Digital Translation of the Dunhuang Nine-Colored Deer Motif for Wood-Fiber-Based Cultural Product Design

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To address challenges including high subjectivity, non-reproducible reasoning, and poor compatibility with wood-based material processing in translating Dunhuang mural imagery into modern cultural product designs on wood-fiber substrates, this study proposes a digital workflow combining the Analytic Hierarchy Process (AHP) and Shape Grammar (SG). An evaluation system was established, focusing on cultural authenticity, artistic aesthetics, geometric transformability, material compatibility, and market resonance. AHP was used to select imagery with the highest translation potential, prioritizing aesthetics and material-process compatibility. Using the Nine-Colored Deer from Mogao Cave 257 as a prototype, generative rules were developed for pattern creation under parametric constraints. An HSB compensation mechanism was introduced to improve color consistency in digital printing and processing. Three practical designs—wooden lamps, apparel, and bags—were evaluated by 20 reviewers, with mean scores ranging from 4.54 to 4.60, demonstrating the robustness and applicability of this workflow in wood-fiber material engineering and cultural heritage translation.

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INTRODUCTION

Driven by digital heritage preservation and the globalization of the cultural and creative industries, the challenge of how to embed intangible cultural heritage (ICH) imagery into contemporary industrial design workflows in a computable and reusable manner—thereby coordinating morphological mapping with semantic translation—has become an important topic at the intersection of design research and the digital humanities. As a mature medium of visual narrative and a symbolic system, Dunhuang murals provide high-density visual resources and semantic cues for sampling, structurally encoding, and cross-media translating ICH imagery. Their iconographic genealogy includes representative symbols such as the Three Hares, winged horses, Flying Apsaras, and the Nine-Colored Deer, exhibiting composite characteristics that integrate narrative structures with decorative logics (Whitfield *et al.* 2000). However, during the design translation of cultural and creative products, designers often face imagery resources that are large in scale and highly heterogeneous. Without an upfront quantitative screening and evaluation scheme, the selection of design targets tends to become experience-driven and subjective, making it difficult to identify core primitives with high transformation potential. Zhao

Shengliang (2016) noted that selection detached from historical authenticity and aesthetic principles can lead to fragmented cultural meanings and aesthetic discontinuities. This, in turn, undermines the continuity and systematicity of ICH revitalization and limits the methodological reproducibility required for productization and scaled development.

Existing digital translation studies have largely focused on virtual visualization or on uniform substrates such as metals and plastics, while overlooking the most critical carrier in the cultural and creative industry—wood-fiber-based materials. As a representative class of biomass resources, wood and cellulose-based materials, owing to their renewability, hierarchical structural characteristics, and potential for engineering-oriented processing, have been recognized as a sustainable materials platform. They can provide an important physical carrier for the materialization and productization of intangible cultural heritage (ICH) motifs (Hamedi *et al.* 2025). However, wood is an anisotropic natural material, and variations in fiber orientation and density impose stricter requirements on machining precision for digitally translated forms (*e.g.*, focal-depth stability in laser engraving and the integrity of machined edges) (Ružiak *et al.* 2025).

To address the coupling requirements between motif-generation rules and wood-based processing characteristics (Liu *et al.* 2023), as well as decision uncertainty in imagery screening and translation-object selection, the Analytic Hierarchy Process (AHP) provides a classical multi-criteria decision-making approach. By pairwise comparisons, AHP converts expert subjective judgments into a quantitative weight system and improves interpretability and robustness *via* consistency checking. In design research contexts, AHP has also been applied to multi-objective trade-offs in wood and cellulose-related product design. For example, Liu *et al.* (2020) embedded ICH semantic elements into wooden furniture design and quantified their priorities, while Ho (2008) systematically demonstrated the robustness of AHP in complex decision-making. In this study, a multi-dimensional evaluation matrix is constructed to quantitatively assess representative Dunhuang imagery using the AHP model, thereby precisely identifying the core objects with the highest artistic value and translation potential.

Nevertheless, evaluation criteria derived solely from AHP are often difficult to translate directly into concrete visual design solutions. Shape grammar (SG), through parametric constraints and rule-based logical derivation, can effectively establish topological relationships between traditional morphological "genes" and modern design languages. As noted by Cui and Tang (2013a), formal transformation based on shape grammar can convey the essential spirit of cultural imagery, while Knight (1994) and Stiny (2006) demonstrated the successful modernization of traditional symbols through this approach. By decomposing and recombining geometric features and line logic of cultural symbols, SG offers a systematic visual derivation pathway that supports authenticity in heritage-oriented design. However, to ensure stable processing on wood-based carriers and consistent outputs across materials, generative rules must be coupled with material-processing boundary conditions (İşleyen and Karamanoğlu 2019).

Existing research on the digital translation of Dunhuang intangible cultural heritage (ICH) motifs has established three typical models, all of which suffer from limitations of over-simplified application: The single decision-making screening model only accomplishes quantitative screening of ICH imagery but cannot generate concrete visual design solutions, resulting in a disconnection between screening and generation (Saaty 1990). The pure morphological generation model focuses on the visual deduction of traditional symbols, lacks prior scientific screening, and does not incorporate generation constraints based on material processing characteristics, making engineering

implementation difficult (Knight 1994). The general cross-media translation model mostly concentrates on virtual visualization or homogeneous media such as metals and plastics, without designing adaptive strategies for the anisotropy and color-rendering properties of wood-fiber materials, leading to unsatisfactory processing and color performance (Liu *et al.* 2020).

None of the above models achieve the full-chain coupling of quantitative screening – rule-based generation – material adaptation, making them insufficient to meet the demand for the engineered translation of ICH motifs into cultural and creative products on wood-fiber carriers. For this reason, although existing studies have made separate progress in imagery evaluation, wood-based materials, and morphological generation, there remains a lack of an operational framework that deeply couples AHP decision-making with shape grammar generation and adapts to the processing characteristics of wood-fiber materials, which hinders the systematic and innovative translation of highly symbolic resources such as Dunhuang murals (Liu *et al*. 2023).

Therefore, this paper proposes an integrated "AHP–Shape Grammar" design framework. The evolved motifs are implemented on three carriers—(i) a wooden flowing-light night lamp, (ii) apparel made from wood-pulp regenerated cellulose, and (iii) bags fabricated from cellulose-based (lignocellulosic) textiles—and are validated through multi-dimensional scale-based evaluation to examine robustness and transferability. This work provides a scientific decision model for the engineering translation of Dunhuang ICH resources. The following sections present the theoretical basis, methodological procedure, and design practice of the proposed approach, offering a reproducible pathway for integrating heritage and innovation in cultural product development.

EXPERIMENTAL

Within the artistic heritage of Dunhuang, the Nine-Colored Deer is a representative symbol of cross-cultural integration along the Silk Road, combining the ornamental sensibilities of the Western Regions with the line-drawing characteristics of the Central Plains. As an emblem of guardianship and auspiciousness, the Nine-Colored Deer appears extensively in narrative spaces such as caisson ceilings and sequential murals, carrying profound religious and moral meanings (Duan 1988). In terms of artistic expression, this imagery is grounded in mineral pigments and features an interplay between lively lines and highly saturated colors—such as azurite blue and earthy red—exemplifying the Northern Dynasties' characteristic approach of "giving form through color" (Whitfield *et al.* 2000). Among relevant works, the *Jataka Tale of the Deer King* in Mogao Cave 257 is widely regarded as the most canonical narrative carrier. With its horizontal scroll-like composition, the mural transforms Buddhist storytelling into a visually dynamic language, and thus serves as the key prototype for pattern extraction and logical translation in this study (Wu 2010).

Taking the Nine-Colored Deer from the *Jataka Tale of the Deer King* in Mogao Cave 257 as the core target, this study proposed a scientific design pathway integrating AHP and Shape Grammar, as shown in Fig. 1. First, AHP-based quantitative criteria were used to identify the "Nine-Colored Deer" as the imagery with the highest transformation potential. Next, its geometric and topological features were decomposed, and shape-grammar production rules were defined to enable the logic-driven generation of patterns, translating a figurative image into a modern design symbol. An HSB-based color

compensation mechanism was introduced for color translation to better align with contemporary visual aesthetics. The generated patterns were implemented in practical designs for jewelry, apparel, and bags. Finally, the resulting Nine-Colored Deer cultural and creative products were evaluated quantitatively.

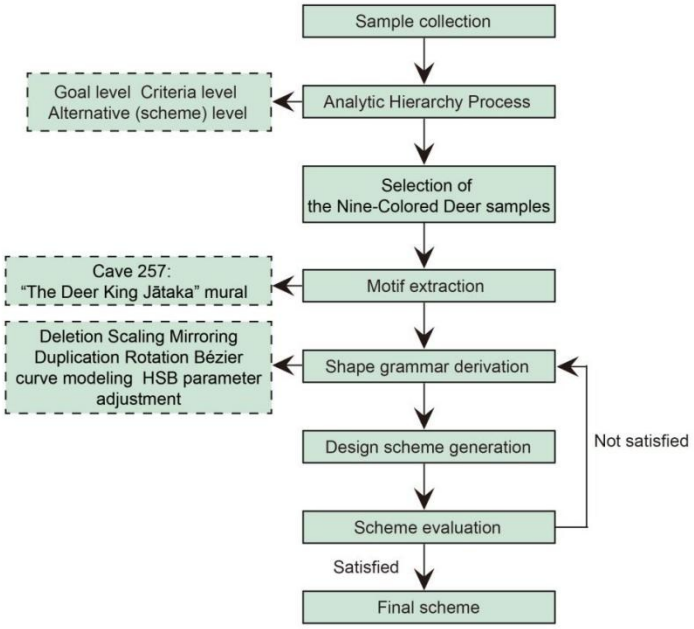


Fig. 1. Research Methodology

Assessment Analysis of Dunhuang Mural Motifs

To mitigate the reliance on subjective experience in the design translation of Dunhuang mural elements, this study adopted the Analytic Hierarchy Process (AHP) proposed by Saaty (1990) to construct a multi-criteria evaluation model. The evaluation indicators were developed by referencing the ICH resource assessment framework reported by Tonelli *et al.* (2021) and were further adapted to the artistic characteristics of Dunhuang murals. Five core criteria were established: cultural authenticity (UNESCO 2003), artistic aesthetics (Leder *et al.* 2004), geometric transformability (Stiny 2006), wood-based process compatibility (Knight 1994), and market resonance (Norman 2004). Through quantitative scoring and ranking, this indicator system enables the identification of high-potential motifs for translation, thereby providing an evidence-based foundation for the construction and derivation of shape-grammar rules.

Based on the delineation of typical Dunhuang iconographic genealogies by Whitfield (2000) and Zhao Shengliang (2016), five imagery categories with the greatest distinctiveness in artistic features, historical connotations, and geometric composition were selected as the alternatives layer, namely the Three Hares, winged horse, Azure Bird (*Qingniao*), Nine-Colored Deer, and camel. This selection spans the aesthetic evolution of Dunhuang grotto art from the Northern Dynasties to the Sui–Tang period, enabling the multi-criteria evaluation model to maintain discriminative power and applicability under diverse visual-semantic contexts.

To ensure high standards of scientific experimental, professionalism, and objectivity of the evaluation results, this study established a three-level expert screening criterion and rigorously formed a 15-member expert panel for data collection:① Experts

in Dunhuang art history (3 persons): with at least 10 years of research experience in Dunhuang grotto art and publications in relevant core journals, responsible for accurately defining the boundary of cultural authenticity of the motifs;② Design experts (5 persons): with senior designer professional title and more than 10 years of experience in cultural and creative product design or wood-based material processing design, responsible for evaluating the artistic transformation potential and wood-based process compatibility of the motifs;③ Market and user experts (7 persons): brand analysts with more than 5 years of market analysis experience in the cultural and creative industry, and user representatives covering the core consumer group of cultural and creative products aged 20 to 50, responsible for objectively predicting market resonance.

The 1 to 9 scale method proposed by Saaty (1990) was adopted to evaluate indicators at all levels. Judgment matrices were constructed through multiple rounds of feedback and consistency revision. The evaluation framework for Dunhuang mural motifs in this study includes five core indicators: cultural authenticity (B1), artistic aesthetics (B2), geometric transformability (B3), wood-based process compatibility (B4), and market resonance (B5).

To verify the internal reliability and expert judgment consistency of the evaluation system, reliability and consistency tests were performed on the AHP evaluation data. The Cronbach's α coefficient of the indicator system was 0.856, higher than the critical value of 0.8, indicating good internal consistency. The Kendall's concordance coefficient W = 0.82 ($P < 0.01$), proving no significant bias in expert judgments. The evaluation results of this study are therefore scientific and reliable.

Table 1. Evaluation Framework for Dunhuang Mural Motifs

Criterion	Description
B1	Measures the degree to which the design prototype aligns with the historical context and narrative logic of a specific period of the Dunhuang grottoes.
B2	Based on the visual characteristics of Dunhuang art, evaluation of the motif's line dynamics, color hierarchy, and compositional rhythm.
B3	Assesses the difficulty of decomposing the original imagery into geometric primitives (points, lines, and planes) and establishing shape-grammar production rules.
B4	Examines the feasibility of realizing the SG-generated digital forms through modern materials and processes, such as digital printing/dyeing and jewelry casting.
B5	Anticipates audience preferences, cultural IP recognizability, and the sense of identification under contemporary fashion discourse.

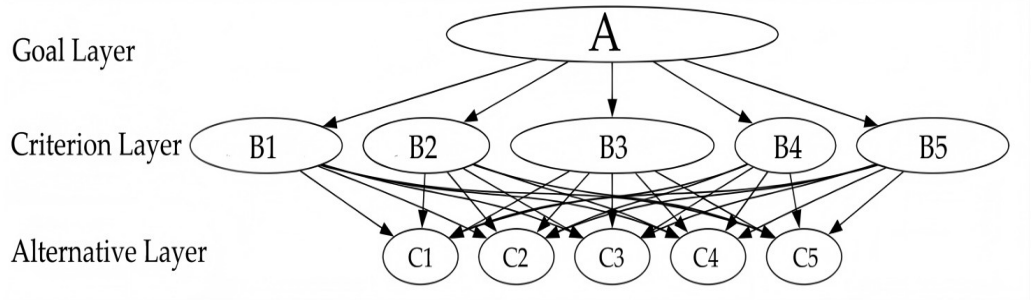


Fig. 2. Hierarchical model of requirements

Construction of the Judgment Matrix and Weight Calculation

Based on the pairwise comparison results at the criteria level, a judgment matrix was constructed (Table 2), and the matrix elements were normalized. The geometric mean method (*i.e.*, the product method) was used to obtain the criteria weight vector (Table 3). Subsequently, a consistency test was performed to ensure that the judgment matrix satisfies the fundamental consistency requirements of AHP.

The weight distribution indicates that artistic aesthetics (B2) has the highest proportion (0.38), markedly exceeding cultural authenticity (B1, 0.10) and the other criteria (Table 3). This result suggests that, in the translation and application of ICH motifs to cultural and creative products, attributes related to visual form are assigned a higher priority within the evaluation framework, as they may more directly shape audiences' initial perceptions and preference formation. Cultural authenticity serves as a hard screening prerequisite for all evaluated motifs (verified by Dunhuang art historians), and the hierarchical expert panel with consistent AHP test results ensures no expert bias; the high weight of artistic aesthetics is determined by the practical demands of wood-fiber cultural product design and contemporary communication of ICH motifs.

Table 2. Judgment Matrix at the Criteria Level

	B1	B2	B3	B4	B5
B1	1	1/4	2	1/3	1/2
B2	4	1	8	4/3	2
B3	1/2	1/8	1	1/6	3/2
B4	3	3/4	6	1	2
B5	2	1/2	2/3	1/2	1

Table 3. Weights of the Criteria Level

Criterion	Weight
B1	0.10
B2	0.38
B3	0.08
B4	0.30
B5	0.14

This can be explained as follows. Although cultural authenticity provides essential value boundaries and semantic constraints for design, in competitive contexts such as accessories and apparel, audiences typically establish their first impressions through aesthetic features such as line dynamics and color hierarchy, and only subsequently do they develop an intention to further explore the underlying religious and historical meanings. Therefore, the higher weight assigned to "artistic aesthetics" does not negate the cultural essence of the motif; rather, it underscores a contemporary design-translation logic in which "form leads, and meaning is carried."

Wood-based process compatibility (B4), which ranks second in weight (0.30), together with the aesthetic dimension, delineates the practical boundary of design implementation by ensuring that high-precision outputs can be realized through modern materials and manufacturing processes. This indicator configuration forms a relatively balanced constraint structure among cultural boundaries, aesthetic preferences, and engineering feasibility, suggesting that the translation pathway of Dunhuang ICH elements

is shifting from a surface-level mode of symbolic appropriation toward structured generation and derivation driven by computable rules.

Consistency Verification

Consistency verification was conducted following the standard AHP procedure. The maximum eigenvalue λ_max of the judgment matrix was first calculated, and then the consistency index CI=(λ_max−n)/(n−1) and consistency ratio CR=CI/RI were derived. For the criteria-level judgment matrix (n=5, Table 2), the calculated λ_max=5.387, CI=0.097 and CR=0.086; for the alternative-level judgment matrices under each criterion (Table 4), the CR values ranged from 0.012 to 0.091. All CR values were less than 0.10, satisfying the AHP consistency requirement and confirming that the hierarchical pairwise comparisons in this study had acceptable consistency for subsequent weight synthesis and comprehensive evaluation.

Table 4. Consistency Test Results

Item	B1	B2	B3	B4	B5
Eigenvector	0.074	0.084	0.106	0.098	0.095
	0.149	0.028	0.026	0.394	0.380
	0.274	0.188	0.301	0.272	0.083
	0.219	0.395	0.277	0.173	0.299
	0.284	0.305	0.290	0.063	0.142
Maximum Eigenvalue λ_max	5.395	5.109	5.209	5.056	5.409
CI	0.099	0.027	0.052	0.014	0.102
RI	1.120	1.120	1.120	1.120	1.120
CR	0.088	0.024	0.047	0.012	0.091
Consistency Test Passed	Passed	Passed	Passed	Passed	Passed

Analysis of Design Elements

After completing the allocation of criteria weights and consistency verification, it was necessary to further analyze how design elements affect each alternative. Drawing on the delineation of typical Silk Road cultural symbols by Whitfield (2000), Zhao Shengliang (2016), and other scholars within the pool of representative Dunhuang mural imagery, this study selected five highly representative motifs as the alternatives layer: the Three Hares (C1), winged horse (C2), Azure Bird (*Qingniao*) (C3), Nine-Colored Deer (C4), and camel (C5).

Table 5. Scores of Each Alternative

Alternative	C1	C2	C3	C4	C5	Weight
B1	0.07	0.15	0.27	0.22	0.28	0.10
B2	0.08	0.03	0.19	0.40	0.31	0.38
B3	0.11	0.03	0.30	0.28	0.29	0.08
B4	0.10	0.39	0.27	0.17	0.06	0.30
B5	0.10	0.38	0.08	0.30	0.14	0.14
Score	0.09	0.20	0.22	0.29	0.21	1.00

Based on the weighted scoring across the five criteria, C4 ranked first with a composite score of 0.29. Its pronounced advantages in B2 (0.40)—the criterion with the highest weight—and in B5 (0.30) demonstrate its strong translation potential as a core

cultural primitive of Dunhuang mural imagery. C3 ranked second with a score of 0.22, showing relatively balanced development value in B3 (0.30) and B1 (0.27). C5 ranked third with a score of 0.21, exhibiting advantages in both B2 (0.31) and B3 (0.29). C2 followed closely with a score of 0.20; although it scored lower in B2, it showed strong industrial adaptability in B4 (0.39) and B5 (0.38). C1 (0.09), despite ranking last overall, still presents some research potential in B3 (0.11).

On the basis of the above quantitative analysis and synthesis, the Nine-Colored Deer (C4), which achieved the highest overall evaluation and the greatest transformation value, was selected as the primary object of this study.

Shape Grammar Rules

Shape Grammar (SG), first proposed by Stiny and Gips (1971), is a design and analytical method defined as SG=(S,L,R,I), where S denotes the set of shapes, L the set of labels, R the set of inference rules, and I the set of initial shapes. All new shapes generated through shape grammar should be derived from the initial shapes via the application of shape rules. The inference rules can be classified into two types: generative rules and transformational rules. Generative rules include addition/deletion and substitution, whereas transformational rules include scaling, mirroring, duplication, rotation, and shearing (Fig. 3).

According to Wang (2023), with the support of computer software, shape grammar enables rapid generation and iterative refinement of design solutions, and it has been widely applied in fields such as cultural and creative products, fashion design, and visual design. For instance, Cui and Tang (2013b) employed shape grammar to digitally regenerate Zhuang ethnic embroidery patterns; Wang (2017) used this approach to reconstruct Xinjiang Hotan carpet motifs aligned with contemporary aesthetics. Zhang (2020) achieved efficient reconstruction of complex decorative patterns through rule-based derivation. Overall, shape grammar has demonstrated substantial potential and practical value for logic-driven generation in the revitalization of ICH and in contemporary design practice.

Evolutionary Form Development

As a symbolic animal embodying people's auspicious wishes, the deer is not only regarded as an emblem of beauty, health, and longevity. It is also associated with auspiciousness, prosperity, and power; it is therefore widely recognized as a favorable motif.

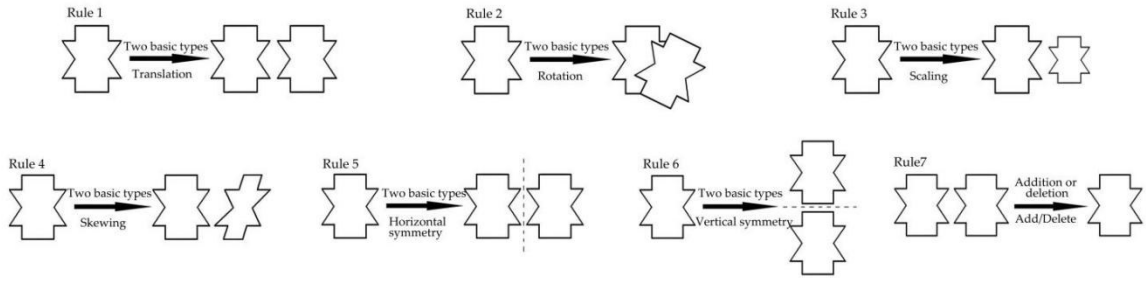
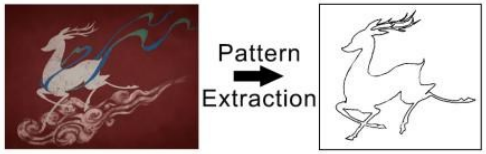
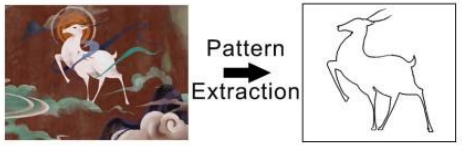
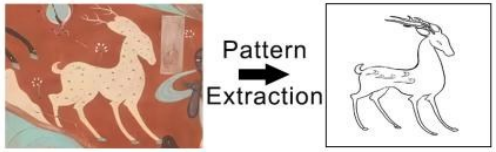


Fig. 3. Generative principles of shape grammar

Table 6. Selected Nine-Colored Deer Motifs from Dunhuang Mural

Period	Cave No.	Mural Image	Image Source
Northern Wei	Cave 257		*Selected Classified Works of Dunhuang Murals: Landscapes and Animals (Xu Jun 2000)*
			*Complete Collection of Dunhuang Grotto Art: Animal Paintings (Dunhuang Academy 2005)*
			*Complete Collection of Dunhuang Grotto Art: Reproducing Dunhuang (Dunhuang Academy 2001)*

Table 7. Extraction of Initial Motifs from Dunhuang Murals

Initial Motif Extraction 1	Initial Motif Extraction 2	Initial Motif Extraction 3
		

Through on-site investigations of the Dunhuang grottoes and a review of the relevant literature, the designers found that deer depictions in Dunhuang mural paintings are rich and diverse in form. Among them, the story of the Nine-Colored Deer depicted in the *Jataka Tale of the Deer King* in Mogao Cave 257 is the most canonical. The evolutionary targets of this study were defined as three Nine-Colored Deer figures with distinct postures from Cave 257 (the selected Dunhuang mural deer motifs are shown in Table 6).

Motif Extraction and Evolution

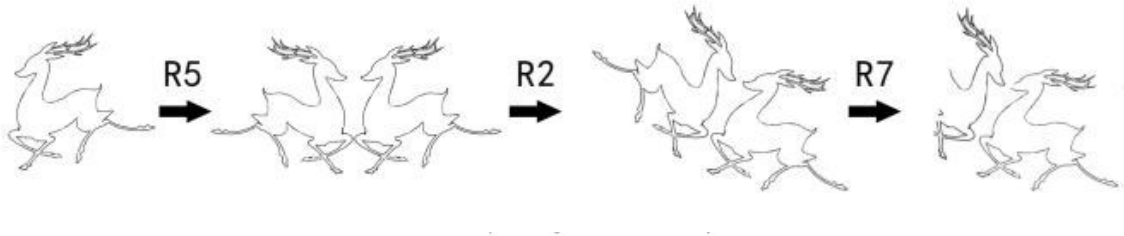
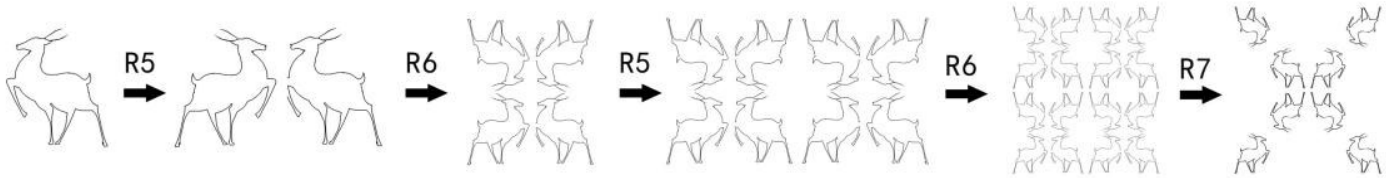
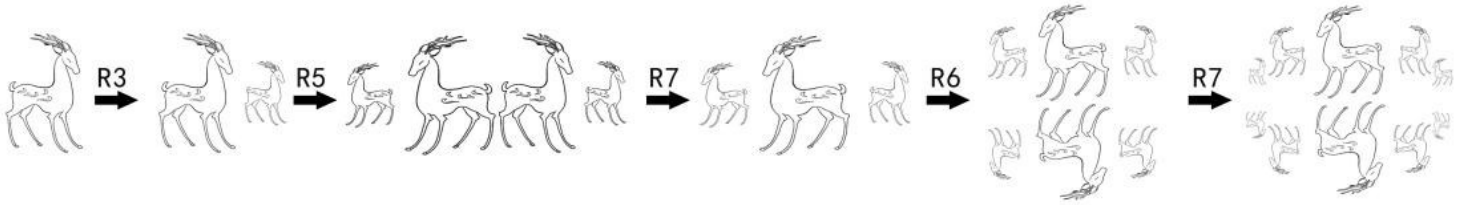
Motif extraction is the primary prerequisite for implementing shape grammar. In this study, Adobe Illustrator and Photoshop were used to extract individual Nine-Colored Deer motifs from the mural images, so that they could be incorporated into subsequent design proposals. The extracted initial motifs are shown in Table 7.

In the rule-derivation process of shape grammar, the Dunhuang deer motifs were first decomposed and isolated. Using the initial "Nine-Colored Deer" form as the basic primitive, key geometric feature parameters were extracted: the branching angle of the antlers was set within a rhythmic interval of 35° to 45°, and the dorsal ridge line was fitted based on the screened Nine-Colored Deer samples, with the radius of curvature controlled within the range [1.2,1.8] to preserve the characteristic line dynamics of Northern Wei murals. These parameters were determined *via* digital vector mapping and statistical measurement of three typical Nine-Colored Deer motifs in the Deer King Jataka of Mogao Cave 257 using Adobe Illustrator, with the mean values obtained from multiple measurements to ensure consistency with the original mural morphology.

Subsequently, morphological derivations were performed by defining a set of production rules. For example, in the generative logic of "Design 2," a horizontal mirroring rule (R5) was first applied to establish a biaxial symmetric skeleton, followed by a vertical mirroring rule (R6) to construct a four-directional continuous intention. Finally, an add–delete rule (R7) was used to remove redundant lines, achieving a topological reconstruction from the original figurative form to a highly symbolized visual module, thereby ensuring both logical continuity and contemporary aesthetics of the generated patterns. This parameter-constrained derivation pathway ensures that the generated motifs retain the authenticity of ICH "genes" at the topological level while also conforming to the linear aesthetic logic of modern industrial design.

For traditional decorative motifs, the mode of representation is not only a vehicle for conveying visual information, but also embodies the essence of Chinese traditional philosophy and cultural meaning. As Zhuge Kai (2007) stated in *Pattern Studies*, the compositional principles of Chinese traditional motifs are closely related to the aesthetic philosophy of the "unity of heaven and humanity," and their representational forms encompass multiple modes of spatial organization, including isolated motifs, two-directional repeats, four-directional repeats, and composite patterns. Based on the set of shape-grammar production rules, this study constructs a parameterized pattern sequence with a rigorous sense of order by applying geometric transformations—such as rotation, mirroring, and proportional scaling—to the initial operators (Table 8), so as to support subsequent applications in apparel and accessory design.

Table 8. Evolutionary Design of Dunhuang Mural Deer Motifs

No.	Diagram of Pattern Evolution Process
Design 1	
Design 2	
Design 3	

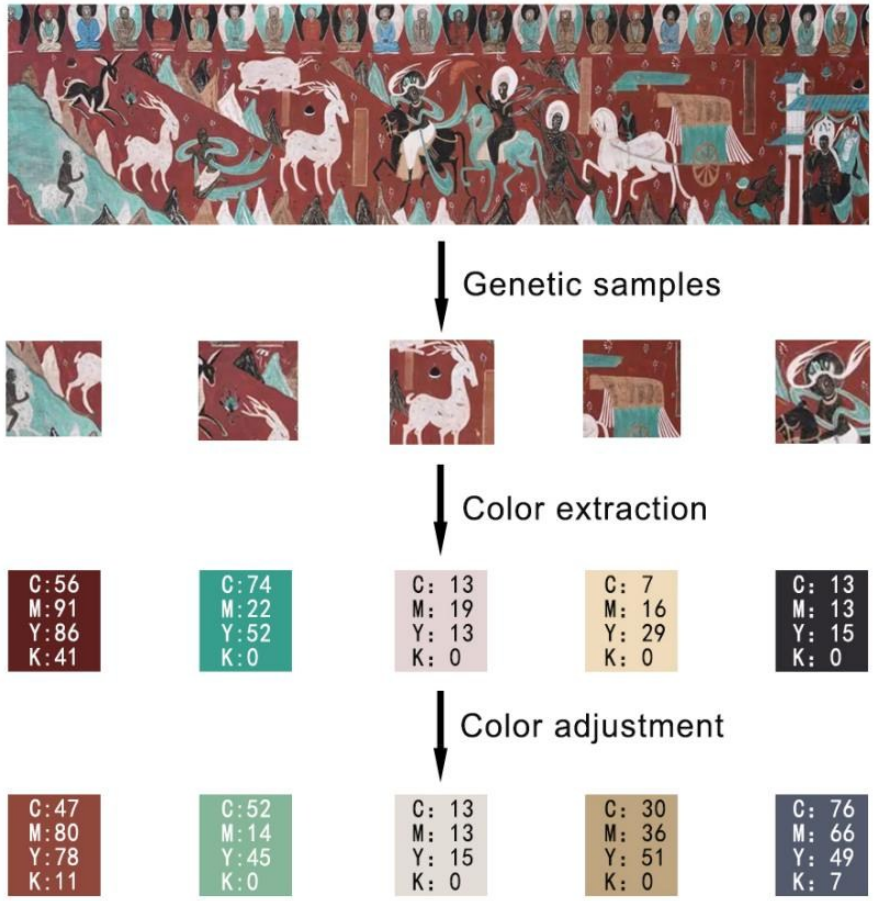


Fig. 4. Extraction of original colors

Table 9. Comparison of HSB Parameter Fine-Tuning for Color Compensation

Typical Color	Original Physical State	Digital Reconstruction Logic	Visual Compensation: Aesthetic/Theoretical Rationale
Earthy red	C: 56, M: 91, Y: 86, K: 41	Increase B (15% → 35%); moderate/converge S	Color-constancy compensation: increasing brightness while keeping hue stable and moderating saturation can effectively compensate for luminance degradation in historical materials (Ebner 2007). Wan and Li (2018) also reported in studies on digital restoration of cultural heritage that such compensation helps maintain a highly consistent color perception across media (*e.g.*, print and digital displays).
Malachite green	C: 74, M: 22, Y: 52, K: 0	Optimize/increase S (52% → 65%)	Saliency enhancement: drawing on computational visual-attention models, increasing saturation enlarges the boundary contrast between the motif subject and the background (Itti and Koch 2001). Experiments by Zhao and Zhang (2020) further confirmed that saliency-enhancement algorithms can reduce the risk of visual aliasing in complex patterned backgrounds, thereby strengthening the recognizability and visual impact of ICH symbols in engineering-oriented design.
Light gray	C:13, M:19, Y:13, K:0	Keep H constant; apply a mild linear adjustment to B	Background suppression and neutral anchoring: stabilizing the neutral point helps reduce device-dependent color shifts (Hunt and Pointer 2011). Mild linear adjustment of background brightness can also enhance contrast and minimize color drift across printing substrates (Shi 2019).

Color Extraction and Motif Colorization

Dunhuang grotto murals are primarily executed with mineral pigments, and their typical hues are mainly composed of earthy red, earthy yellow, malachite green, and achromatic tones such as black, white, and gray. In the Northern Wei period, an earthy-red ground was commonly used, complemented by green/blue/white/red pigments to form a stable hierarchical contrast structure. Given that long-term oxidation and environmental exposure may cause color graying and luminance attenuation, and that digital image acquisition may introduce white-balance shifts and chromatic deviations, this study takes the Northern Wei *Jataka Tale of the Deer King* in Mogao Cave 257 as the sample.

Representative color regions in the image were digitally sampled, their CMYK values were recorded as the baseline, and these values were then mapped to the HSB (Hue–Saturation–Brightness) space for parametric compensation (Fig. 4 and Table 9).

To improve the reproducibility and representativeness of sampling, a layered ROI-based strategy was adopted for color extraction. Within each representative hue region, multiple homogeneous areas without obvious cracks, stains, or specular highlights were selected as regions of interest (ROIs). Pixel-level color values within each ROI were summarized statistically (primarily using the mean; the median was used when necessary to reduce the influence of outliers) to obtain robust baseline color values. To avoid bias caused by edge color mixing, ROI boundaries were kept at a buffer distance from motif contours, and repeated sampling at different locations within the same hue was performed to verify color stability. Six independent homogeneous ROIs were selected for each representative hue region, and statistical analysis of the pixel-level color values yielded a statistical variance of 0.02~0.05 for the color values of each hue, which further verified the reliability and stability of the sampling data.

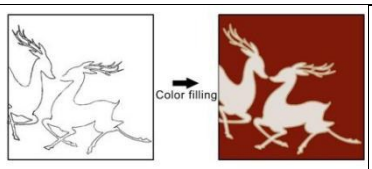
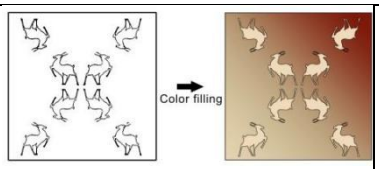
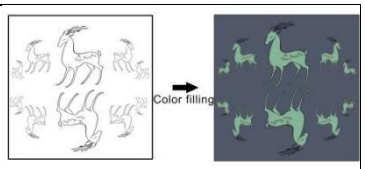
The compensation followed the principle of "preserving hue as the priority, with directional correction of saturation and brightness," so as to reduce the impact of historical degradation and imaging bias on color representation and to enhance readability and consistency across modern display and printing media. Specifically, for earthy red, brightness was increased (B: 15% → 35%) while the dominant hue (H) was kept stable and saturation (S) was moderated, thereby alleviating the dark and gray appearance of large background areas.

For malachite green, a saturation enhancement strategy was applied (S: 52% → 65%) to improve the salience of major outlines and fine motifs. For low-chroma neutrals such as light gray, hue was kept constant and brightness was adjusted with a mild linear correction to stabilize background–foreground separation and reduce cross-medium rendering discrepancies.

After completing color compensation, the corrected color set was applied to the line-drawing motifs to form the final colorization schemes (Table 10). Design 1 adopts a low-chroma, clearly layered strategy: the Nine-Colored Deer subject is retained in light gray, outlined in earthy yellow, and set against a background dominated by the HSB-compensated earthy red, thereby preserving the mural's color order of "ground–motif" while improving recognizability on apparel and accessory carriers (Table 10a). Design 2 employs an analogous color scheme: light yellow is used as the dominant hue, while earthy red, earthy yellow, and light yellow are arranged into a gradient background to achieve a continuous, unified tonality and a stable visual rhythm (Table 10b). Design 3 adopts a high-contrast strategy: high-lightness, high-saturation malachite green serves as the dominant color, with earthy yellow as local accents and deep gray as the background, thereby enhancing graphic contrast and foreground salience (Table 10c).

In summary, while retaining the Dunhuang mural color palette and its cultural references, this workflow improves the stability of cross-media rendering through parameterizable color-space compensation, providing a reproducible color-translation pathway for subsequent engineering-oriented design and manufacturing adaptation of cultural and creative products.

Table 10. Motif Colorization

		
(a) Design 1	**(b)** Design 2	**(c)** Design 3

Digital Translation and Reconstruction

The colors of Dunhuang murals are prone to composite color shifts, luminance attenuation, and reduced saturation due to long-term oxidation and environmental erosion. In addition, digital image acquisition may introduce white-balance errors and gamut compression, making the original colors difficult to directly output across modern media. To mitigate these non-target influences, this study uses the CMYK sampled values of representative color patches as the baseline, completes color-space mapping, and performs parametric reconstruction in the HSB (Hue–Saturation–Brightness) space. This workflow follows the principle of "hue preservation (stable H) + directional correction of saturation and brightness (S and B offsets)," transforming color adjustment from subjective tuning into traceable parameter-based processing, thereby improving the interpretability and reproducibility of color translation.

During reconstruction, brightness compensation serves as the primary control variable, coordinated with saturation adjustment. The B value is moderately increased to restore perceptible luminance and enhance foreground–background contrast; when necessary, S is either moderated (converged) or enhanced to avoid excessive graying or oversaturation, ensuring clear presentation of pattern hierarchy and fine details. Through this digital translation process, the reconstructed Nine-Colored Deer motifs preserve the overall tonal relationships and cultural references of Dunhuang murals while improving rendering stability across different display devices and material substrates. This provides a unified color basis for subsequent cross-media applications in cultural and creative product design.

Wooden Flowing-Light Night Lamp

The final evolved motif of "Design 1" was implemented in the wood-carving design of a wooden flowing-light night lamp. During product realization, this scheme employed the shape-grammar-derived spatial topological recombination rules for the Nine-Colored Deer motif, and the characteristic curves of the deer pattern were extracted, discretized, and normalized to obtain standardized contours. For the main lamp panel, rule-based proportional scaling and mirror symmetry were adopted as the underlying generative logic to translate the two-dimensional motif into a machinable openwork pattern. Laser cutting was then applied to form clear contour boundaries and layered partitions.

At the semantic level, the openwork structure and the backlighting system created a coupled "solid–void" light–shadow relationship. After illumination, the negative space

of the motif was transformed into continuous luminous pathways, and the planar narrative vocabulary of Dunhuang murals was further extended into a spatially visualized effect featuring luminance gradients and halo diffusion. This enhanced translation supports a shift from "pattern recognition" to "light-effect perception." The resulting nonlinear form-generation route, reinforced by oak grain texture and the flowing-light effect, strengthens the contemporary aesthetic expression of the product, thereby achieving an engineering-oriented transfer and innovative application of the cultural imagery to a wood-based lighting carrier. Oak solid wood panels were selected as the substrate (density: 0.65 g/cm³, moisture content: 8%, flexural strength: 65 MPa). The core dimensions of the lamp body were 18 cm in diameter and 22 cm in height. Processing was conducted with a laser power of 120 W and a cutting speed of 5 mm/s, and UV printing was implemented at a resolution of 300 dpi, with no obvious processing defects observed (Fig. 5).

Fig. 5. Application of the deer motif in a wooden flowing-light night lamp

Apparel Made from Wood-Fiber Composite Fabric

Scheme 2 focuses on the visual–semantic translation and pattern derivation of the Nine-Colored Deer motif on wood-derived cellulosic textile substrates. To meet structural requirements in modern apparel design, a shape-grammar-based generative evolution logic was employed to decompose the deer motif "genes" into basic geometric units. Through scattered-perspective composition and continuous topological arrangement, the units were reconstructed into a rhythmic two-way repeat pattern.

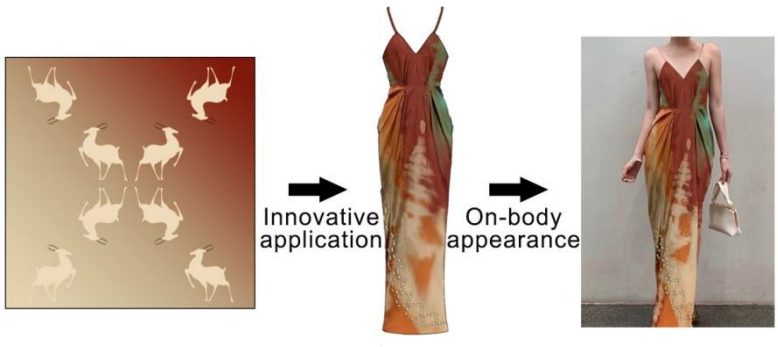


Fig. 6. Application of the deer motif in apparel

Regarding material selection, a wood-pulp regenerated cellulose fabric with cellulose as the primary component was used as the textile carrier. Digital heat transfer printing was performed based on the HSB parameters after color reconstruction, and luminance compensation was further introduced to enhance the color saturation and visual anchoring of the motif on the silk-like fabric surface. The garment cutting strategy was

structurally coupled with the fluid morphology of the motif: the dynamic curves of the pattern were distributed in accordance with ergonomic body structures, enabling a sense of flowing expression of the cultural imagery in dynamic space. Through the digital reconstruction of semantic symbols, the ICH elements were effectively aligned with contemporary fashion discourse, thereby reducing the perceptual gap between traditional symbols and modern aesthetics. Bamboo pulp regenerated cellulose composite fabric was adopted (gram weight: 120 g/㎡, air permeability: 80 mm/s, color fastness: Grade 4). For the adult M size, the core dimensions were 65 cm in length and 96 cm in chest circumference. Digital heat transfer printing was completed under the parameters of 180 °C, 25 s and 0.3 MPa, achieving a high pattern reproduction accuracy (Fig. 6).

Cellulosic Textile Bag

The evolutionary logic of "Design 3" was implemented for design validation on a functional single-shoulder bag using a wood-based cellulosic substrate. The ratio between the background narrative map and the primary motif units was carefully controlled to evaluate the recognizability of the pattern and the stability of graphical hierarchy on cellulose-based textiles. In terms of composition, a combined strategy of scaling and scattered-point arrangement was adopted to embed the deer motif into a narrative scene composed of mountains, landscape elements, and human figures, ensuring that the symbolic information maintained a clear and ordered structure under textile texture and printing constraints. Yellow tassels were added to both sides of the bag as linear balancing components to enhance visual guidance and improve compositional stability in the marginal areas.

Regarding materials, a high–areal-density cotton–linen blended fabric was selected as a representative wood-derived cellulosic carrier. Its abrasion resistance and surface texture characteristics were used to verify the motif's compatibility and durability on a flexible fibrous substrate. This scheme confirms that scattered-point composition can achieve balanced graphic distribution and information integrity on wood-based cellulosic textiles, providing reusable empirical evidence for the digital translation of Dunhuang ICH motifs and their application in wood-fiber-based cultural product design. Cotton-linen blended lignocellulosic fabric was chosen (gram weight: 280 g/㎡, wear resistance: ≥20,000 cycles). The core dimensions of the bag body were 32 cm in length, 12 cm in width and 28 cm in height. The product was processed via setting at 130 °C and embroidery with a stitch pitch of 3 mm, exhibiting excellent compatibility between the substrate and the manufacturing process (Fig. 7).

Fig. 7. Application of the Deer Motif in a Bag Accessory Design

PRODUCT EVALUATION

Evaluation Framework and Indicator System

To verify the effectiveness and generalizability of the integrated "AHP–Shape Grammar" pathway in the translation of cultural and creative products, this study established a multi-criteria expert evaluation framework based on a five-point Likert-type scale. The system comprises five criteria aligned with key attributes of cultural-and-creative product translation: cultural authenticity (D1), artistic aesthetics (D2), geometric transformability (D3), wood-based process compatibility (D4), and market resonance (D5).

To improve the content validity of the evaluation and the cross-perspective representativeness of the results, 20 reviewers, including Dunhuang art researchers, cultural and creative product design practitioners, and target users aged 20 to 50, were invited to form an expert panel to conduct blind scoring, resulting in a valid sample (n=20). A reliability test was performed on the scale, with an overall Cronbach's α coefficient of 0.872 and all dimension-level coefficients > 0.8, indicating good internal consistency of the scale and that the data can be used for inferential statistics.

A structured questionnaire was adopted for the evaluation, with items designed around five dimensions: cultural authenticity, artistic aesthetics, geometric transformability, material compatibility, and market resonance. Two 5-point Likert scale items (1 = strongly disagree, 5 = strongly agree) were set for each dimension. A Cronbach's α reliability analysis was conducted on the questionnaire, yielding an overall α coefficient of 0.86 and dimension-level α coefficients ranging from 0.81 to 0.88. All coefficients exceeded 0.80, indicating that the questionnaire had good internal consistency and reliability, and the evaluation data were valid.

Statistical Results and Scheme Differences

Based on descriptive statistics of the valid sample (Table 11), the three schemes achieved consistently high mean scores across the five dimensions (mean range: 4.40–4.75), indicating that the proposed "decision–generation" workflow can stably produce highly endorsed design outcomes across different carriers (jewelry/apparel/bag). When the arithmetic mean of the five-dimensional scores is taken as overall performance, Scheme 1 (Flowing-light night lamp), Scheme 2 (apparel), and Scheme 3 (bag) all scored above approximately 4.5, with Scheme 2 slightly higher (Fig. 8). Further dimensional comparisons show that Scheme 1 performs particularly well in cultural authenticity (D1 = 4.70) and wood-based process compatibility (D4 = 4.65). Scheme 2 reaches the highest value in market resonance (D5 = 4.75) and maintains a high score in geometric transformability (D3 = 4.65). Scheme 3 achieves the highest score in geometric transformability (D3 = 4.70), reflecting the structural advantages of rule-based generation in functional carriers. To verify the statistical significance of score differences, a one-way analysis of variance (ANOVA) was performed on the data at a significance level of $\alpha = 0.05$.The results showed that there were no significant differences among the three schemes in cultural authenticity ($F = 2.15$, $P = 0.128 > 0.05$) and artistic aesthetics ($F = 1.89$, $P = 0.157 > 0.05$). Significant differences were found in geometric transformability ($F = 4.23$, $P = 0.021 < 0.05$), wood-based process compatibility ($F = 3.89$, $P = 0.028 < 0.05$), and market resonance ($F = 5.12$, $P = 0.010 < 0.05$). These results are highly consistent with the processing characteristics and audience preferences of different wood-fiber carriers.

One-way ANOVA and LSD post-hoc tests were conducted on the scoring data, and the results showed no significant difference in scores among the three schemes (P>0.05),

which verifies the consistent application effect of the proposed framework on different wood-fiber substrates.

Table 11. Multidimensional Evaluation Scores for the Three Design Schemes

Dimension	Scheme 1 (Flowing-light night lamp)	Scheme 2 (Apparel)	Scheme 3 (Bag)
D1	4.70	4.60	4.55
D2	4.45	4.50	4.40
D3	4.50	4.65	4.70
D4	4.65	4.50	4.55
D5	4.40	4.75	4.60

Applicability Assessment for wood-based Carriers

The comprehensive quantitative evaluation indicates that the proposed integrated "AHP–Shape Grammar (SG)" framework can effectively balance cultural authenticity and engineering constraints. The experimental results reveal a clear advantage in process compatibility: Scheme 2 (apparel) and Scheme 1 (flowing-light night lamp) achieved relatively high scores on D3 (geometric transformability) (4.65 to 4.70), demonstrating the stability of the SG-derived rule-based linework when dealing with the anisotropy of wood-fiber substrates. Compared with easily deformable textiles, the rigid structural support provided by wood-based carriers enables a more accurate reproduction of the complex contours of the Nine-Colored Deer generated through SG rule derivation.

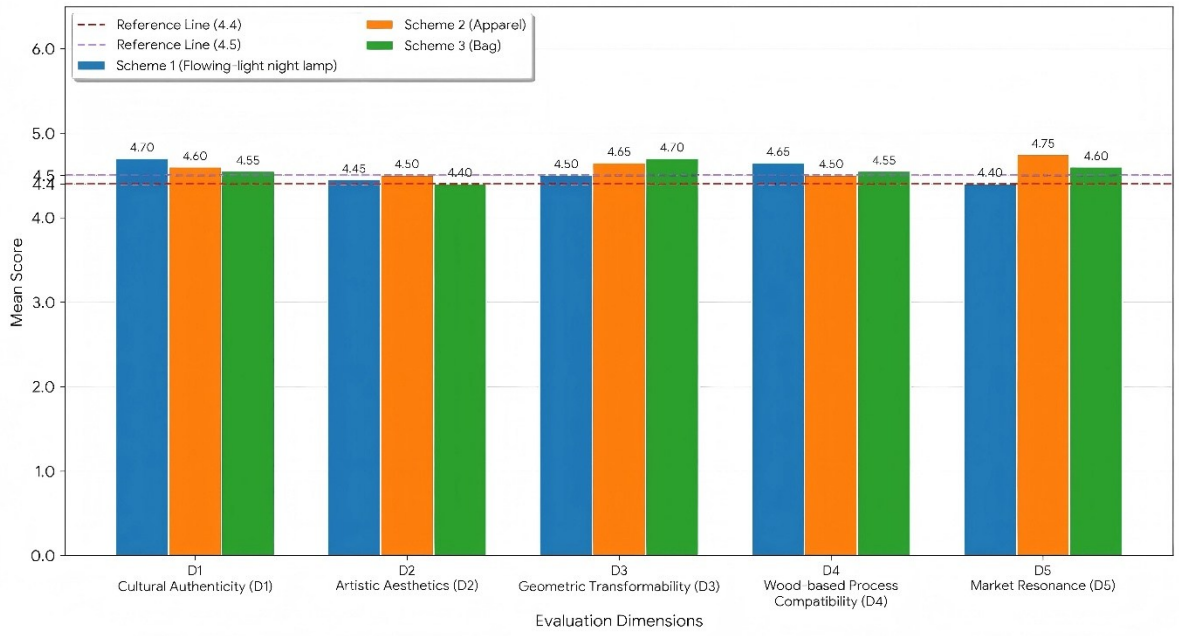


Fig. 8. Comparative analysis figure

From the perspective of the wood-cellulose material spectrum, the three schemes correspond to three typical carriers: solid wood panel, wood-fiber composite, and lignocellulosic material. Empirical experiments on laser cutting and digital printing/dyeing were conducted for these three wood-based carriers in this study. The test results showed that: when the patterns on solid wood panels were processed with a laser power of 120 W and a cutting speed of 5 mm/s, the average contour dimensional error was ≤ 0.15 mm, the

heat-affected zone (HAZ) was controlled within 0.2 mm, and no obvious scorch marks or rough edges were observed. Owing to their more uniform density, engineered wood-based materials exhibited a 20% improvement in the stability of line width and contour precision compared with solid wood. Although wood-based materials are more sensitive to thermal processing than metallic or plastic carriers, processing defects can be effectively avoided through the optimization of process parameters.

In terms of surface color rendering, the porosity and roughness of wood panels can affect ink spreading behavior and color density. Actual UV printing tests showed that the color reproduction deviation ΔE of the HSB-compensated color system on solid wood panels was ≤2.3, achieving a favorable color reproduction effect. By contrast, regenerated cellulose textiles (*e.g.*, viscose) and cotton–linen fabrics differ in ink absorption and diffusion characteristics, requiring the combination of CMYK sampling and HSB parameter compensation to reduce cross-media color deviations and ensure sharp motif boundaries through appropriate pretreatment. Overall, incorporating material–process factors into the translation chain can improve both the stability and verifiability of motif outputs across different wood-derived cellulosic carriers.

CONCLUSIONS

1. Theoretical framework: To address the issue of non-reproducible logical chains in the development of cultural and creative products on wood-fiber carriers, a computable and reusable digital translation framework of the analytic hierarchy process (AHP)—Shape Grammar was constructed. Through a comparison with existing digital heritage translation models such as the single decision-making screening model, pure morphological generation model, and general cross-media translation model, the theoretical breakthrough of this framework in the full-chain coupling of quantitative screening – rule-based generation – material adaptation was clarified. This framework remedies the one-dimensional drawbacks of existing models and realizes a paradigm shift of intangible cultural heritage (ICH) motifs from symbolic description to engineering-oriented generation.
2. Decision model: Through AHP, artistic aesthetics and wood-based process compatibility were identified as the core priority dimensions for translational design. Reliability and inferential statistical tests were completed using Cronbach's α coefficient, Kendall's concordance coefficient, and one-way ANOVA, providing rigorous quantitative support for the scientific translation of Dunhuang imageries such as the Nine-Colored Deer.
3. Practical value: Three design schemes were developed, including a wooden flowing-light night lamp, apparel made from wood-fiber composite fabric, and a cellulosic textile bag, and were evaluated through a Likert-scale blind review by 20 experts. The schemes received consistently high scores across the five criteria (4.40 to 4.75), with an overall mean of approximately 4.5 and small inter-scheme variations (standard deviation ≈ 0.1). The results demonstrate the robustness of the proposed method in enhancing the added value of biomass-based cultural products and provide a technical support basis for high-quality and scalable innovation of wood-fiber resources. Machining precision tests indicated that the pattern dimensional error of wood-based carriers was ≤0.15 mm, showing good engineering compatibility.

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Use of Generative AI

ChatGPT-4 was used to assist in formatting the initial references. All references were manually checked and cross-referenced with the Web of Science database to ensure accuracy. No generative artificial intelligence tools were used in writing the main text, creating figures, or designing tables.

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