exploration only.

R6 (Translation): micro-adjust feature lines to anatomical landmarks (shoulder point, waistline) for pattern operability.

R7 (Duplication): enforce bilateral symmetry where culturally required (left–right sleeve/body panels).

R8 (Stretching): adjust sleeve and shawl drape length to meet Song-era draping ratios while preserving overall volume.

To avoid derivation conflicts and non-termination, a deterministic precedence and stopping policy is adopted: R1 > R2-del > R2-add > R7 > R3 > R4 > R5 > R6 > R8 (higher first). Matching uses an outermost-leftmost maximal policy over anchors, with tie-breaks by 1) minimum edit distance to the canonical seam graph and 2) a stable anchor order [neck→shoulder→waist→hem]. Once a micro-part is transformed by R1/R2, it is tagged to prevent re-entry in the same pass. Termination occurs when 1) no enabled match exists at higher precedence, or 2) the potential function F (sum of edit distances to the canonical seam graph) does not decrease after a full pass, or 3) a maximum depth of 10 rule firings is reached.

Before morphological derivation, two-dimensional morphological features of the selected high-weight cultural genes had to be extracted. Taking the "Literature & Arts" gene, which received the highest weight in the AHP analysis, as an example, the contour lines of the garments in the original painting were first extracted, while non-morphological factors such as colour and material were excluded. Only structural and configurational features were retained, as illustrated in Figure 4. This preprocessing step ensured that the input forms for Shape Grammar derivation possessed a high degree of abstraction and operability.

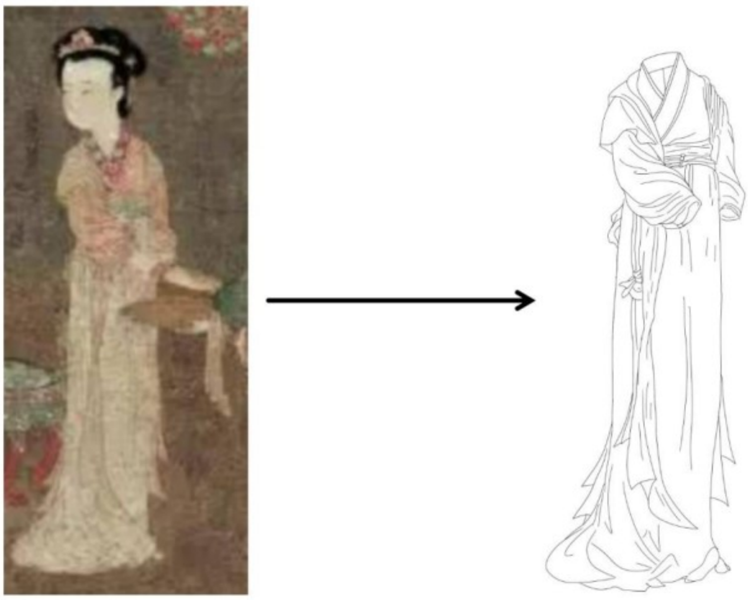

Figure 4. Extraction of Morphological Genes (Self-drawn)

After contour extraction, the process entered the critical stage of two-dimensional to three-dimensional transformation. First, rules R1 (substitution) and R2 (addition/deletion) were applied to simplify and merge local details of the garments, resulting in more concise and intuitive forms. Then, rules R3 (scaling) and R8 (stretching) were used to adjust the proportions of key structures, producing forms that were more suitable for modern design requirements. This process was illustrated in Figure

5, which demonstrated the transformation of feature lines from the original state to a minimalised outline. For operational clarity, each rule is expressed in a concise match→rewrite form with guards and notation for mandatory ⟨…⟩ and optional […] features; a minimal before/after micro example is given per rule, and precedence/termination are specified to avoid non-terminating derivations (see Table 13).

R1 was selected to replace painterly, non-constructive curves with canonical seamlines of Song robes, and R2 removed occluded or redundant folds, together preserving structural genes while minimising noise for downstream operations.

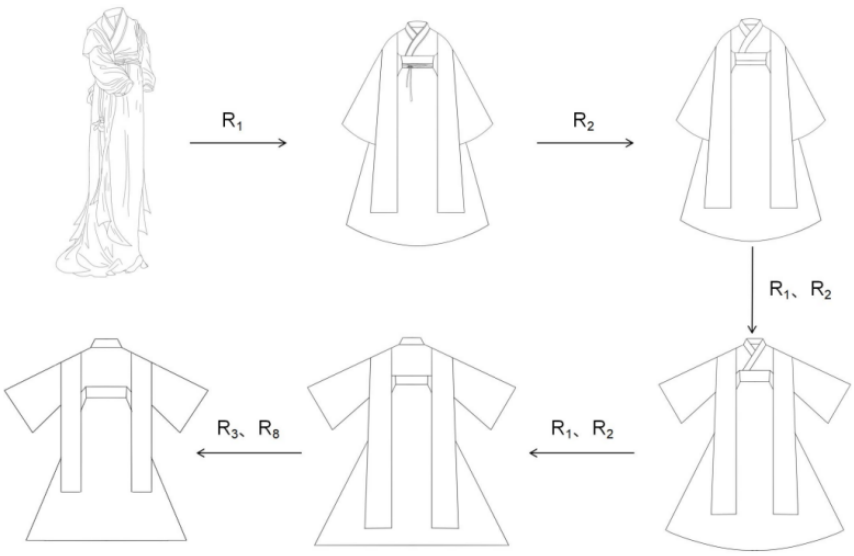

Figure 5. Processing of Feature Lines (Self-drawn)

Once the optimised two-dimensional morphology was obtained, multi-step derivations of Shape Grammar were performed to construct the three-dimensional structure. The feature-to-garment derivation used in this study is summarised in Figure 6. As illustrated in Figure 6, the derivation process sequentially presented the evolution from simplified contour lines to a complete three-dimensional garment model. In this study, the preferred carrier follows a motif → painted feature → morphology chain, mapping calligraphic S-curves and crossed rhythms to panels and seams; ornamental or utensil-based carriers were not prioritised because they do not robustly govern silhouette or pattern constraints in reproduction. This process not only preserved key cultural symbols of Song Dynasty attire - such as cross-collar robes and draped shawls - but also integrated modern fashion design concepts into structural layering, proportional distribution, and detail treatment. Consequently, the final morphology embodied both traditional charm and contemporary aesthetics.

Not all cultural motifs can be structurally realised under the current ruleset. In such cases, our framework classifies the motif as ornament-only, maps it to trims/prints/appliqués on the corresponding panels, and keeps the structural layer governed by R1 - R8 unchanged. The hand-off is recorded in the rule log for auditability, making the boundary of applicability transparent while preserving cultural semantics.

R3 was chosen to normalise culturally significant proportions (collar depth, shawl drop, sleeve span), while R8 provided controlled drape extension; auxiliary rules R4 and R6 were used only for axis alignment and landmark positioning, R7 for symmetry enforcement, and R5 was not used to avoid ritual asymmetry.

Figure 6. Derivation Process Based on Feature Lines (Self-drawn)

Through the introduction of Shape Grammar, satisfactory results were achieved in terms of controllability of morphological variation, fidelity of cultural characteristics, and diversity of design generation. Compared with the traditional method of directly applying pattern motifs, this approach enabled a deeper deconstruction of cultural forms and realised systematic innovation through a rule-based generative process.

For later verification, the derived 3D forms were planned to be assessed by the silhouette IoU and feature-line Hausdorff distance, aggregated into the composite score M.

CASE STUDY

Selection of Cultural Artefact

To verify the feasibility and effectiveness of the proposed method, the Song Dynasty painting *Washing Hands and Viewing Flowers* was selected as the case object for cultural gene extraction and morphological transformation. This artwork, currently housed in the Tianjin Museum, was regarded as one of the masterpieces in its "Eternal Brushwork" collection and represented one of the very few surviving early lady paintings [1,2,4]. A reference image of the case artwork is provided in Figure 7, which is cited here before placement. This study reproduces a low-resolution reference image (≤1200 px long edge) for scholarly, non-commercial commentary consistent with fair-use norms; no high-resolution distribution is provided. The scene depicted noble women in a Southern Song courtyard, engaged in flower arranging while immersed in morning sunlight and floral fragrance. The painting not only reflected the aesthetic taste of the period but also revealed the etiquette and spatial atmosphere of court life. The costumes of the figures were portrayed with great delicacy and vividness, and the structural layering and proportional lines exhibited a high degree of cultural distinctiveness. Therefore, the painting was highly suitable as the research object for cultural gene-based morphological analysis and redesign. Given that "Literature & Arts (C7)" received the highest AHP weight, the painting functions as the dominant carrier for C7, and the corresponding morphological operation object is the garment contour system extracted from its figures, in accordance with the above AHP→carrier→operation mapping.

Figure 7 presents the original composition of *Washing Hands and Viewing Flowers*. The costumes of the noble women preserved typical elements of Song Dynasty attire, such as cross-collar robes, draped shawls, and wide sashes, while also demonstrating the aesthetic essence of Song Yun Culture in decorative details and structural layering. These characteristics provided rich morphological information and cultural connotations for subsequent two-dimensional feature extraction and three-dimensional design transformation.

Figure 7. *Washing Hands and Viewing Flowers* (Source: http://xn--vcsu3i05le6a3dq38n.com/digital/edit/267.htm, accessed Oct 5, 2025)

Rights: scholarly, non-commercial reference under fair use; low-resolution reproduction limited to ≤ 1200 px long edge to avoid market substitution.

Design Process

This section instantiates the pipeline summarised above (see Methodology Summary and Methodology). This study takes Washing Hands and Viewing Flowers as the dominant carriers of C7 (Literature & Arts) and extract the garment contour system as the operation object; subsequent steps apply the predefined grammar rules to achieve 2D→3D elevation for design.

The design process of the case study was divided into two major stages. To ensure reproducibility of the 2D-to-3D transition, this study specifies the implementation details as follows. Software & version: CLO3D 7.2 (build 7.2.176) on Windows 11; Blender 4.0.2 for format conversion only. Meshing: panel particle distance 3.0 mm (≈ 25 triangles/cm²) with triangulation; garment–garment and self-collision enabled; continuous collision detection on. Fabric parameters: cotton-shirting preset with areal density 130 g/m², thickness 0.35 mm, bending stiffness B_warp = 0.80 N·mm, B_weft = 0.70 N·mm, stretch stiffness k_warp = 12 N/mm, k_weft = 10 N/mm, shear 5 N/mm, damping 0.02, static/dynamic friction µ_s/µ_d = 0.45/0.35. Mannequin sizing: female A-pose avatar, height 168 cm; bust/waist/hip 88/68/94 cm with ease +4/+2/+3 cm. Simulation boundary conditions: gravity 9.81 m/s²; mannequin fixed; wind off; time step 1/60 s; collision thickness 2.0 mm; initial 20 frames with shoulder anchor pins, then release for settling. The first stage involved the extraction and simplification of two-dimensional morphology from the original painting. The contour lines of the noble women's garments in *Washing Hands and Viewing Flowers* were extracted, while non-morphological factors such as colour and material were removed, and only the linear structures constituting the core features of the clothing were retained. Subsequently, Shape Grammar rules such as R1 (substitution) and R2 (addition/deletion) were applied to simplify local details and reduce excessive internal structural lines, thereby making the morphological features more concise and intuitive. This procedure ensured that the preserved lines not only reflected the cultural genes of Song Dynasty attire but also retained operability for subsequent derivation and variation.

The second stage involved the generation of three-dimensional models from the two-dimensional morphology. In the 2D-to-3D realisation, modelling and fitting were performed in CLO3D 7.2 (build 7.2.176) on Windows 11; panels were triangulated at a target edge length of 3.0 mm (≈ 25 tri/cm²) with self-collision enabled (thickness 2.0 mm) and continuous collision detection. The fabric used a cotton-shirting preset with areal density 130 g/m², thickness 0.35 mm, bending stiffness B_warp = 0.80 N·mm, B_weft = 0.70 N·mm, stretch stiffness k_warp = 12 N/mm, k_weft = 10 N/mm, shear 5 N/mm, damping 0.02, and friction (µ_s/µ_d = 0.45/0.35). The mannequin followed a standard female, A-pose avatar with height 168 cm, bust/waist/hip 88/68/94 cm and ease allowances +4/+2/+3 cm. After the optimisation of two-dimensional feature lines, Shape Grammar modification rules such as R3 (scaling) and R8 (stretching) were applied to adjust garment proportions and structures, making them suitable for modern ergonomics while retaining the layering and iconic elements of Song Dynasty clothing. Three-dimensional modelling was carried out using virtual fitting and digital simulation techniques, which transformed the two-dimensional contours into three-dimensional garment models with real spatial volume. In terms of styling, the simplified structure of a modern trench coat was integrated with details from Song Dynasty attire, including draped shawls and cross-collar robes. Moreover, geometric and floral patterns popular during the Song Dynasty were digitally introduced into fabric textures. As a result, the final design combined traditional charm with contemporary fashion aesthetics.

Figure 8 displayed the modern trench coat designed based on extracted feature lines from *Washing Hands and Viewing Flowers*. The resulting garment preserved cultural characteristics of the original attire, such as the loose waist proportion and front closure design, while structural simplification and material optimisation enhanced practicality and modern appeal. This outcome verified the operability and application value of the proposed "cultural gene extraction-morphological transformation-innovative design" process in real-world design practice.

Figure 8. Modern Trench Coat Design Based on Extracted Feature Lines From *Washing Hands and Viewing Flowers* (Self-drawn Using Style 3D Software)

RESULTS

The weight ranking of Song Yun's cultural genes was first obtained based on the AHP analysis. After judgment matrices had been constructed from expert scoring and tested for consistency, the comprehensive weight values were derived as shown in Table 12. This study re-estimated local and global weights by removing one rater at a time. The top-k ordering remained stable under all removals, and the mean absolute change of global weights was small. The comprehensive global weights across alternatives are summarised in Table 12, with numeric columns aligned by the decimal point. The results indicated that Literature & Arts (C7) had the highest global weight (0.2329), which suggested that it possessed the most prominent representativeness and cultural value in the overall system of Song Yun Culture. For transparency, agreement beyond CR is reported: Kendall's W for the criterion layer and alternative layers is summarised in Appendix S6, together with IQR flags; all statistics are formatted to three decimals.

Causal chain from the highest-weighted dimension to garment construction is as follows. Cultural source (C7 Literature & Arts under B3 Spiritual Culture) emphasises poised elegance, balanced proportion, and linear brushwork rhythm. Visual motifs are therefore abstracted as long S-curves, crossed neckline rhythm, vertical-horizontal cadence, and restrained floral-cloud boundaries. These motifs map to garment parts as: 1) panels - front wrap and shoulder-yoke panels that preserve the crossed rhythm and vertical cadence; 2) seams - princess seams and centre-front seams that follow S-curves to guide drape and shaping; 3) trims - low-saturation piping and knot/frog closures echoing calligraphic strokes. This chain is implemented in the 2D feature-line derivation and the 3D fitting shown in Figures 5 - 8, making the design translation explicit and defensible. Craft Products (C4) and Religious Beliefs (C6) ranked second and third, respectively, which demonstrated that both material craftsmanship and spiritual belief systems were equally critical components of Song Yun Culture. In contrast, elements such as Clothing Forms (C1) and Accessory Culture (C2) were assigned relatively lower weights, implying that their importance within the broader cultural gene system was secondary. This weight ranking provided a scientific basis for prioritisation in subsequent Shape Grammar derivations [22,23]. These results follow the procedures defined in the Methodology Summary / METHODOLOGY and will not be reiterated here. The above verification metrics and scripts would be released together with the reproducibility inputs to enable independent checking.

At the stage of morphological derivation, the cultural gene of Literature & Arts**,** which had received the highest weight, was selected. The garment morphology of noble women depicted in *Washing Hands and Viewing Flowers* was used as the morphological source, and multiple-step derivations were conducted through Shape Grammar. The process sequentially included the extraction of original feature lines, simplification of local structures, proportional adjustments, and the final elevation into three-dimensional form. Each stage of morphological change strictly followed the pre-defined rule system, thereby ensuring fidelity to cultural characteristics and controllability of morphological variations. This procedure not only achieved a progressive transformation from traditional to modern morphological structures but also generated diverse design possibilities for the final design solutions.

The final three-dimensional garment design model successfully integrated key cultural symbols of Song Dynasty attire with the structural logic and functional design of a modern trench coat. The results of model visualisation demonstrated that the outcome achieved a balanced design goal between tradition and modernity in terms of proportion, detailing, and material performance. The model preserved typical Song elements such as draped shawls and cross-collar robes, while digital fabric texturing incorporated geometric and floral patterns characteristic of the Song period. These design features enhanced visual distinctiveness and continued the aesthetic traits of Song Yun Culture. Moreover, structural optimisation improved wearing comfort and practicality, thereby suggesting the potential feasibility of introducing such garments into the contemporary fashion market.

This series of results verified the effectiveness of the proposed "cultural gene extraction-morphological transformation-innovative design" methodology. The AHP analysis ensured the scientific rationality of cultural gene selection, Shape Grammar derivation guaranteed the systematic and controllable nature of morphological changes, and the final three-dimensional model demonstrated the application potential and cultural heritage value of this approach in practical product design. For an explicit statement of evaluation dimensions demonstrating innovative effectiveness, see Discussion.

DISCUSSION

The proposed methodology of "cultural gene extraction-morphological transformation-innovative design" demonstrated significant innovation and scientific rigour at both theoretical and practical levels. The methodological novelty was primarily reflected in the integration of quantitative analysis tools with generative design techniques. The AHP provided a data-driven basis for extracting cultural genes and establishing priority rankings, which helped to reduce subjectivity and arbitrariness in the traditional process of selecting cultural elements. Meanwhile, Shape Grammar transformed the evolutionary process of cultural morphology into a repeatable and controllable rule system, so that morphological variation was no longer dependent on the intuition of designers but instead followed a systematic generative logic. This cross-methodological integration offered a novel operational pathway for the living transmission and contemporary interpretation of traditional cultural heritage.

Compared with the traditional approach of directly applying pattern motifs, the proposed method exhibited clear advantages in terms of scientific reliability and flexibility in design generation. Conventional approaches often remained at the superficial level of referencing cultural symbols in two-dimensional form, lacking in-depth deconstruction of underlying structures and morphological logic. Such limitations frequently led to shallow reuse of cultural content, or even to the superficial "symbolisation" of heritage. By contrast, the workflow in this study began with the extraction of cultural genes, and both the selection of cultural elements and the subsequent morphological derivations were based on quantitative analysis and rule-based generation. As a result, core cultural characteristics were preserved, while design solutions became more diverse and adaptable.

In addition, the methodology played a positive role in guiding the positive mutation of cultural genes. By introducing a controllable rule system during morphological derivation, the direction of form evolution was ensured to remain consistent with the cultural prototype. This process effectively avoided the occurrence of "negative mutations" that might conflict with cultural essence during modernisation. Such positive guidance not only contributed to the integrity and authenticity of cultural heritage but also created conditions for its cross-domain application in different design fields.

From the perspective of applicability, the methodology was not limited to the study of Song Yun Culture. Provided that a corresponding cultural gene database and morphological data were available, it could be extended to other types of cultural heritage design, including but not limited to ethnic costumes, traditional handicrafts [24], and historical architectural ornamentation. Nevertheless, certain limitations remained. First, the outcomes of AHP assessments largely depended on the representativeness and authority of the expert sample; when the scale or diversity of the expert group was insufficient, the universality of weight results might be compromised. Second, Shape Grammar required a high level of professional judgment and cultural understanding in defining morphological rules. Inaccurate definitions might lead to generated forms deviating from cultural authenticity. Moreover, the three-dimensional transformation and digital modelling process required specific hardware and software resources, which could restrict its direct application in resource-limited contexts.

In the present study, the use of five experts was a methodological trade-off favouring depth over breadth; however, the results proved stable under leave-one-out checks. Expanding the sample size and introducing complementary quantitative techniques (e.g., fuzzy-AHP or entropy weighting) will be a focus of subsequent work to further enhance external validity.

To demonstrate the superiority of the integrated AHP - Shape Grammar approach within the current structure, this study articulate four evaluative dimensions applied to the case: E1) Cultural fidelity—etiquette-bound structures and canonical proportions are preserved, as evidenced by rule-controlled derivations (Figures 5–6) and the retention of cross-collar robes and draped shawls in the final 3D model (Figure 8); E2) Controllability/traceability - every transformation is recorded as a rule application (R1–R8), enabling step-wise backtracking and targeted edits, in contrast to direct motif placement; E3) 2D→3D integrability and functional adaptation—the elevation to Style3D confirms pattern-operable geometry and modern ergonomics while maintaining cultural semantics; E4) Reproducibility/robustness - AHP consistency (all CR<0.10) and leave-one-out stability on the top-three priorities reduce evaluator arbitrariness and anchor downstream grammar choices. Collectively, these criteria indicate that the proposed pipeline achieves deeper structural innovation than surface-level pastiche while improving design editability and manufacturability. In addition to consistency checks, weight robustness was planned via (a) bootstrap recomputation of weights/CR and (b) one-at-a-time perturbations of $a_{ij}a$ on the Saaty scale, with rank-stability summarised by Kendall's τ and maximum Δrank.

Therefore, the proposed research methodology exhibited clear advantages in preserving core cultural characteristics, achieving morphological innovation, and improving scientific rigour in design processes, while further research remained necessary to optimise its applicability and expand its use across broader cultural heritage domains.

CONCLUSION

This study demonstrates a reproducible pipeline that integrates AHP-derived priorities with operational Shape Grammar rules to translate cultural genes into controllable garment morphology. On this basis, Shape Grammar was employed to conduct rule-based derivations of the high-weight cultural genes, thereby achieving a controlled transformation from two-dimensional feature forms to three-dimensional design morphologies.

The case study, based on the garment morphology depicted in *Washing Hands and Viewing Flowers*, transformed the extracted cultural genes into modern clothing design schemes, ultimately generating a three-dimensional garment model that combined the traditional elegance of Song Dynasty attire with contemporary fashion characteristics. The findings indicated that the proposed method effectively preserved the core cultural characteristics while achieving morphological innovation and functional modernisation, enabling traditional cultural elements to acquire renewed vitality within contemporary design contexts.

Looking forward, this study pivots to three actionable directions that extend the current pipeline: 1) broadening and stratifying expert cohorts to improve external validity while reporting agreement alongside leave-one-out stability; 2) automating contour extraction with a semi-automatic computer-vision routine (edge/curve detection plus motif filters) to standardise inputs and reduce manual bias; and 3) validating beyond garments on adjacent artifacts where panel/seam analogs exist to probe generality and boundary conditions. These directions directly connect to the present results - prioritised criteria feed automation targets, and grammar rules carry over to new carriers - thereby making future evaluation concrete and testable.

Conflicts of Interest

The authors declare no competing financial interest.

Author Contributions

Conceptualization, Chenlu WANG and Hongbo WANG; methodology, Chenlu WANG; formal analysis, Luyao CHENG and Chenlu WANG; investigation, Luyao CHENG and Yiheng ZHANG; resources, Chenlu WANG and Hongbo WANG; data curation, Luyao CHENG and Yiheng ZHANG; writing – original draft preparation, Luyao CHENG; writing – review and editing, Chenlu WANG, Hongbo WANG, and Chen YANG; visualization, Luyao CHENG and Yiheng ZHANG; supervision, Chenlu WANG and Hongbo WANG; project administration, Chenlu WANG; funding acquisition, Chenlu WANG. All authors have read and agreed to the published version of the manuscript.

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