Design and Sustainability Assessment of Dunhuang Mural-Inspired Wood-Based Products *via* an AHP-LCA Coupling Framework

Zunying Bian *

To address the lack of quantitative environmental footprint assessment in design translation of intangible cultural heritage products, this study takes Dunhuang Nine-Colored Deer themed wood-based cultural and creative products as objects and constructs a green assessment path based on Analytic Hierarchy Process-Life Cycle Assessment (AHP-LCA). A three-level AHP model established by 30 interdisciplinary experts identified and prioritized the core bionic elements (galloping deer morphology: 0.344; mineral white: 0.121; line drawing outline: 0.057). According to ISO 14040 (2006) and ISO 14044 (2006) standards, dual-dimensional life cycle assessment is adopted to compare the baseline scheme and optimized scheme. The results show that the optimized scheme achieved 4.3% full life cycle carbon emission reduction, 52.8% raw material emission reduction, and 65% material recovery rate. The study shows that the AHP-LCA model can effectively balance cultural aesthetic demands and low-carbon properties of wood-based materials and provides a systematic methodological reference for green and sustainable development of biomass-based products.

DOI: 10.15376/biores.22.1.109-134

Keywords: Dunhuang mural; Wood-based products; Life-cycle assessment; Analytic hierarchy process; Sustainable design; Cultural creative products

*Contact information: School of Fine Arts and Design, Lanzhou University of Arts and Science, Lanzhou, Gansu 730000, China; *Corresponding author: 13233529007@163.com*

INTRODUCTION

Under the dual background of the global "dual carbon" strategy and the living inheritance of cultural heritage, cultural and creative products have become the core carrier for the modern translation of intangible cultural heritage. With the advancement of the global sustainable development agenda, wood, as a typical biomass resource, has become an irreplaceable low-carbon engineering carrier in the green transformation of cultural and creative products by virtue of its natural carbon sequestration property, excellent renewability, and biodegradability (Ma *et al.* 2026). Current cultural and creative development mostly focuses on perceptual translation of cultural symbols, and often ignores the quantitative assessment of environmental loads of wood-based products throughout their life cycle from raw material extraction, processing and manufacturing to waste disposal (Zhao and Zhang 2020). As a treasure of cultural integration on the ancient Silk Road, Dunhuang murals contain profound artistic essence. Among them, the image of the Nine-Colored Deer in Cave 257 of the Mogao Grottoes, with its unique bionic characteristics and cultural implications, is an ideal object for exploring the integration of traditional aesthetics and green engineering design. Therefore, the in-depth integration of

green design principles and wood-based material properties is not only the core demand of the cultural and creative industry in responding to low-carbon transformation, but also a key path to realize the sustainable utilization of cultural heritage and the coordinated development of green assessment of biomass products (Jin and Sharudin 2023).

In recent years, there have been multi-dimensional explorations on the extraction, translation, and productization paths of Dunhuang cultural elements. Through artistic feature analysis and morphological bionic design, the artistic value of Dunhuang culture has been verified fully in modern design (Xiong and Li 2023; Li *et al.* 2025). However, in view of the rigorous requirements for biomass product development under the dual carbon goals, existing studies still have the following limitations in green sustainability and quantitative assessment systems. Firstly, the screening of core elements lacks a scientific weight distribution mechanism and excessively relies on designers' subjective experience, making it difficult to realize accurate translation of cultural connotations and quantitative decision-making in an interdisciplinary context (Jiang *et al.* 2024). Secondly, life cycle thinking has not been deeply integrated into the development process of cultural and creative products. Most existing studies focus on qualitative analysis of single materials or processing links and lack systematic quantitative assessment in accordance with ISO 14040 (2006) and ISO 14044 (2006) standards. This results in insufficient data support for biomass resource utilization efficiency and carbon emission reduction performance of products (Ghazali *et al.* 2023). Finally, there is a disconnection between cultural representation and green engineering logic, and traditional elements have not been deeply integrated with the structural properties, low-carbon technologies and recyclable packaging of wood-based materials. The asynchrony between design and assessment restricts the optimal balance of environmental performance for wood-based cultural and creative products while meeting aesthetic demands (Kazancoglu *et al.* 2023).

The Analytic Hierarchy Process (AHP) and Life Cycle Assessment (LCA) are core quantitative tools in the field of green and sustainable development, and their collaborative application has become a research hotspot in the field of sustainable engineering (Elshafei *et al.* 2022). AHP can decompose complex design decision-making into a hierarchical structure, convert qualitative cultural elements into quantifiable weight data through expert evaluation, and solve the problem of strong subjectivity in the selection of cultural and creative elements. LCA systematically evaluates the resource consumption and environmental emissions of products throughout their life cycle in accordance with ISO standards, accurately identifies key nodes of environmental load, and provides a scientific basis for the green optimization of cultural and creative products. At present, the collaborative application of AHP and LCA has been verified in the field of industrial product green development, but its application in the field of Dunhuang mural cultural and creative products is still relatively scarce. There has been no targeted development path and comprehensive evaluation system, which has become a key bottleneck restricting the green and sustainable development of Dunhuang cultural and creative products (Li 2023; Cholewa *et al.* 2024; Liu 2025).

Accordingly, based on the research orientation of sustainable development and the demand for green transformation of the cultural and creative industry, this study takes the Dunhuang Nine-Colored Deer bionic cultural and creative products as the research object, and constructs a green sustainable development and assessment path integrated with AHP-LCA. Scientific quantitative screening of core cultural bionic elements is realized through AHP, and full life cycle environmental performance assessment is carried out through LCA. Combined with engineering design methods, targeted green optimization strategies are

proposed to solve the core problem of disconnection between cultural translation and environmental assessment in cultural and creative product development, achieve the coordinated balance between cultural aesthetics and environmental performance, and provide methodological reference for the green sustainable development of biomass-based products.

The Nine-Colored Deer lamp is positioned as a mid-market, industrially produced table lamp for individual consumers (1,000 to 10,000 units/year, 200 to 400 CNY, service life ≥ 5 years), not as a museum-grade exhibit or short-term display. This scale makes the per-unit burdens environmentally meaningful, while the cost ceiling requires every Scheme B measure to be achievable with commercial materials and conventional equipment, and sets the furniture-grade acceptance criteria applied to the recycled cellulose composite. Near-commercial measures such as the bio-based low-VOC coating can be replaced by mature substitutes in the short term; the framework then serves as a screening tool for emerging low-carbon materials.

The engineering decision-making process of the AHP-LCA framework constructed in this study was divided into five core stages: (1) sample extraction was carried out for Dunhuang Nine-Colored Deer murals and systematic induction of morphological bionic elements; (2) weight calculation was done for Nine-Colored Deer morphological elements and screening of core design elements based on AHP; (3) product structural design schemes were generated combined with LCA environmental constraints according to the screening results of AHP; and (4) an LCA qualitative assessment system was established for comprehensive analysis of indicators such as material selection, structural design, and recyclability; and (5) the two candidate design schemes were compared in terms of cultural recognition and whole life cycle environmental performance, and the optimal scheme and its sustainable design strategy were identified, providing a quantitative basis for the sustainable design of wood-based cultural and creative products. The quantitative LCA assessment and carbon emission modelling were conducted under the ISO 14040 (2006) and ISO 14044 (2006) framework to calculate the environmental impacts of different wood-based design schemes in the stages of raw material acquisition, production and manufacturing, transportation, service use, and waste disposal (Fig. 1).

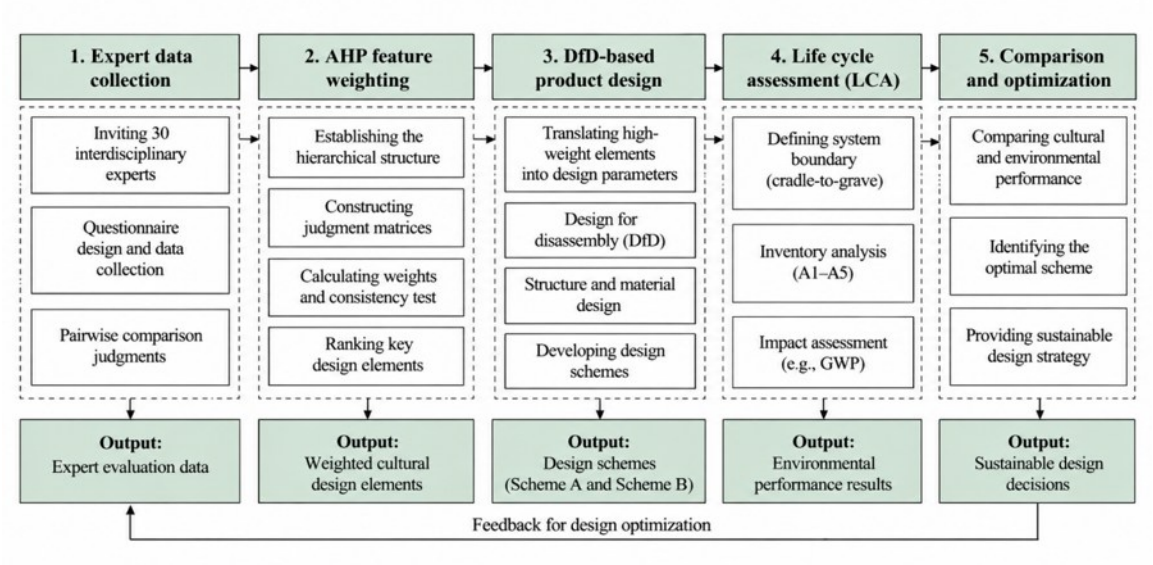


Fig. 1. Research methodology

LCA-based Sustainable Evaluation Theory of Dunhuang Murals

LCA is a standardized quantitative assessment method for environmental impact in the field of green engineering design. Combining it with the modern translation of Dunhuang mural cultural elements can provide systematic theoretical support and practical paths for the green engineering application of traditional artistic symbols in cultural and creative products. A LCA sustainable evaluation theoretical framework adapted to the bionic cultural and creative products of the Dunhuang Nine-Colored Deer is constructed, with the evaluation boundary covering the whole life cycle of the product from raw material acquisition, production and manufacturing, transportation and circulation, use stage to final disposal. By establishing the whole life cycle inventory data and environmental impact quantitative model, the resource consumption characteristics and environmental load distribution rules in the whole life cycle of the product are systematically identified. The contribution ratio of resource energy consumption and environmental emissions in each stage is clarified, and the environmental load transfer problem caused by local optimization is effectively avoided.

AHP-based Morphological Elements of the Dunhuang Nine-Colored Deer

AHP is a classic quantitative method for solving multi-criteria complex decision-making problems. It solves the problem that non-quantitative engineering decision judgments are difficult to quantify in the screening of traditional cultural visual elements. It provides a scientific weight basis for the extraction and optimization of Nine-Colored Deer bionic elements and offers stable and reliable design input parameters for the subsequent LCA environmental evaluation and product scheme iteration. Referring to the core logic of the AHP method proposed by Saaty (1990), this study constructs a three-level hierarchical evaluation system of "target layer, criterion layer, indicator layer". The target layer is the screening of bionic elements of the Nine-Colored Deer in Dunhuang murals. Combined with the artistic characteristics of the Dunhuang Nine-Colored Deer, the adaptability of green engineering design and development of cultural derivative products and the engineering requirements of cultural translation, the shape elements, color elements, and style elements are set as the criterion layer (Xu *et al.* 2024). Based on the element induction results of mural samples, typical visual elements that can be quantified and designed in practice are further disassembled as the indicator layer, among which the shape elements include curled deer, standing deer, and galloping deer. The color elements include mineral white, azurite blue, vermilion, and malachite green, and the style elements include flat color blocks, serrated mountain stone composition, and line drawing outline. An interdisciplinary evaluation team consisting of Dunhuang culture research experts, industrial design engineers and experts in the green engineering design and development of cultural derivative products were invited to score each level of indicators through pairwise comparison using the classic AHP 1-9 scaling method. The arithmetic mean was taken to construct the judgment matrix, the weight of each element was solved by the characteristic root method, and a consistency test was carried out (consistency ratio $CR < 0.1$ is qualified) to ensure the statistical reliability and engineering design rationality of the weight calculation results.

LCA-driven Sustainable Design of Nine-Colored Deer Cultural and Creative Products

After completing the screening of core bionic elements of the Nine-Colored Deer through AHP, with the LCA whole life cycle environmental performance as the core

engineering constraint, a green and sustainable design path covering the whole product process was constructed. On the premise of maintaining the integrity and recognizability of the cultural characteristics of Dunhuang murals, the systematic engineering control of the environmental load of cultural and creative products was realized, and finally the coordinated unification of accurate cultural morphological translation and whole life cycle ecological performance was achieved. Targeted design strategies were formulated from five key links: raw material selection, production and manufacturing, transportation, use stage, and final disposal.

Raw material selection

The resource selection in the raw material stage directly determines the basic level of the overall environmental load of the product. With the core design goals of reducing resource depletion potential and improving the end-of-life recycling efficiency of products, renewable or recyclable materials such as FSC-certified wood, bamboo and recycled pulp composite materials are preferred. Such materials have controllable production energy consumption, good biodegradability and regenerative recyclability, and their whole life cycle carbon emission level is significantly lower than that of traditional high-energy-consuming plates (Verma *et al.* 2025). Raw material selection strictly follows the relevant environmental protection and safety standards, avoiding the use of materials containing harmful components such as high volatile organic compounds (VOCs) and heavy metals, and reducing the potential impact of the product use stage on human health and indoor environment (Del Curto and Turrina 2023). Under the premise of product structural design permission, the use of composite non-separable materials is minimized to improve the resource classification and recycling efficiency in the product waste stage from the source.

Production and manufacturing

The environmental impact in the production and manufacturing stage mainly comes from energy consumption and material utilization efficiency, and the selection of processing technology has a decisive effect on the overall sustainability of the product, with the core design principles of minimizing manufacturing energy consumption and reducing material processing loss (Frumușanu and Epureanu 2014). Numerical control processing technology is adopted to realize the precise forming of product components, and the raw material utilization rate is improved by combining digital modeling and plate layout optimization strategies, effectively reducing the generation of leftover waste in the processing process (Kim *et al.* 2024). In the surface treatment link, traditional high-pollution and high-emission solvent-based coatings are abandoned, and environmentally friendly treatment processes mainly based on water-based coatings and natural oil wax are adopted to reduce VOC emissions. For the visual expression of Nine-Colored Deer cultural elements, a combination of local coloring and carved texture technology is used to replace large-area full-coverage coating, which reduces the amount of colorant used and processing energy consumption while ensuring the accurate presentation of cultural characteristics, realizing the organic unity of low-carbon production technology and cultural expression (Wang *et al.* 2024a,b).

Transportation

Combined with the industrial characteristics of mass production and cross-regional circulation of cultural and creative products, energy consumption and carbon emissions in the transportation stage cannot be ignored. Reducing the carbon footprint of the product

circulation process is the core design goal, and logistics optimization considerations are integrated into the initial stage of product structural design. Detachable and flat structural design is adopted to reduce the volume occupancy rate of products during transportation and improve transportation loading efficiency; the size of products and packaging is standardized to realize stacking optimization and maximum space utilization in the transportation process. Through the engineering design of structure and packaging, energy consumption and carbon emissions in the transportation stage are controlled from the source (He and Hua 2017).

Use stage

Extending the product life is a key engineering strategy to reduce its whole life cycle environmental load, with the core design principles of improving the durability and maintainability of products. By integrating replaceable functional components, such as replaceable light sources and modular functional components, the overall scrapping of products caused by local damage is avoided, effectively extending the actual service life of products (Maldini *et al.* 2025). The size ratio and structural stability of products are strictly matched with the actual use scenarios and needs, avoiding the premature elimination of products due to inconvenience in use and structural failure. The emotional expression and value transmission of Nine-Colored Deer cultural elements are strengthened, and cultural identity is combined with product use experience to improve users' willingness to retain products. The dual improvement of the engineering strategy for extending the product service cycle through product structural durability and cultural identity is realized, reducing resource waste and environmental emissions from the use end.

Final disposal

The resource recovery efficiency in the product end disposal stage directly affects the resource circulation performance of the whole life cycle. With the core of realizing material closed-loop circulation and reducing waste generation, the design concept for disassembly is introduced, and the material separation method and component disassembly path are defined at the initial stage of product design (Brändström and Saidani 2022). Physical connection methods such as mortise and tenon joints and buckles are used to replace traditional chemical gluing to construct an adhesive-free green connection system, reducing the difficulty of product disassembly. The combination of non-separable composite materials is avoided in structural design to ensure that each component can be efficiently classified and recycled according to material types after product scrapping. The Nine-Colored Deer bionic components are designed as recombinable structures, and some components can continue their functions or be transformed into decorative parts through secondary design, extending the actual service cycle of materials, improving resource utilization rate and reducing the final disposal amount of waste.

EXPERIMENTAL

Determination of Design Elements by AHP

High-definition digital rubbings of the Deer King Jataka in Cave 257 of the Dunhuang Mogao Grottoes and the official restored drawings of the Nine-Colored Deer released by the Dunhuang Academy were taken as the core samples, with the sample selection meeting the requirements of authority, typicality, and comprehensiveness (Fig. 2) (Yin *et al.* 2019; He 2022).

A bionic element model of the Nine-Colored Deer in Dunhuang murals was constructed. The bionic elements of the Nine-Colored Deer in Dunhuang murals were taken as the target layer (A). Combining the artistic characteristics of the Dunhuang Nine-Colored Deer, the adaptability of green engineering design and development of cultural derivative products and the requirements of cultural translation, shape (B1), color (B2), and style (B3) were established as the criterion layer. This layer was refined to obtain the indicator layer (C1–C10), forming a three-level AHP evaluation system of "target layer, criterion layer, indicator layer" (Fig. 3, Table 2).

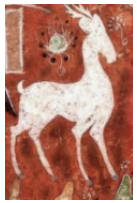
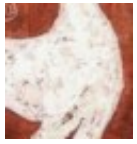
Thirty interdisciplinary experts were invited to form an evaluation team, covering core fields such as Dunhuang culture research, industrial design, cultural and creative product design, environmental assessment, production technology, and green design (among whom 60% have senior professional titles and the average working experience is ≥ 8 years). All experts received unified research background materials (high-definition samples of Nine-Colored Deer murals, explanation of the three-level AHP evaluation system, and rules of the 1 to 9 scaling method), and completed the filling of the judgment matrix by anonymous independent scoring. After collecting the data, the arithmetic mean of the scoring results of the 30 experts was taken to construct the final judgment matrix.

Prior to aggregation, the individual pairwise comparison matrix submitted by each expert was tested separately for consistency using Eqs. 1 to 3, and matrices returning a CR of 0.1 or higher were fed back to the corresponding expert for revision and were included in the aggregation only after the revised matrix satisfied the CR < 0.1 criterion; in the present study all 30 valid questionnaires passed the individual consistency test, so no expert response had to be discarded. Because averaging can in principle degrade the consistency of an aggregated matrix, the consistency of the aggregated judgment matrix was re-tested after aggregation, and the CR values reported in Table 7 are those of the final aggregated matrices, all of which are well below the 0.1 threshold. Through weight calculation and consistency test, the core bionic elements suitable for the green engineering design and development of cultural derivative products were identified to provide a scientific basis for subsequent design practice (Table 2). The results included the judgment matrix B1 among various elements of the shape criterion (Table 3), the judgment matrix B2 among various elements of the color criterion (Table 4), and the judgment matrix B3 among various elements of the style criterion (Table 5).



Fig. 2. Deer King Jataka, Mogao Grottoes of Dunhuang

Table 1. Bionic Elements of the Nine-Colored Deer in Dunhuang Murals

Item	Typical Sample			Extracted Element			
Modeling				 Crouching Deer	 Standing Deer	 Galloping Deer	
Color		 		 Stone Cyan：R=37，G=54，B=36，	 Vermilion：R=167，G=64， B=74，	 Stone Green：R=81， G=109，B=83，	Mineral White：R=245，G=242，B=233，
Style				Flat Color Blocks	Jagged Mountain and Rock Composition	Line-drawn Outline	

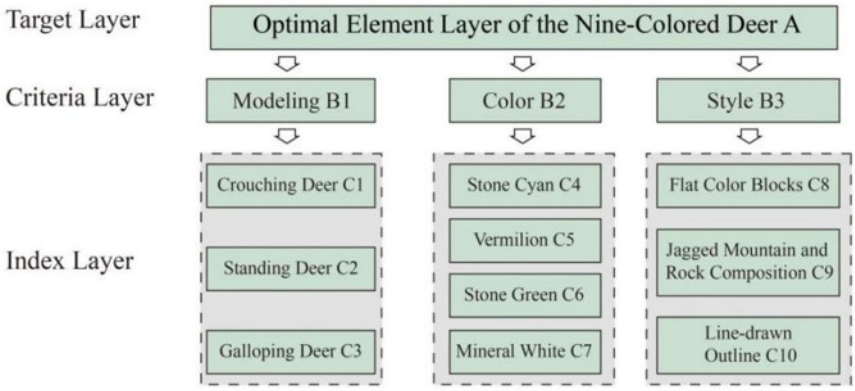


Fig. 3. Bionic element model of the Nine-Colored Deer in Dunhuang murals

Table 2. Judgment Matrix of Target Layer A for the Optimal Elements of the Nine-Colored Deer

A	B1	B2	B3
A	1	3	5
B1	1/3	1	3
B2	1/5	1/3	1

Table 3. Judgment Matrix of Shape Criterion Layer B1

B1	C1	C2	C3	B1
C1	1	1/2	1/3	C1
C2	2	1	1/2	C2
C3	3	2	1	C3

Table 4. Judgment Matrix of Color Criterion Layer B2

B2	C4	C5	C6	C7
C4	1	1/2	2	1/3
C5	2	1	3	1/2
C6	1/2	1/3	1	1/4
C7	3	2	4	1

Table 5. Judgment Matrix of Style Criterion Layer B3

B3	C8	C9	C10
C8	1	2	1/2
C9	1/2	1	1/3
C10	2	3	1

The weight of each level was calculated by the root mean square method, and the consistency test was carried out through the consistency index (CI), average random consistency index (RI), and consistency ratio (CR). When CR < 0.1, the consistency of the judgment matrix is considered to meet the requirements, and the weight allocation result is valid. The values were calculated as follows,

$$\lambda_{max} = \sum_{i=1}^{n} \frac{(AW)_i}{nW_i} \quad (1)$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (2)$$

$$CR = \frac{CI}{RI} \quad (3)$$

where λ_{max} is the maximum characteristic root of the judgment matrix, n is the order of the judgment matrix, $(AW)_i$ is the i-th component after the product of the judgment matrix A and the weight vector W, W_i is the i-th component of the weight vector W, CI is the consistency index of the judgment matrix, and RI is the average random consistency index (Table 6).

Table 6. Average Random Consistency Index

matrix order n	1	2	3	4	5	6
RI	0	0	0.52	0.89	1.12	1.24

Table 7. Summary of Consistency Test Results at Each Level

Judgment Matrix	Order n	Maximum Eigenvalue λ_{max}	CI	RI	CR	Test Result
A	3	3.037	0.0185	0.52	0.036	Pass
B1	3	3.002	0.001	0.52	0.002	Pass
B2	4	4.021	0.007	0.89	0.008	Pass
B3	3	3.002	0.001	0.52	0.002	Pass

Table 8. Overall Hierarchical Ranking of Bionic Elements of the Nine-Colored Deer

Criteria Layer	Criteria Layer Weight	Index Layer	Index Layer Weight	Total Weight
B1	0.637	C3	0.540	0.344
		C2	0.297	0.189
		C1	0.163	0.104
B2	0.258	C7	0.469	0.121
		C5	0.279	0.072
		C4	0.161	0.042
		C6	0.091	0.024
B3	0.105	C10	0.540	0.057
		C8	0.297	0.031
		C9	0.163	0.017

From the results of the hierarchical total sorting, the top 5 core bionic elements by total weight were galloping deer (C3, 0.344), standing deer (C2, 0.189), mineral white (C7, 0.121), curled deer (C1, 0.104), and line drawing outline (C10, 0.057). The total weight of these 5 elements accounted for 0.815, which are the core materials for the green engineering design and development of the bionic cultural derivative products of the Dunhuang Nine-Colored Deer.

The shape criterion (B1) had the highest weight (0.637), indicating that the posture and shape of the Nine-Colored Deer were the core carrier of the cultural recognizability of cultural and creative products. The galloping deer (C3) is the most dynamic and representative posture of the Nine-Colored Deer. Its streamline outline and sense of vitality are more suitable for the shape design of cultural and creative products. The color criterion (B2) had the second highest weight (0.258). As a classic color of the Nine-Colored Deer in

Dunhuang murals, mineral white (C7) had a high level of engineering visual representation and recognizable design of cultural elements, and it conforms to modern aesthetics. The style criterion (B3) had a relatively low weight (0.105), but the line drawing outline (C10) simplified the shape, reducing the processing difficulty and adapting to the mass production demand of cultural and creative products.

Construction of Design Strategy Based on AHP-LCA

Design decision-making was defined as a rational intervention process driven by both AHP weight allocation and LCA environmental indicators. The core bionic elements of the Nine-Colored Deer and the constraint conditions of LCA whole life cycle assessment anchored three core dimensions: cultural characteristic translation, structural performance optimization, and whole life cycle low-carbon control. An AHP-LCA coordinated design strategy system adapted to traditional cultural morphological bionic cultural and creative products was constructed for the collaborative unification of the accuracy of cultural expression. This design provided engineering and standardized decision-making basis for the implementation of subsequent design schemes.

Strategy for Realizing the Cultural Semantics of Core Elements

Based on the weight calculation results of the AHP analytic hierarchy process, the shape characteristics (weight 0.637) in the criterion layer, the dynamic curve of the galloping deer (total weight Wi=0.344), and the color perception of mineral white (total weight Wi=0.121) in the indicator layer dominate users' cultural identity, the line drawing outline (total weight Wi=0.057) was chosen as the core style expression element. The engineering morphological mapping and process implementation principle of "priority of key features" for cultural elements was adopted to realize the modern and engineering translation of Dunhuang Nine-Colored Deer cultural elements and to avoid material and process losses caused by excessive cultural expression.

Morphological characteristic mapping

The typical curve momentum of the Nine-Colored Deer with "raised head and soaring into the air, stretched limbs" was extracted and transformed into the main outline or functional support structure of the product. Through the concrete expression of high-weight morphological symbols, the engineering visual representation and recognizable design of cultural elements at the product visual level were ensured. The shape translation adopted an abstract and concise technique, retaining the iconic features such as the galloping deer and spiral forked antlers, avoiding processing energy consumption and material waste caused by complex shapes, and taking into account both cultural and ecological attributes.

Color and material coordination

In response to the core visual demand of "mineral white", renewable materials with natural mineral color (FSC-certified ash wood, recycled pulp composite materials) were screened through LCA pre-assessment, which restores the authentic texture of Dunhuang murals and reduces the resource depletion potential (ADP) in the raw material acquisition stage from the source (He 2022). The color matching strictly followed the classic color system of mineral white, azurite blue, and vermilion screened by AHP. It adopted a local coloring strategy to reduce the amount of colorant used, achieving the dual goals of cultural color expression and material low-carbonization.

Integration of style elements

The line drawing outline was combined with green processing technologies such as laser engraving and deep carving. The style expression was realized without additional material input and processing links, making cultural style an organic part of the product green design.

Structural Reduction Strategy in Response to LCA Evaluation Indicators

To improve the quantitative performance of products in the LCA whole life cycle assessment, the core indicators of material consumption, modularity, and disassembly in the evaluation system were used to establish dual criteria of reduced design and Design for Disassembly (DfD). The resource efficiency of products in the whole life cycle was improved through structural optimization.

Structural integration and lightweighting

The topological optimization method was used to streamline the non-functional decorative structure of the product and merge redundant parts. The reduction in the total number of parts reduce the assembly energy consumption and material consumption in the production stage, directly responding to the assessment requirements for simplicity and low material consumption in the LCA evaluation model (Deng *et al.* 2024). The structural design was centered on meeting the use functions, and it was combined with the modular units of the Nine-Colored Deer bionic shape to realize the three-dimensional unification of "morphological bionics, functional integration and material reduction".

Modular structure for disassembly

Considering the service cycle of cultural and creative products and the demand for later resource utilization, physical connection methods such as mortise and tenon joints and buckles were used strategically to replace traditional chemical gluing to construct an adhesive-free green connection system (Arun *et al.* 2024). The Nine-Colored Deer bionic components (deer body, antlers) and product functional components were designed as standardized modular units with unified size and connection standards. Using efficient classification and recycling of materials in the final treatment stage improved the scores of recyclability and disassembly indicators in the waste disposal stage, which facilitates the daily maintenance and functional reuse of products and extending the service cycle.

Whole Life Cycle Low-Carbon Process and Logistics Intervention Strategy

To achieve better sustainability performance in the LCA quantitative evaluation, the process and structural intervention of the production and manufacturing and transportation circulation links are involved in the design stage. Low-carbon, lightweight, and modular indicators in the evaluation system were used to control the carbon emission of the product from the process and logistics dimensions, ensuring the environmental competitiveness of the design scheme in the production and circulation links.

Low-energy forming process intervention

Priority was given to cold processing and physical surface treatment processes such as laser cutting, laser engraving, and compression molding to replace traditional high-pollution and high-energy-consuming processes such as electroplating and thermal spraying, controlling the Global Warming Potential (GWP) and volatile organic compound emissions in the production and manufacturing stage (Akhter *et al.* 2024). The surface

treatment uniformly adopted water-based paint spraying process, and only local coloring was carried out on the key parts of cultural expression to reduce colorant consumption and environmental load, forming a low-carbon manufacturing system adapted to the bionic cultural and creative products of the Nine-Colored Deer (De Aguiar *et al.* 2017).

Flat and compact logistics design

In response to the lightweight and modular indicators of LCA transportation process evaluation, combined with the modular and detachable structural characteristics of the product, a nestable and stackable product shape was designed to improve the space utilization rate of logistics transportation. The packaging adopted a foldable and card slot integrated structure, and green lightweight materials such as recyclable kraft paper were selected to match the product modular components, reducing packaging material consumption and storage and transportation space occupancy. By reducing the transportation volume and quality of a single product, the emission reduction target in the logistics link of the whole life cycle is achieved, and at the same time, the simple bionic elements of the Nine-Colored Deer are integrated into the packaging design to realize the unification of logistics low-carbonization and cultural expression.

Explanation of Design Schemes

Based on the core bionic elements of the Nine-Colored Deer screened by AHP (galloping deer, mineral white, line drawing outline, etc.) and green sustainable design strategies, two sets of differentiated bionic cultural and creative schemes were designed — Scheme A (benchmark control scheme) and Scheme B (LCA optimized scheme). Both schemes used "accurate cultural translation" as the core premise, but the core difference was in the orientation of the design logic. Scheme A focused on the complete morphological presentation and functional integration of cultural elements without additional green engineering optimization constraints. Scheme B took the LCA whole life cycle environmental performance as the constraint, reducing the environmental load through material substitution, structural splitting, and process simplification. It provided a clear comparison sample for the subsequent qualitative and quantitative evaluation assessment of the proposed design schemes.

Scheme A: Cultural Morphological Integration Scheme Based on AHP Weight (Benchmark Scheme)

The core design of Scheme A was "full morphological translation of cultural elements+functional integrated integration", which strictly used concrete presentation according to the high-weight elements (galloping deer, mineral white, line drawing outline) screened by AHP, without integrating green design optimization strategies. It served as a benchmark reference for environmental performance comparison.

Morphological representation and parametric translation

Scheme A extracted the dynamic soaring curve of the galloping deer in Dunhuang murals (weight Wi= 0.344). Parametric modeling technology was adopted to transform this core visual feature into the main geometric structure and functional support frame of the lamp. Through morphological mapping of high-weight symbols, high cultural semantic recognition of the product was ensured to meet users' aesthetic and emotional demands.



Fig. 4. Conceptual visualization of Scheme A

Material configuration and low-carbon technology

The main material was FSC-certified ash wood multi-layer board. Computer numerical control laser cutting of wood-based panels was applied in the processing procedure to guarantee precise forming of complex bionic curves. Water-based environmentally friendly paint with low VOC emission was selected for surface coating, which maintains the natural wood aesthetic texture and realizes basic environmental load control during the manufacturing stage.

Structural characteristics and functional integration

Scheme A integrated multiple functions including ambient lighting, artistic display, and wall-mounted support. The key of the product were 28 cm in total height, 25 cm in width, 16 cm in base diameter, and 24 cm in lampshade diameter, which is suitable for conventional scenarios such as desktop placement, exhibition cabinet display, and wall installation. Interlocking joints were adopted for glue-free assembly. Due to the non-detachable integrated wood-based structure of this scheme, the requirement of classified recycling of biomass resources at the end-of-life (EoL) stage was neglected, which limited the material recycling capability.

Scheme B: Whole Life Cycle Optimization Scheme Based on AHP-LCA

Scheme B focused on "cultural feature preservation and full life-cycle low-carbon optimization". Using core elements identified by AHP, it introduced LCA full life-cycle constraints (from raw material acquisition to end-of-life disposal). By adopting strategies including high-performance biomass composite materials, modular structural separation, and process simplification, this scheme aimed to reduce the environmental footprint of products without weakening cultural recognition.



Fig. 5. Conceptual visualization of Scheme B

Material innovation and environmental load reduction

To maintain the visual semantics of "mineral white" while improving resource utilization efficiency, Scheme B adopted wood fiber reinforced recycled pulp composites to replace partial solid wood. Compared with energy-intensive mechanical processing, such wood-based composites possess lower manufacturing energy consumption and favorable biodegradability. This decision reduced the ADP and cumulative energy demand of products in the pre-manufacturing stage from the source, which conformed to the sustainability criteria of biomass material selection.

Scheme B substitutes solid wood with a wood fiber-reinforced recycled cellulose composite consisting of a recycled cellulose pulp matrix (the binder phase, from recovered paper and paperboard), 25 to 40 wt% wood fiber from processing residues, and below 10 wt% bio-based binder and processing aids; no urea- or phenol-formaldehyde resin is added, so the material remains re-pulpable and underpins the 65% recovery rate assumed in stage A5. Feasibility was assessed by standard methods: modulus of rupture and elasticity (ISO 16978, EN 310, ASTM D1037), 24-h thickness swelling (EN 317), and luminaire temperature rise (IEC 60598-1). For the specified shell, the composite is required to reach a modulus of rupture of at least 20 MPa and a modulus of elasticity of at least 2 GPa; these thresholds are set by the present design brief and are to be verified by the confirmatory testing recommended below. The accepted trade-offs are higher moisture sensitivity, which restricts use to indoor conditions at 40 to 60% RH and requires the sealed low-VOC coating, and somewhat lower surface hardness. The 8 W LED source keeps the lamp-shade shell within the temperature-rise limits for luminaire parts specified in IEC 60598-1. Confirmatory testing to these standards is recommended before tooling.

DfD and wood structure logic

Scheme B followed DfD principle, adopting a split modular structure of "deer body-base". Chemical adhesives were abandoned in connection modes, and traditional mortise-and-tenon joints combined with magnetic components were applied instead. This non-adhesive design prolongs the service life of wood-based components and ensures that all biomass materials can be recycled at the End-of-Life (EoL) stage. Its assembly

dimensions were consistent with Scheme A (28 cm in height, 25 cm in width), and the modular splicing gap was controlled within ≤ 0.5 cm.

Flat packaging and logistics performance optimization

Benefiting from the modular detachable design, Scheme B used a flat-pack design layout. In the logistics process, all wood-based components can be nested and stacked, which greatly improves the loading efficiency per unit volume. This intervention directly improved the energy performance of the transportation stage in the LCA model. It amplified exerts the low-carbon emission reduction potential of wood-based biomass products in the supply chain by reducing transportation energy consumption per product.

Construction of LCA Qualitative Evaluation System

To ensure the scientificity and comparability of the evaluation results, the evaluation boundary was set as the whole process of "Cradle-to-Grave", including raw material acquisition (A1), production and manufacturing (A2), transportation and circulation (A3), use stage (A4), and waste disposal (A5). To ensure the comparability of the evaluation results, one Nine-Colored Deer bionic lamp was set as the functional unit in this study. The evaluation followed the life cycle assessment logic, and the material composition and expected energy consumption of Scheme A and Scheme B were deconstructed, providing data support for the subsequent quantitative evaluation of the AHP-LCA coordinated path.

As a standardized method for quantifying the whole life cycle environmental impact of products, LCA was reconstructed for the classic LCA evaluation dimensions in this study according to the engineering attributes of "fast iteration and flexible batch" of cultural and creative products. A sustainability evaluation system was constructed to include five dimensions of raw material selection, production and manufacturing, transportation process, use stage, and final treatment (Table 9).

Table 9. LCA Sustainability Evaluation System

Life Cycle Stage	Design Objective	Key Design Intervention Methods	Core Evaluation Indicators
A1	Resource depletion potential (ADP)	Select renewable materials and control material consumption	Low material consumption, environmental friendliness
A2	Minimize manufacturing energy consumption and leftover materials	Modular design, generalized components, low-carbon processes	Simplicity, universality, modularity
A3	Reduce carbon footprint in circulation process	Flat packaging, lightweight design, high loading rate	Lightweight, loading efficiency
A4	Prolong product service life	Emotional translation, functional reuse, safety assurance	Practicality, durability, aesthetic appeal
A5	Realize material closed-loop circulation	DfD, material degradability	Recyclability, disassembly

To verify the effectiveness of the aforementioned AHP-LCA coordinated path, this study adopted the expert evaluation method to conduct a quantitative assessment of Scheme A and Scheme B. The evaluation team consisted of 10 cultural research experts, 6 industrial design engineers, and 20 potential users. The evaluation team conducted a blind

evaluation of 12 core evaluation indicators according to the Likert 5-level scale (1=extremely poor, 5=excellent). The arithmetic mean of each indicator was taken as the final score, as shown in Table 10.

Table 10. LCA Whole Life Cycle Evaluation Scores of the Two Design Schemes

Life Cycle Stage	Evaluation Indicator	Score of Scheme A	Score of Scheme B
A1	Low material consumption	3.76	4.28
	Environmental friendliness	4.05	4.33
A2	Simplicity	4.12	3.95
	Universality	3.88	4.41
	Modularity	3.65	4.62
A3	Lightweight	3.78	4.45
A4	Practicality	4.31	4.08
	Durability	4.22	4.15
	Safety	4.35	4.29
	Aesthetic appeal	4.53	4.12
	Comfort	3.89	3.96
A5	Recyclability	3.77	4.48
Comprehensive average	—	3.98	4.23

Considering the volatility of the supply chain in engineering practice, this study conducted a sensitivity analysis on the core variables of Scheme B. Assuming that affected by logistics fluctuations, the transportation distance (A3 stage) of recycled pulp materials in Scheme B increased by 50%. Its comprehensive environmental score decreased by 1.2%, which was significantly better than Scheme A. This result indicated that the efficient loading and lightweight design realized through the DfD structure has strong environmental robustness and will not change its sustainable advantage due to the increase of local logistics energy consumption.

Construction of LCA Quantitative Evaluation System and Carbon Emission Modeling

To improve the engineering rigor and repeatability of life cycle assessment, a quantitative LCA model based on the ISO 14040 (2006) and ISO 14044 (2006) standards was introduced. The evaluation boundary adopted the "Cradle-to-Grave" system boundary, covering five stages: raw material acquisition (A1), production and manufacturing (A2), transportation process (A3), use stage (A4), and waste disposal (A5). In view of the research goal focusing on emission reduction optimization under the background of "dual carbon", this study prioritized the selection of GWP as the core evaluation indicator.

The Functional Unit was defined as 1 Nine-Colored Deer bionic lamp with a designed service life of 5 years. The life cycle environmental impact takes the Global Warming Potential (GWP100) as the core evaluation indicator, with the unit of kg CO_2-eq.

Life cycle inventory (LCI)

Based on the product structural design and Bill of Materials (BOM), the life cycle input parameters of the two schemes are shown in Table 11.

Table 11. Life Cycle Inventory Parameters (Functional Unit = 1 Product)

Category	Parameter	Unit	Scheme A	Scheme B
A1	Wood (FSC-certified ash wood)	kg	1.2	—
	Recycled pulp composite material	kg	—	1
	Hardware connectors	kg	0.15	0.1
	Paperboard packaging	kg	0.3	0.22
A2	Manufacturing electricity consumption	kWh	4.2	3.1
A3	Transportation distance	km	500	500
A4	Lamp power	W	8	8
	Average daily usage time	h/day	3	3
A5	Material recovery rate	%	40	65

The sources of material and process emission factors were as follows:
Material emission factors: Ecoinvent v3.8 database
GWP characterization factors: IPCC 2021 GWP100
Power emission factor: average value of regional power grid 0.581 kg CO_2/kWh
Highway transportation emission factor: 0.12 kg CO_2/(t·km)
Waste disposal emission factor: 0.18 kg CO_2/kg

Quantitative calculation model

The total life cycle carbon emission of the product was calculated by Eq. 4, and the raw material stage (A1) was calculated by Eq. 5,

$$GWP_{total} = GWP_{A1} + GWP_{A2} + GWP_{A3} + GWP_{A4} + GWP_{A5} \quad (4)$$

$$GWP_{A1} = \sum(m_i \times EF_i) \quad (5)$$

where m_i is the material quality (kg), and EF_i is the corresponding material emission factor (kg CO_2-eq/kg).

The production and manufacturing stage (A2) was determined as follows,

$$GWP_{A2} = E_{mfg} \times EF_{electricity} \quad (6)$$

where E_{mfg} is the total electricity consumption in the manufacturing stage (kWh).

The transportation stage (A3) was determined as follows,

$$GWP_{A3} = \frac{m_{total}}{1000} \times D \times EF_{transport} \quad (7)$$

where m_{total} is the total transportation quality (kg), and D is the transportation distance (km).

The use stage (A4) was calculated by Eqs. 8 and 9,

$$E_{use} = \frac{P}{1000} \times h_{day} \times 365 \times L \quad (8)$$

$$GWP_{A4} = E_{use} \times EF_{electricity} \quad (9)$$

where P is the lamp power (W), h_{day} is the average daily use time (h/day), and L is the service life (years).

The final disposal stage (A5) was determined as follows,

$$GWP_{A5} = (1 - r) \times m_{EOL} \times EF_{disposal} \quad (10)$$

where r is the material recovery rate. The optimization percentage was calculated according

to Eq. 11,

$$Improvement(\%) = \frac{GWP_A - GWP_B}{GWP_A} \times 100\% \quad (11)$$

RESULTS AND DISCUSSION

This study evaluated the logical closed loop of AHP quantitative decision-making and LCA performance verification through the mapping mechanism of "cultural elements–engineering parameters". In the development process of wood-based products, the core cultural attributes determined by AHP directly drove staged emission reduction strategies. In the raw material extraction stage (Stage A1), constrained by the visual feature of "mineral white", biomass-based low-VOC coatings were adopted to replace traditional synthetic paints, which reduced environmental toxic loads from the source. In the end-of-life disposal stage, the dynamic curve of the galloping deer was transformed into wood structure parameters supporting Design for Disassembly. The replacement of chemical bonding with physical mortise-and-tenon joints significantly improved the recycling potential of wood fibers. This method verified the deep coupling between Dunhuang cultural elements and green assessment of wood-based materials and provided quantitative evidence for the precise development of biomass-based cultural and creative products and their coordinated environmental performance.

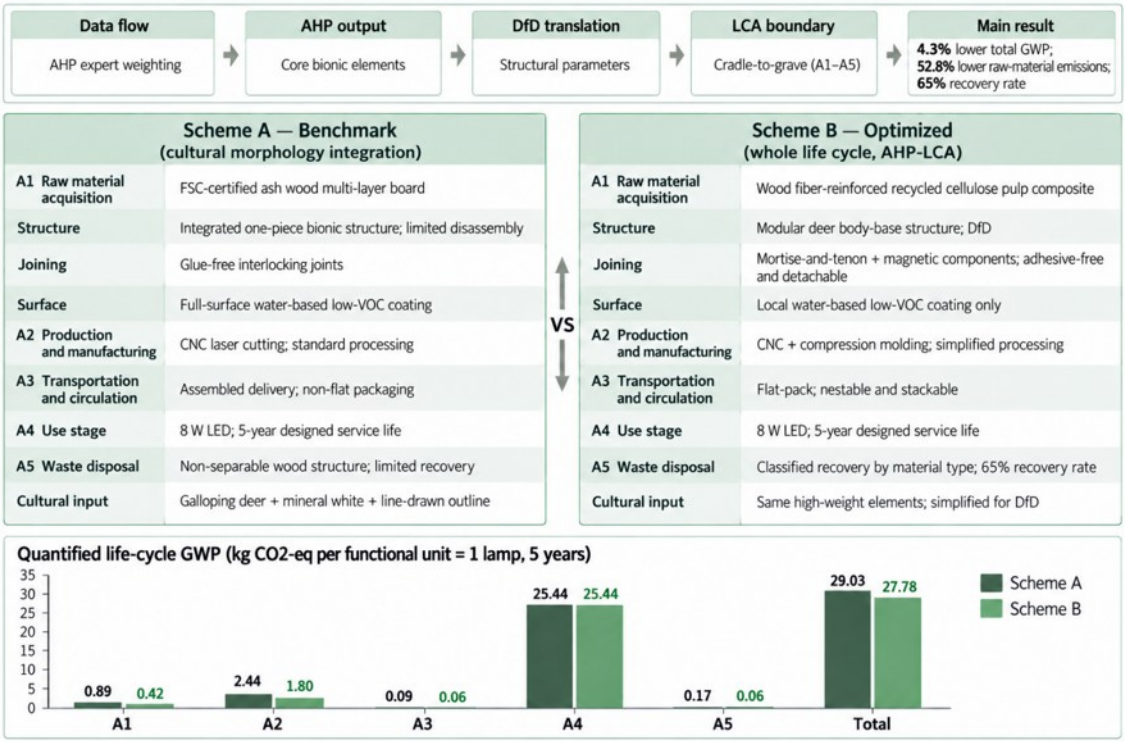


Fig. 6. Schematic comparison of Scheme A (benchmark) and Scheme B (AHP-LCA optimized)

Analysis of Life Cycle Emission Characteristics

The full life cycle carbon footprints of Scheme A and Scheme B were 29.03 and 27.78 kg CO_2-eq, respectively. According to Eq. 11, Scheme B achieved a carbon emission reduction of 4.3% over the whole life cycle. Although this reduction is small on a micro

scale, it possesses remarkable cumulative emission reduction potential in large-scale production.

The phased results calculated according to the above model are shown in Table 12.

Table 12. Life Cycle GWP Results (kg CO_2-eq / Functional Unit)

Stage	Scheme A	Scheme B
A1	0.89	0.42
A2	2.44	1.8
A3	0.09	0.06
A4	25.44	25.44
A5	0.17	0.06
Total	29.03	27.78

The use stage (A4) accounted for approximately 88% of total emissions due to continuous energy consumption. Nevertheless, the raw material acquisition stage (A1) was the core reflecting differences in green design. The emission reduction of Scheme B in stage A1 verified the effectiveness of the wood-based composite replacement strategy in reducing environmental footprints from the source of resource acquisition.

Although emissions from transportation (A3) and end-of-life disposal (A5) stages contributed relatively little, the DfD wood structure of Scheme B improved the recycling percentage of wood fibers in stage A5. This transformation from linear consumption to circular utilization has limited short-term proportional values, yet carries important engineering practical significance from the perspective of sustainable cyclic utilization of wood-based resources. Moreover, the lightweight and modular structure of Scheme B retains cumulative emission-reduction potential under mass-production conditions.

The reductions obtained here are of the same order as those reported in published quantitative LCA work on wood- and wood-fiber-based products, although they act on a different stage of the life cycle. Coloma-Jiménez *et al.* (2022) reported 1.71 kg CO_2-eq per kg for an eco-designed wooden bunk bed, 15.1% below conventional furniture; the 4.3% obtained here is smaller because the benchmark Scheme A is already eco-designed and because the inventory is use-stage dominated, with A4 accounting for approximately 88% of the burden. Cui *et al.* (2025) reported GWP reductions of 38.9% from material- and energy-side measures and 84.2% from mechanical recycling versus incineration in Chinese wood-plastic composite manufacturing; the 52.8% reduction in stage A1 falls within that range and comes from substituting solid sawn wood with a recycled-fiber composite. Ijeoma *et al.* (2026) modelled a design-for-deconstruction timber floor at 90%, 60% and 30% recovery, with adhesive-free fastening outperforming bonded connections; the 65% recovery of Scheme B lies between their 60% and 90% scenarios and is limited mainly by the hardware connectors. The present study therefore attaches a quantified inventory, 29.0 against 27.8 kg CO_2-eq per functional unit, and a recovery rate of 40% against 65%, to a product class for which comparable work (Ma *et al.* 2026; Xu *et al.* 2024; Kazancoglu *et al.* 2023) remains design-oriented.

Qualitative–Quantitative Correspondence

By comparing the expert scoring and the quantitative LCA results, a significant correlation was found between them in key dimensions. The high scores of Scheme B in material recyclability and structural disassembly efficiency in expert evaluation were

verified by quantitative calculation. The emission intensity of Scheme B in the raw material acquisition stage (A1) was reduced, and the residual environmental load was lowered greatly in the end-of-life disposal stage (A5) due to the improved recycling of wood fibers.

The results indicated that the material replacement strategy directly determines the emission flux of stage A1, while the mortise-and-tenon structure design based on DfD was the key to the optimization of disposal mode in stage A5. The design logic provided by qualitative assessment was consistent with the emission differences revealed by quantitative calculation, which shows the inherent logical consistency of the AHP-LCA coupling model in addressing the "design decision-environmental response" mechanism. The mutual support of multi-dimensional evaluation results improved the reliability of the green development pathway for wood-based cultural and creative products.

Key Influencing Factors and Model Stability

Material emission factors, operational energy consumption, and wood fiber recycling rate were key variables determining the life-cycle environmental load of products. Emission fluctuations in the raw material stage (A1) were affected significantly by the density of biomass materials. Benefiting from the DfD adopted in Scheme B, the recycling potential in the waste stage (A5) was released, which greatly expands the space for circular optimization of wood-based resources.

To verify the robustness of the assessment model under parameter disturbance, transportation distance was selected as the key variable for sensitivity analysis in this study. The results indicated that when the transportation distance increased by 50% on the baseline, the environmental loads of both Scheme A and Scheme B rose slightly, while their ranking of environmental performance remained unchanged. This result demonstrates that within the defined system boundary, transportation energy consumption is not the dominant factor affecting environmental performance.

Material replacement strategies and structural optimization schemes had higher control weights in the assessment system. Regardless of changes in boundary conditions, the emission reduction advantages of the optimized scheme in the raw material stage and disposal stage remained stable. This result verified the reliability of the AHP-LCA collaborative pathway in cultural element translation and engineering intervention.

Engineering Implications

The low-carbon development of wood-based cultural and creative products relies on the collaborative optimization of material properties and structural logic. The proposed AHP-LCA coupling method introduced qualitative assessment in the decision-making stage, which compensated for the deficiency of traditional LCA in quantifying cultural genes. It provides an operable decision-making framework for the engineering transformation of intangible cultural heritage resources into sustainable biomass products. Compared with existing literature, this pathway emphasizes the systematic correlation between cultural design elements and environmental performance, and possesses favorable universality.

The main findings of the AHP-LCA comparative assessment are consolidated in Table 13, which combines the quantitative LCA results with the qualitative expert evaluation.

Table 13. Summary of Main Findings from the AHP-LCA Assessment

Item	Scheme A	Scheme B	Main finding
Total life cycle GWP (kg CO2-eq per functional unit)	29.03	27.78	4.3% reduction over the full life cycle
Raw material stage (A1) GWP (kg CO2-eq)	0.89	0.42	52.8% reduction by material substitution
End-of-life material recovery rate (A5)	40%	65%	+25 percentage points enabled by DfD
AHP core bionic elements retained	Galloping deer, mineral white, line drawing outline	Galloping deer, mineral white, line drawing outline	Cultural recognition preserved in both schemes
Structure and disassembly	Integrated, non-detachable	Modular, adhesive-free DfD	Qualitative advantage in A2, A3 and A5
Comprehensive expert score (Table 10)	3.98	4.23	Qualitative and quantitative results are consistent

This study had the following limitations. The life cycle model was constructed based on a single functional unit, and the impacts of regional energy structure differences on wood processing efficiency were not considered fully. Secondly, there was a certain deviation between the static emission factors of the LCA database and actual complex production conditions. Future research should focus on the establishment of dynamic LCA models, and it should expand to multi-criteria environmental impact analysis (such as acidification, eutrophication, and other indicators) to improve the full life cycle management system of wood-based cultural product designs. The proposed design schemes have not been validated through physical prototype fabrication. In particular, the manufacturability of Scheme B, including its porcelain-like surface appearance and potential cracking during forming and drying, requires experimental verification. Future research should fabricate prototypes and evaluate their material properties, dimensional stability, and crack development.

CONCLUSIONS

1. Based on the dual demands of cultural heritage protection and low-carbon transformation of the biomass industry, this study constructs a systematic development framework coupling the analytic hierarchy process (AHP) and life cycle analysis (LCA). Through empirical research on Dunhuang Nine-Colored Deer wood-based cultural and creative products, this work breaks the disciplinary barrier between cultural aesthetic translation and environmental performance assessment. The framework forms a logical closed loop ranging from quantitative screening of perceptual cultural elements to rational green engineering design, and offers a systematic methodological reference for the modern transformation of intangible cultural heritage resources and high-quality development of wood-based biomass products.
2. The research results verify that the AHP-LCA coupling model can effectively support green decision-making for cultural and creative products. On the one hand, the constructed three-level evaluation index system enables the scientific screening of core

bionic elements (with a total weight proportion of 81.5%), translating abstract aesthetic requirements into precise engineering input parameters. On the other hand, ISO-standardized LCA assessment demonstrates that the adoption of wood fiber reinforced recycled materials, DfD mortise-and-tenon structures and optimized manufacturing processes delivers a 4.3% reduction in full life cycle carbon emissions, a 52.8% emission reduction contribution at the raw material stage, and a material recycling rate up to 65%. These findings demonstrate that precise cultural expression and low-carbon performance of wood-based materials can be improved synergistically, and provide quantitative evidence to address the industrial bottleneck of "valuing culture while neglecting environmental protection".

3. While this study contributes innovations in both theory and practice, several limitations remain. Follow-up research can expand the scope of environmental impact assessment indicators (*e.g.*, acidification potential, eutrophication potential) and introduce cost-benefit analysis for mass production. Furthermore, research objects can be extended from this single lamp product to broader application scenarios of wood-based biomass composite materials. Deepened industry-university-research cooperation and dynamic LCA model development will help upgrade case-based findings into an industrial standard system, promoting deeper integration between the cultural and creative industry and dual-carbon targets.
4. Two extensions are recommended: the environmental assessment should be repeated for acidification potential and eutrophication potential in addition to GWP100, so that any burden shifting between categories is detected; and a life cycle costing analysis should be run in parallel with the LCA to establish whether the additional tooling, the tighter dimensional tolerance and the extra assembly time required by the modular mortise-and-tenon and magnetic DfD structure are offset by the savings from flat-pack logistics and end-of-life fiber recovery. The mechanical and hygrothermal properties assumed for the composite should also be verified by testing to the standards identified above before tooling.

ACKNOWLEDGMENTS

The authors acknowledge the following funding:
This work was supported by the Doctoral Research Startup Fund of Lanzhou University of Arts and Science, "Research on Artistic Creation Transformation and Application of Dunhuang Mural Elements under the Background of Cultural-Tourism Integration" (Grant No.: 2025BSQD29).

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.

REFERENCES CITED

Akhter, P., Arshad, A., and Hussain, M. (2024). "A review on environmental impacts of paints and strategies for producing eco-friendly-paints," *International Journal of Environmental Science and Technology* 22(1), 555-578. https://doi.org/10.1007/s13762-024-05760-z

Arun, M., Barik, D., and Chandran, S. S. R. (2024). "Exploration of material recovery framework from waste – A revolutionary move towards clean environment," *Chemical Engineering Journal Advances* 18, article 100589. https://doi.org/10.1016/j.ceja.2024.100589

Brändström, J., and Saidani, M. (2022). "Comparison between circularity metrics and LCA: A case study on circular economy strategies," *Journal of Cleaner Production* 371, article 133537. https://doi.org/10.1016/j.jclepro.2022.133537

Cholewa, M., Helman, J., Rosienkiewicz, M., Molasy, M., Oleszek, S., and Berselli, G. (2024). "GreenPLM: The concept of sharing community knowledge for new green product development and process planning," *Annals of Operations Research* 364, 2253-2275. https://doi.org/10.1007/s10479-024-05932-7

Coloma-Jiménez, M., Akizu-Gardoki, O., and Lizundia, E. (2022). "Beyond ecodesign, internationalized markets enhance the global warming potential in the wood furniture sector," *Journal of Cleaner Production* 379, article 134795. https://doi.org/10.1016/j.jclepro.2022.134795

Cui, H., Zheng, Y., Wang, Z., Wang, Z., Li, G., Wong, K. H., Wang, J., Zhou, Y., and Hall, P. (2025). "Life cycle assessment of wood plastic decking manufacturing: Reduction of environmental impacts based on an industrial case study in China," *Environmental Research* 287, 123147. https://doi.org/10.1016/j.envres.2025.123147

De Aguiar, J., De Oliveira, L., Da Silva, J. O., Bond, D., Scalice, R. K., and Becker, D. (2017). "A design tool to diagnose product recyclability during product design phase," *Journal of Cleaner Production* 141, 219-229. https://doi.org/10.1016/j.jclepro.2016.09.074

Del Curto, D., and Turrina, A. (2023). "Towards a reasoned glossary of green conservation: A semantic review of green-oriented terms in the field of cultural heritage," *Sustainability* 15(16), article 12104. https://doi.org/10.3390/su151612104

Deng, Z., Huang, J., and Li, X. (2024). "Topology optimization design of typical functional structural parts," *Scientific and Social Research* 6(1), 205-210. https://doi.org/10.26689/ssr.v6i1.6037

Elshafei, G., Katunský, D., Zeleňáková, M., and Negm, A. (2022). "Opportunities for using analytical hierarchy process in green building optimization," *Energies* 15(12), article 4490. https://doi.org/10.3390/en15124490

Frumușanu, G., and Epureanu, A. (2014). "Conceptual approach of the environmental impact issued by the manufacturing process," *Applied Mechanics and Materials* 555, 485-490. https://doi.org/10.4028/www.scientific.net/AMM.555.485

Ghazali, I., Abdul-Rashid, S. H., Dawal, S. Z. M., Irianto, I., Herawan, S. G., Ho, F. H., Abdullah, R., Rasib, A. H. A., and Padzil, N. W. S. (2023). "Embedding green product attributes preferences and cultural consideration for product design development: A conceptual framework," *Sustainability* 15(5), article 4542. https://doi.org/10.3390/su15054542

He, B., and Hua, Y. (2017). "Feature-based integrated product model for low-carbon conceptual design," *Journal of Engineering Design* 28(6), 408-432.

https://doi.org/10.1080/09544828.2017.1316833
He, W. (2022). "The image narration of Jataka: Analysis of the Deer King Survana in Cave 257," *International Journal of Education and Humanities* 4(3), 32-34. arthttps://doi.org/10.54097/ijeh.v4i3.1648
Ijeoma, M. W., Ou, S., Nabati, A., Chen, H., Stoner, M., Layton, P., Albright, D., Ross, B., Pang, W., and Carbajales-Dale, M. (2026). "End-of-life and beyond building life: Carbon benefits of a novel mass timber wood floor system, evaluating end-of-life strategies, recovery rates, and circular design implications," *International Journal of Life Cycle Assessment* 31, 115. https://doi.org/10.1007/s11367-026-02678-1
ISO 14040 (2006). "Environmental management — Life cycle assessment — Principles and framework," International Organization for Standardization (ISO), Switzerland.
ISO 14044 (2006). "Environmental management — Life cycle assessment — Requirements and guidelines," International Organization for Standardization (ISO), Switzerland.
Jiang, M., Deng, W., and Lin, H. (2024). "Sustainability through biomimicry: A comprehensive review of bionic design applications," *Biomimetics* 9(9), article 507. https://doi.org/10.3390/biomimetics9090507
Jin, J., and Sharudin, S. A. (2023). "Design of the Mogao Caves caisson and its application to modern interior design," *Global Journal of Emerging Science, Engineering & Technology* 1(1), 26-36. https://doi.org/10.56225/gjeset.v1i1.18
Kazancoglu, Y., Ada, E., Ozbiltekin-Pala, M., and Uzel, R. A. (2023). "In the nexus of sustainability, circular economy and food industry: Circular food package design," *Journal of Cleaner Production* 415, article 137778. https://doi.org/10.1016/j.jclepro.2023.137778
Kim, S. G., Heo, E. Y., Lee, H. G., Kim, D. W., Yoo, N. H., and Kim, T. H. (2024). "Advanced adaptive feed control for CNC machining," *Robotics and Computer-Integrated Manufacturing* 85, article 102621. https://doi.org/10.1016/j.rcim.2023.102621
Li, J., Tian, Y., and Xie, K. (2023). "Coupling big data and life cycle assessment: A review, recommendations, and prospects," *Ecological Indicators* 153, article 110455. https://doi.org/10.1016/j.ecolind.2023.110455
Li, N., Zhang, J., and Chen, J. (2025). "Application of Dunhuang decorative tile elements in children's furniture based on symbolic duality and D4S theory," *Results in Engineering* 26, article 105422. https://doi.org/10.1016/j.rineng.2025.105422
Liu, Y. (2025). "Integrating AI and sustainability in cultural and creative product design for environmentally conscious innovations," *International Journal of Information and Communication Technology* 26(18), 18-32. https://doi.org/10.1504/IJICT.2025.146695
Ma, C., Wen, Y., and Wang, Y. (2026). "Digital translation of the Dunhuang nine-colored deer motif for wood-fiber-based cultural product design," *BioResources* 21(2), 3981-4002. https://ojs.bioresources.com/index.php/BRJ/article/view/25573
Maldini, I., Klepp, I. G., and Laitala, K. (2025). "The environmental impact of product lifetime extension: A literature review and research agenda," *Sustainable Production and Consumption* 56, 561-578. https://doi.org/10.1016/j.spc.2025.04.020
Saaty, T. L. (1990). "How to make a decision: The analytic hierarchy process," *European Journal of Operational Research* 48(1), 9-26. https://doi.org/10.1016/0377-2217(90)90057-I

Verma, A. K., Gulati, R., and Bano, F. (2025). "Advantage of recycle materials for life cycle assessment and carbon footprint," *International Journal for Multidisciplinary Research* 7(1), 38149. https://doi.org/10.36948/ijfmr.2025.v07i01.38149

Wang, L., Chen, L., and Li, C. (2024a). "Research on strategies for improving green product consumption sentiment from the perspective of big data," *Journal of Retailing and Consumer Services* 79, article 103802. https://doi.org/10.1016/j.jretconser.2024.103802

Wang, Y., Xi, Y., Liu, X., and Gan, Y. (2024b). "Exploring the dual potential of artificial intelligence-generated content in the esthetic reproduction and sustainable innovative design of Ming-style furniture," *Sustainability* 16(12), article 5173. https://doi.org/10.3390/su16125173

Xiong, S., and Li, Y. (2023). "Creative product design and research based on the emotional background of Dunhuang flying astronomy," *Highlights in Art and Design* 4(1), 81-83. https://doi.org/10.54097/hiaad.v4i1.11856

Xu, Y. S., He, L. J., and Zhi, J. Y. (2024). "Research on bionic form design of rattan furniture under the concept of sustainability," *Packaging Engineering* 45(4), 336-344. https://qikan.cqvip.com/Qikan/Article/Detail?id=7111423891

Yin, Y., Sun, D., Su, M., Yu, Z., Su, B., Shui, B., Wu, C., Han, W., Shan, Z., and Dong, C. (2019). "Investigation of ancient wall paintings in Mogao Grottoes at Dunhuang using laser-induced breakdown spectroscopy," *Optics & Laser Technology* 120, article 105689. https://doi.org/10.1016/j.optlastec.2019.105689

Zhao, H. C., and Zhang, Y. (2020). "Saliency enhancement algorithm for digital restoration of ancient murals," *Computer Engineering* 46(8), 210-217 (in Chinese).

Article submitted: September 3, 2026; Peer review completed: October 10, 2020; Revised version received: October 16, 2026; Accepted: October 18, 2026; Published: November 9, 2026.
DOI: 10.15376/biores.22.1.109-134