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# Digital restoration of ancient loom: evaluation of the digital restoration process and display effect of Yunjin Dahualou Loom



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The Yunjin Dahualou Loom is a precious artifact of China's cultural heritage, with its production and weaving techniques recognized as invaluable intangible cultural heritage. This paper presents a digital restoration of the Yunjin Dahualou Loom, utilizing digital technology to preserve and inherit textile artifacts while addressing challenges such as the difficulty in the long-term preservation of wooden structures and the lengthy cycles involved in traditional restoration processes. Initially, field research was conducted to gather detailed information regarding the loom's dimensions, structure, materials, manufacturing principles, and weaving techniques. Using AutoCAD software, the overall structure and weaving principles of the Yunjin Dahualou Loom were systematically organized and visually mapped. Next, Autodesk 3ds Max software was employed to digitally restore and assemble the loom's various components, while also reconstructing its manufacturing and weaving principles in a digital environment. VRay software was then used to generate materials for the loom and render the scene in high fidelity. Finally, a combined approach using the Analytic Hierarchy Process (AHP) and fuzzy comprehensive evaluation is employed to assess the quality of digital restoration. The AHP is used to calculate weight coefficients, which are then verified through consistency checks. These weights are combined with data collected from fuzzy comprehensive evaluation to assess the digital restoration results. Finally, based on the principle of maximum membership degree, the digital restoration of the Yunjin Dahualou Loom is rated as "very good." These findings demonstrate that the proposed method effectively reconstructs the loom's form, structure, and weaving principles, completing its digital restoration. This approach provides a novel and relatively comprehensive method for the dynamic protection of cultural heritage and intangible cultural heritage.

In the context of rapid global technological development, the unique advantages and broad application prospects of 3D digital technology have made it an essential field of scientific research and industrial development around the world[1–5]. 3D digital technology offers significant potential and broad applications in cultural heritage, presenting innovative approaches for the preservation, protection, and restoration of cultural assets and artifacts[6–10]. In recent years, international frameworks, including the Athens Charter (1931), the Venice Charter (1964), the UNESCO World Heritage Convention (1972), and the Nara Document (1992), have been instrumental in advancing and standardizing approaches to cultural heritage protection and restoration[11].

Traditional methods for restoring cultural heritage primarily rely on manual techniques, which often necessitate direct physical interaction with artifacts. This frequent handling can lead to unintentional secondary damage to the valuable cultural heritage[12–14]. In recent years, scholars have applied various advanced technological means and scientific protection methods in cultural relic and heritage protection and restoration[15–19]. The use of 3D digital technology in cultural heritage restoration (such as historical sites[20,21], buildings[22–24], murals[12,25], statues[26,27], ancient books[28],

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cultural relics[29–31], and ancient clothing[32,33]) can effectively address potential threats like human destruction, natural disasters, artifact aging, and information loss. 3D modeling[34,35], 3D digital printing[6,26], 3D scanning[22,34], and other digital technologies can facilitate the long-term preservation of cultural heritage artifacts, effectively avoiding secondary damage. Moreover, 3D digital technology can be utilized for promotional, educational, and exhibition purposes in the field of cultural heritage protection. The application of digital technologies, such as Virtual Reality (VR)[36,37], Augmented Reality (AR)[38,39], and X-reality (XR)[40], has provided new ideas for virtual archeology and exhibitions.

In recent years, the application of 3D digital technology for the digital preservation of intangible cultural heritage has emerged as a significant research method in the realm of intangible cultural heritage protection[41,42]. Through means such as video recording of intangible cultural heritage[43,44], digital platform development[45], and virtual space interaction[46], traditional cultures and expressions of various countries can be effectively protected and widely disseminated through global internet platforms, transcending time and space limitations to benefit a broader international audience. As technological advancements continue to evolve, 3D digital technology will assume an increasingly vital and expansive role in the protection and restoration of cultural relics and heritage. This technology will contribute significantly to the preservation and development of human civilization, providing valuable insights and support for the inheritance of cultural legacies.

At present, there is a slightly deficiency in international research concerning the cultural heritage of the Yunjin Dahualu Loom and the preservation of its intangible cultural heritage, particularly regarding its manufacturing and weaving techniques. This field urgently necessitates increased scholarly attention and comprehensive investigation. At present, research on China's Yunjin Dahualu Loom only focuses on three aspects, constructing knowledge graphs for Yunjin[47], developing question-answering systems[48], and designing virtual interactions for the Yunjin Dahualu Loom[49]. Therefore, there is a pressing need for in-depth research focused on the comprehensive digital restoration and protection of both the tangible and intangible cultural heritage associated with the Yunjin Dahualou Loom, as well as the evaluation of the outcomes of these digital restoration efforts.

In the context of current international research trends, this paper conducts an in-depth study on China's Yunjin Dahualou Loom and its manufacturing and weaving techniques. This artifact has a complex structure and is made of wood and silk threads and its preservation over long periods of history is difficult due to its materials' perishable nature and lack of weather resistance. The Yunjin Dahualou Loom represents an important aspect of Chinese cultural heritage, with its manufacturing and weaving techniques classified as intangible cultural heritage. To address this, dynamic 3D digital restoration of the loom, along with its manufacturing techniques and weaving skills was conducted using 3D digital modeling technology. This approach incorporates an evaluation method that combines the Analytic Hierarchy Process (AHP) with Fuzzy Comprehensive Evaluation to systematically and comprehensively protect this cultural heritage. This innovative work aims to enhance the preservation of cultural and intangible heritage through 3D digital technology. It aims to offer a relatively comprehensive digital preservation approach for future digital restoration projects, non-contact restoration of artifacts, restoration assessment, and art archeology.

## Background of the study object

The Yunjin Dahualou Loom is a remarkable treasure of Chinese cultural heritage, having profound historical and cultural significance while encompassing a range of traditional techniques and cultural elements. As a quintessential example of ancient Chinese jacquard looms, it exemplifies complex weaving processes and serves as an exceptional tool for artistic creation.

The Yunjin Dahualou Loom is custom-designed specifically for Yunjin fabrics, and its development signifies the maturation of Yunjin textiles[50]. Evolving from the smaller pattern loom, the Yunjin Dahualou Loom can weave intricate designs in larger loops, producing textiles with more vibrant colors and enabling the creation of jacquard fabrics featuring diverse textures and asymmetrical patterns. As illustrated in Fig. 1, the l Yunjin Dahualou Loom is depicted in the Qing Dynasty's "Kangxi Emperor's Imperially Commissioned Illustrations of Agriculture and Weaving."

The Yunjin Dahualou Loom features a manual operation structure, requiring weavers to coordinate the use of both their hands and feet in conjunction with the flower-pulling workers. The flower-puller, positioned on the upper level of the loom, lifts the warp threads. Meanwhile, the weaver operates the opening mechanism with their feet using bamboo pedals and is responsible for various tasks, including shuttle throwing, pattern knife weaving, and arranging the weave[51]. As shown in Fig. 2, the manual weaving of Yunjin ensures that the fabric quality is exquisite, while infusing each piece with the soul and emotions of the artist.

As illustrated in Fig. 3, the dimensions of the Yunjin Dahualou Loom are ~5600 mm in length, 1400 mm in width, and 3700 mm in height. The design of the Yunjin Dahualou Loom accommodates complex mechanical structures while ensuring ample space for workers to operate effectively. The value of Yunjin is often described as "each inch of Yunjin is as valuable as gold," reflecting the high-quality materials used, the intricacy of the weaving process, and the low production output[52]. Two weavers can produce only 5–6 cm of fabric per day, and this technique remains irreplaceable by machines even today[53]. During the weaving process, workers must patiently weave out each detail, precisely adjusting the tension of the warp and weft to ensure the clarity and symmetry of the brocade patterns.

Moreover, the Yunjin Dahualou Loom is a significant artwork that embodies rich craftsmanship and cultural significance. It represents the pinnacle of ancient Chinese weaving technology and reflects the craftsman's spirit and pursuit of beauty. The loom has become an integral part of textile cultural heritage, featured in museums and art exhibitions that highlight the allure of ancient textile culture. To preserve this ancient cultural legacy, it is essential to utilize digital methods for in-depth exploration and analysis of the Yunjin Dahualou Loom. Such efforts will enhance future generations' understanding and appreciation of the illustrious history of China's textile cultural heritage.

## Methods

### Data collection and model establishment

The structural dimensions and assembly methods of the Yunjin Dahualou Loom were established based on the specifications, nomenclature, structures, and assembly techniques of each component provided by Jianming Zhu, a researcher at the Institute of Archeology, Chinese Academy of Social Sciences, as well as an inheritor of the intangible cultural heritage of ancient Chinese loom-making techniques. The research team collected data on 1924 parts of the Yunjin Dahualou Loom, thereby confirming its structural components and dimensions.

After establishing the dimensions of the Yunjin Dahualou Loom, the structure of its various components is drawn using Autodesk CAD software. Upon completion of the drawings, information for each part of the loom is recorded, and the Yunjin Dahualou Loom drawings are saved in ".dwg" format to facilitate the subsequent restoration and modeling processes, as illustrated in Fig. 4.

The Yunjin Dahualou Loom structure diagram in ".dwg" file format was imported into Autodesk 3DsMax software for reference and digital modeling[54]. During the modeling process, each component of the loom was modeled and frozen to prevent errors in the subsequent assembly phase. Based on prior research and analysis, the Yunjin Dahualou Loom was constructed using mortise and tenon joints. The "3D dynamic capture" tool was employed during assembly to ensure precise alignment of the mortise and tenon slots across the various components, as shown in Fig. 5.

### Restoration and repair of materials

**Material creation process**. The restoration process of the Yunjin Dahualou Loom's material texture primarily involves two key

**Fig. 1 |** The Jacquard Weaving Machine in the Yunjin Dahualou Loom in the Kangxi Imperial Farming and Weaving Painting.

components: the creation of material texture images and the establishment of material quality parameters. Preliminary research indicates that the loom is primarily constructed from wood and bamboo. Accordingly, wood grain and bamboo texture bitmaps were created and subsequently imported into the material parameter creation process. By adjusting the material parameters associated with these different bitmaps, the digital restoration of the Yunjin Dahualou Loom's material texture was successfully achieved, as illustrated in Fig. 6.

**Creation of material textures**. The restoration and repair of the loom materials is aimed at improving the material effects of the Yunjin Dahualou Loom, enhancing their realism and glossiness. Given that the loom is constructed from wood and bamboo, the creation of material textures includes the development of wood grain textures, bump maps, and bamboo grain textures, as detailed in Table 1.

**Loom Material parameter tuning**. By creating material maps for different looms, the material parameters of the Yunjin Dahualou Loom were refined using VRay rendering software. Material parameter tuning involves simulating the ideal physical properties of an object as it appears under illumination. Wood, in general, is thick, rough to the touch, and has low reflectivity, while bamboo is hard, smooth, and exhibits medium to low reflectivity. The tuned parameters for the wood grain and bamboo pattern materials are presented in Tables 2 and 3, respectively.

### 3D dynamic digital restoration of production principle

To the best of the author's knowledge, the digital reconstruction of the production principles related to the Yunjin Dahualou Loom has not been explored in the existing literature. Recognizing the significance and urgency of this task, the research team undertook the digital reconstruction of these production principles. This effort not only safeguards the invaluable intangible cultural heritage of ancient Chinese loom-making techniques but also revitalizes cultural heritage that dates back over 2000 years in contemporary society.

To digitally restore the Yunjin Dahualou Loom production principles, the frame sequence technology in Autodesk 3ds Max is utilized to dynamically demonstrate the production process of the Yunjin Dahualou Loom[55], aiming to visualize its production principles.

Before initiating the digital restoration of the production principles, it is essential to categorize the various parts of the Yunjin Dahualou Loom and establish the demonstration sequence for each group. The categories include the frame, shedding, warp feeding, weft insertion, and take-up sections. This organization enables the weaving machine to be animated in a systematic and predetermined order.

**Fig. 2 |** Nanjing Yunjin Museum Yunjin Dahualou Loom.

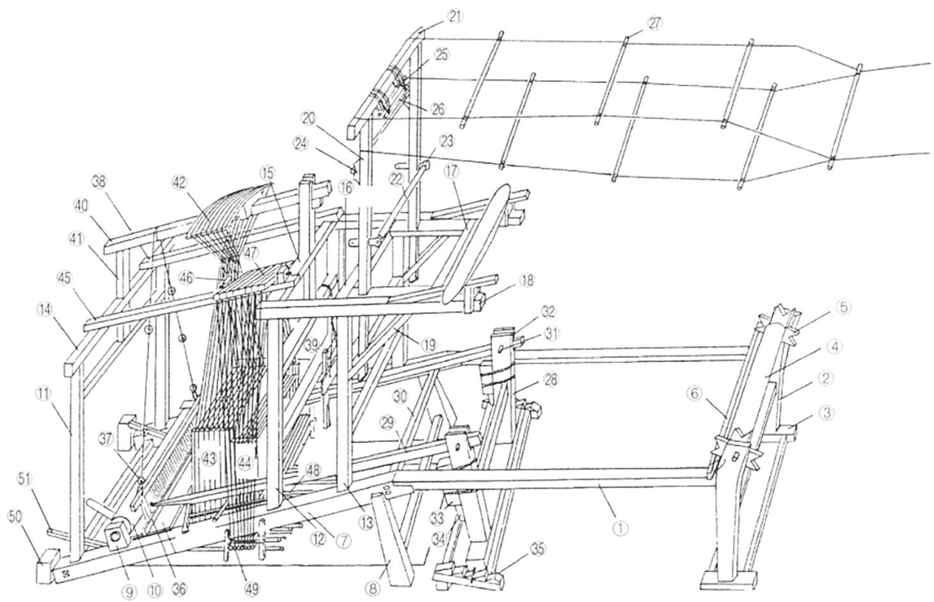


**Fig. 3 |** Complete Collection of Traditional Chinese Crafts - Silk Weaving and Dyeing - Yunjin Dahualou Loom[68].

Once the demonstration sequence for each group has been established, the durations for each group's appearance and the transitions between camera angles are determined. Using these calculations, the overall length of the frame sequence is specified, and parameters such as frame count, frame rate, start time, and end time are set.

To facilitate a multi-angle restoration demonstration of the Yunjin Dahualou Loom's production principles, inertia growth is applied along the X, Y, and Z axes for each group. Keyframes are established for camera angle transitions to highlight various dynamic effects, as detailed in Table 4.

### 3D dynamic digital restoration of weaving principles

Following the dynamic restoration of the Yunjin Dahualou Loom's production principles, this study conducts a digital dynamic restoration of the weaving principles. To the best of the authors' knowledge, research on the weaving techniques of Yunjin has only been reported in a few publications[47–49]. To achieve a detailed digital dynamic restoration of these principles, the team systematically classified the different weaving structures of the loom, performed skeletal binding, and created corresponding keyframes for each weaving component. The core weaving process of the Yunjin Dahualou Loom consists of five fundamental movements: shedding, weft insertion, beating-up, warp let-off, and fabric take-up. These movements work together in coordination to complete the weaving process, as outlined in Table 5.

The shedding movement, a crucial aspect of the Yunjin weaving process, is executed by the jacquard worker, who controls the heddle openings, while the flower picker manages the lifting of the warp threads. Through their coordinated efforts, the heddles are raised, and the warp threads are lifted according to the pattern design, enabling the shedding movement. The jacquard worker is responsible for overseeing the weft insertion and beating-up movements. This involves inserting the shuttle back and forth or winding the yarn tube within the opening for weft weaving. Afterward, a bamboo reed is used to firmly press the newly inserted weft yarns into place. The warp let-off movement continuously supplies warp threads throughout the weaving process, while the fabric take-up movement winds the woven fabric

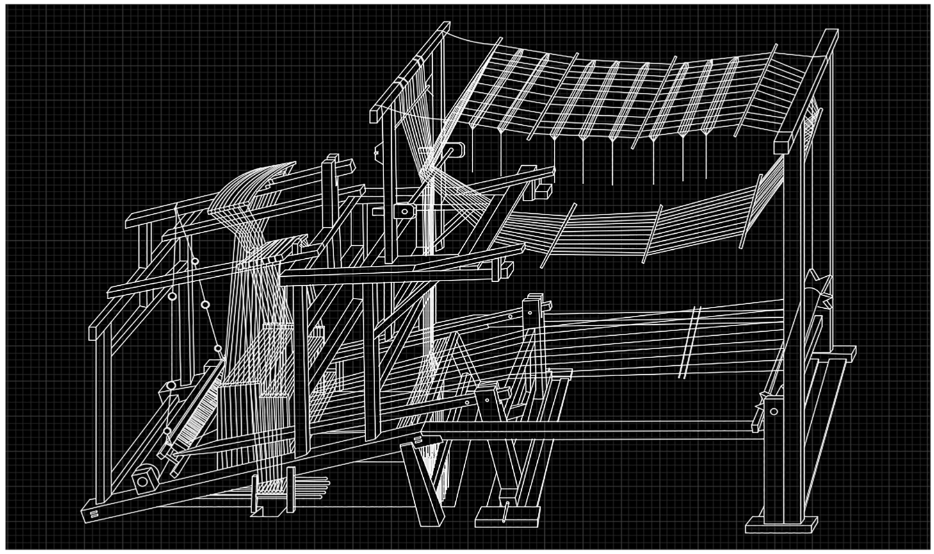


**Fig. 4 |** Schematic diagram of the Yunjin Dahualou Loom Structure.

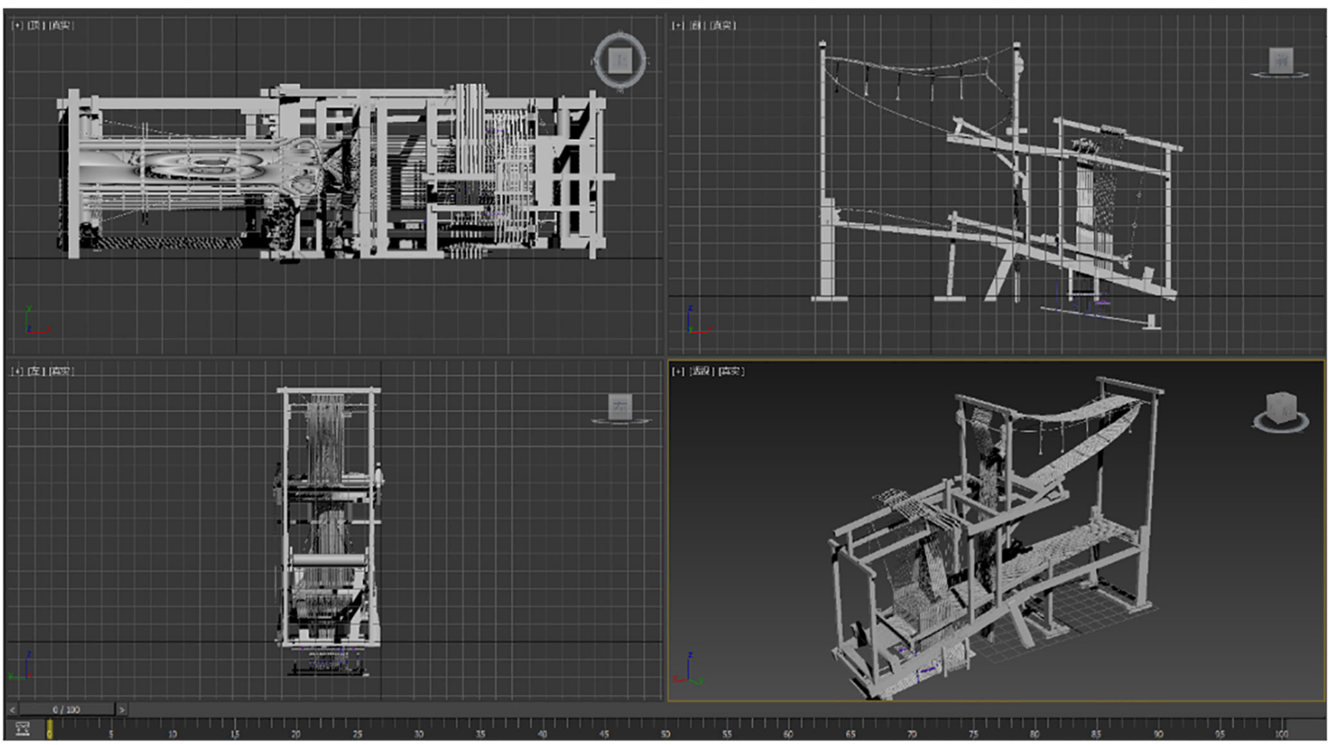


**Fig. 5 |** The digital model of the Yunjin Dahualou Loom.

onto the cloth beam. A detailed analysis of the structure and weaving process of the Yunjin Dahualou Loom plays a crucial role in the digital preservation and transmission of both textile and intangible cultural heritage.

**Zhangzi (幛子) opening mechanism**. The "Zhangzi" refers to the plain shedding mechanism controlled by the weaver during the weaving process. The Zhangzi opening mechanism mainly comprises Jiaozhu, Jiaozhu cord, Zhangzi, Hengzhugan, Meridian, Diaozong cord, and Gongpeng components.

When downward pressure is applied to the Jiaozhu, the α end remains stationary as the pivot point, while the β end exerts a downward force. The Jiaozhu is connected to the Jiaozhu cord, which also applies a downward force when pressure is applied to the β end. The Jiaozhu cord is linked to the Hengzhugan, so when the Jiaozhu cord exerts downward pressure, the Hengzhugan follows suit, creating a downward force. Similarly, the Hengzhugan is connected to the Zhangzi; when the Hengzhugan is pressed downward, the Zhangzi also exerts a downward force. This connection extends to the Meridian, which is activated when the Zhangzi is pressed down, generating a downward force that creates an opening. The Zhangzi is also connected to the Diaozong cord, so when the Zhangzi is pressed, the Diaozong cord applies a corresponding downward force. Finally, the Diaozong cords are linked to the Gongpeng, which exerts a downward force when the Diaozong cord is pressed.

The Gongpeng structure has elastic characteristics. When the force is stopped from being applied to the above components, the γ part of the Gongpeng generates a rebound force, closing any existing openings of the

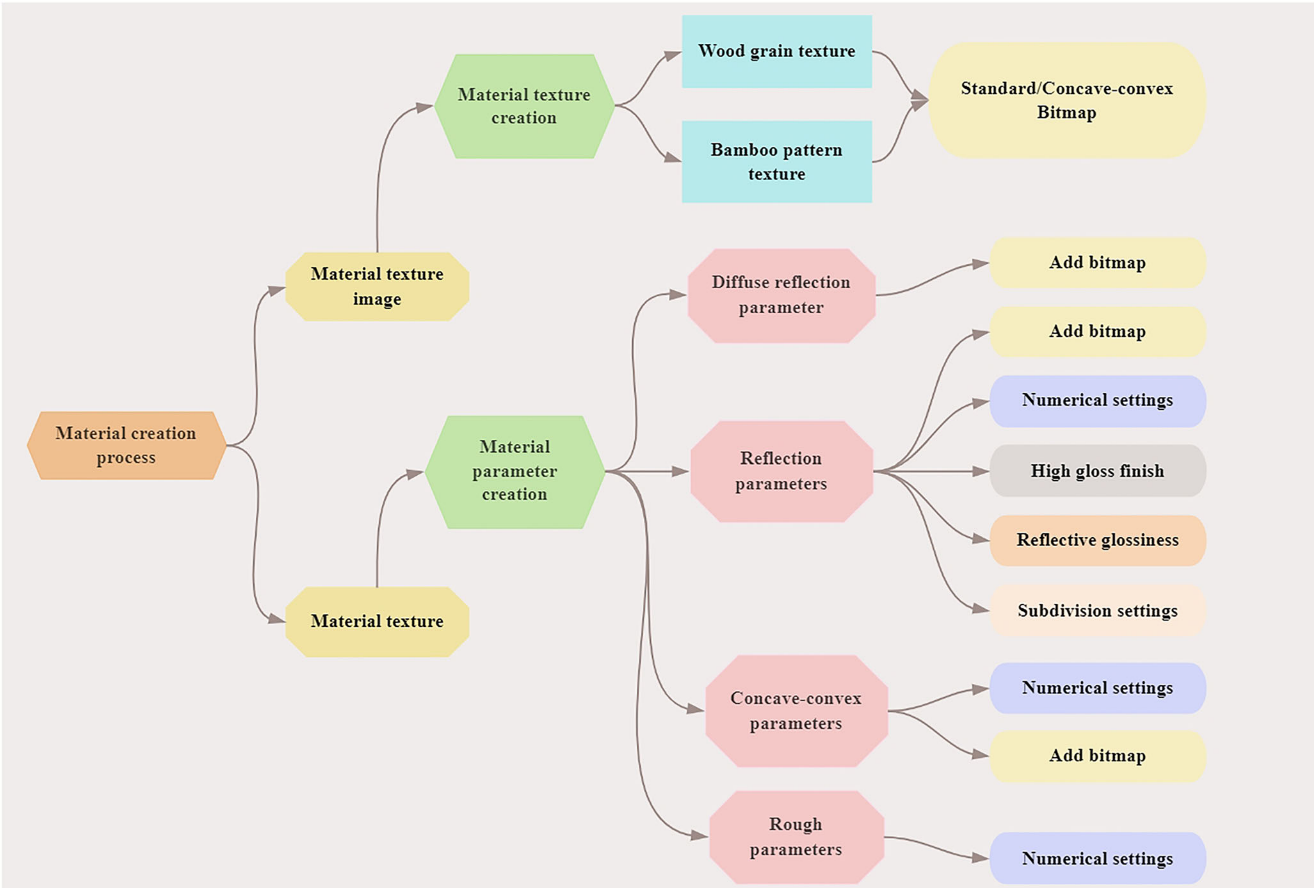
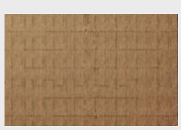



**Fig. 6 |** The process of material restoration for the Yunjin Dahualou Loom.

**Table 1 | Schematic material texture diagram of the Yunjin Dahualou Loom**

| Map Name | Standard Bitmap | Bump Map |
|---|---|---|
| Wood grain texture |  |  |
| Bamboo texture |  |  |

Zhangzi, thus allowing the components to return to their original position, as shown in Table 6.

**Fanzi (范子) opening mechanism**. The term "Fanzi" refers to the pattern-shedding mechanism that the weaver controls during the weaving process. Similar to the Dizong system, the pattern-opening mechanism consists mainly of the following components: Jiaozhu, Jiaozhu cord, Hengyanzhu, Xiaxu cord, Laoyachi, Chengqiangduo, Diaozong cord, Meridian, and Fanzi.

When downward pressure is applied to the Jiaozhu, its α end acts as a fixed axis, while the β end generates a downward force. The Jiaozhu is connected to the Jiaozhu cord, which also produces a downward force when pressure is applied to the β end of the Jiaozhu. This cord is linked to the Hengyanzhu, causing the α end of the Hengyanzhu to remain stationary while the β end exerts a downward force due to pressure from the Jiaozhu cord. The β end of the Hengyanzhu is connected to the Xiaxu cord, which generates a downward force when pressure is applied. The Xiaxu cord is linked to the β end of the Laoyachi, which also produces a downward force in response to pressure from the Xiaxu cord. At the same time, the γ part of the Chengqiangduo acts as a pivot point for the Laoyachi. As the β end of the Laoyachi exerts downward pressure, the α end generates an upward force. The α end of the Laoyachi is connected to the Diaozong cord, which responds to this upward pressure by producing an upward lifting force. The Diaozong cord is linked to the Fanzi, creating an upward lifting force when it is raised. Finally, the Fanzi and Meridian interact: when the Fanzi exerts an upward force, the Meridian responds by producing an upward lifting force, resulting in the formation of an opening.

When the applied force on the components is released, the Fanzi is influenced by gravity, causing it to exert a downward force. This action closes all previously opened sections and returns all components to their original positions. Table 7 illustrates the schematic diagram of the Fanzi opening mechanism principle.

**Shuttle throwing and weft insertion section**. Shuttle throwing and weft insertion are parts of the weaving process controlled by the Weaver machine operator. This mechanism primarily consists of components such as the Jutou, Gounao, Meridian, shuttles, Velvet tube, Zhukou, Koukuang, Diaokuang cord, Zhuanggan, Liren, Lirenpan, and Lirenshao. Gounao is fixed to Jutou; Zhuanggan is attached to both Lirenshao and

Table 2 | Wood grain material parameters for the Yunjin Dahualou Loom

| Wood grain material | Material type | Diffuse reflection | Reflex | | | | | Concavity and convexity | | Rough |
|---|---|---|---|---|---|---|---|---|---|---|
| | VRayMtl | Standard Bitmap | Numerical value | Hilight glossiness | Reflection glossiness | Reflection type | Subdivision | Bump map | numerical value | numerical value |
|  | | | 15 | 0.85 | 0.85 | Fresnel | 32 | | 25 | 5 |

Table 3 | Material parameters of bamboo pattern on Yunjin Dahualou Loom

| Bamboo grain material | Material type | Diffuse reflection | Reflex | | | | | | Concavity and convexity | | Rough |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | VRayMtl | Standard Bitmap | Bump map | Numerical value | Reflection glossiness | | Reflection type | Subdivision | Bump map | numerical value | numerical value |
|  | | | | 245 | Bump map | numerical value | Fresnel IOR: 1.9 | 24 | | 2 | 5 |
| | | | | | | 0.9 | | | | | |

**Table 4 | Keyframe capture for growth animation (partial)**

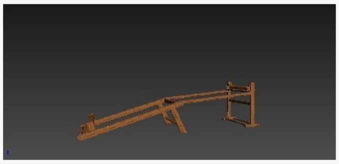
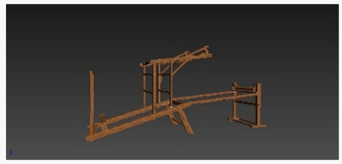
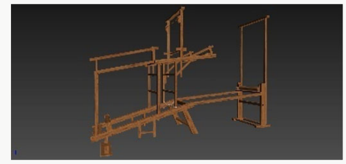
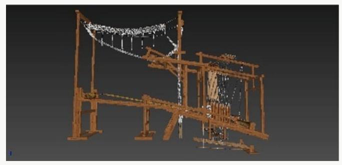
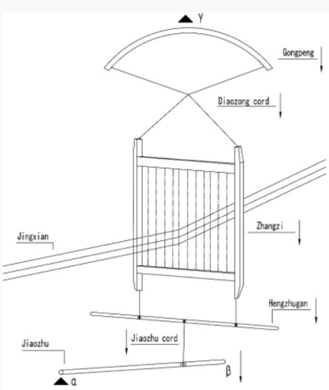
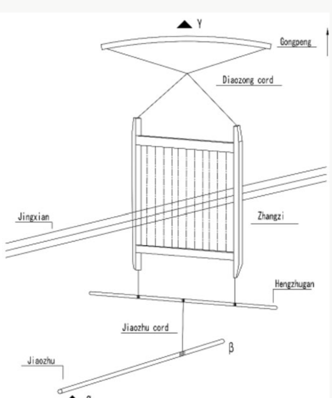
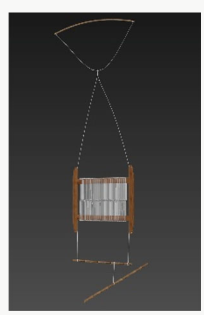
| 175/1050 FPS | 345/1050 FPS | 500/1050 FPS |
|---|---|---|
|  |  |  |
| **760/1050 FPS** | **900/1050 FPS** | **1000/1050 FPS** |
|  |  |  |

**Table 5 | Correspondence of loom components and their descriptions**

| Name of the sport | Institution name | Main components | Function description |
|---|---|---|---|
| Opening movement | Zhangzi opening mechanism | Jiaozhu, Jiaozhu cord, Hengzhugan, Zhangzi, Meridian, Diaozong cord, Gongpeng | Foot pedal controls the downward opening of the warp. |
| | Fanzi opening mechanism | Jiaozhu, Jiaozhu cord, Hengyanzhu, Fanzi, Meridian, Diaozong cord, Xiaxu cord, Chengqiangduo | Foot pedal controls the warp yarn opening upwards. |
| | Hualou Opening mechanism | Qianjintong, Huaben cord, Erzi cord, Jiaozi cord, Qian cord, Zhujiaopen, Qujiao. | The lifting wire controls the warp threads to open upwards. |
| Weft insertion motion | Shuttle mechanism | Meridian, Shuttle, Parallel | The shuttle weaves the weft back and forth. |
| Latitude tightening movement | Latitude tightening mechanism. | Zhukou, Diaokuang cord, Zhuanggan, Liren, Lirenpan, Lirenshao | The impact latitude tightens and compresses the fabric. |
| Transmission meridian Movement | Transmission meridian organization | Digang, Meridian, Yangjiao | Transmission meridian |
| Curling motion | Curling mechanism | Jutou, Gounao, Qiaochi | Winding the fabric |

**Table 6 | Schematic diagram illustrating the principle of the Zhangzi opening mechanism**

| Schematic diagram of the Zhangzi opening mechanism principle | | Keyframe capture of Zhangzi's opening mechanism animation | |
|---|---|---|---|
| | | 1/1050 FPS | 25/1050 FPS |
|   |   |  |  |

Liren; Liren is connected to the Lirenpan; and Koukuang is fixed to both Zhukou (hereafter referred to as Kou) and Zhuanggan.

Shuttle Throwing/Warp Threading. When the Zhangzi is controlled or the Fanzi is operated, the Meridian creates openings that allow for movement in either the upward or downward direction. Shuttles then move back and forth through these openings, while Velvet tubes wrap around sections of the exposed warp threads. Decorative threads, such as gold, are inserted into the warp openings, as shown in Table 8.

**Table 7 | Schematic diagram illustrating the principle of the Fanzi opening mechanism**

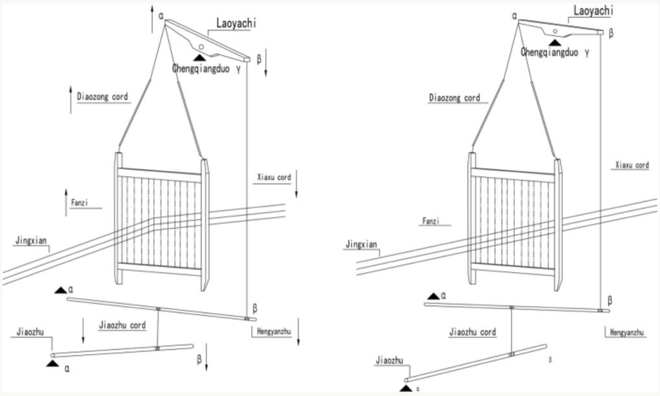
| Schematic diagram of the Fanzi opening mechanism principle | Keyframe capture of the Fanzi opening mechanism animation | |
|---|---|---|
| | 360/1050 FPS | 440/1050 FPS |
|  |  |  |

**Table 8 | Diagram illustrating the principle of the shuttle system**

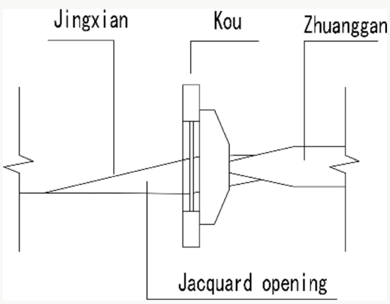
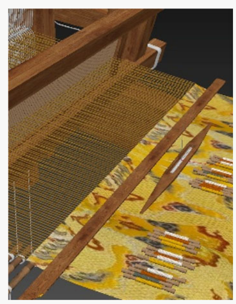
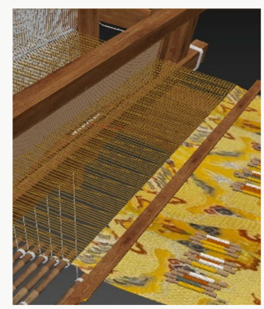
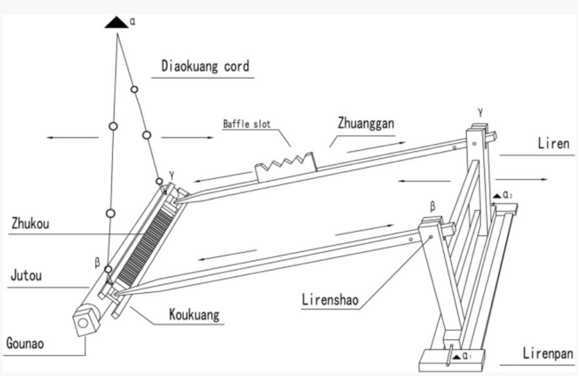
| Diagram illustrating the principle of the shuttle system | Keyframe extraction for shuttle animation | |
|---|---|---|
| | 1/1050 FPS | 30/1050 FPS |
|  |  |  |

**Table 9 | Illustration of the principle for tightening the latitude lines**

| Illustration of the principle of tightening the latitude lines | Tightening the latitude lines: capturing keyframes in animation | |
|---|---|---|
| | 360/1050 FPS | 440/1050 FPS |
|  |  |  |

Weft Insertion. The Kou, Diaokuang cord, and Zhuanggan are interconnected. When the Kou moves back and forth, the Zhuanggan reciprocates along with it, while the α end of the Diaokuang cord remains fixed, and its β and γ ends move in sync with the Kou. The Zhuanggan is connected to the Liren and Lirenshao; as the Zhuanggan reciprocates, the $\alpha_1$ and $\alpha_2$ ends of the Liren stay stationary relative to the Lirenshao, while the β and γ ends of the Liren move reciprocally with the Zhuanggan. The Liren is linked to the Lirenpan, which remains stationary at the $\alpha_1$ and $\alpha_2$ ends of the Liren as the β and γ ends of the Liren move back and forth. Table 9 illustrates the principle of tightening the latitude lines.

**Table 10 | Principal schematic of the Zhuanggan baffle**

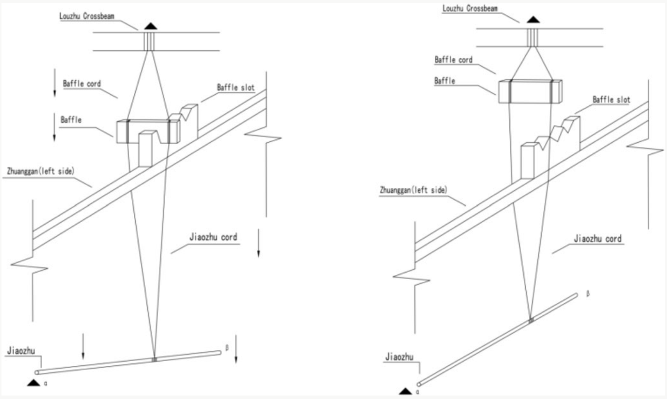
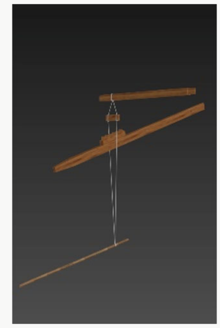
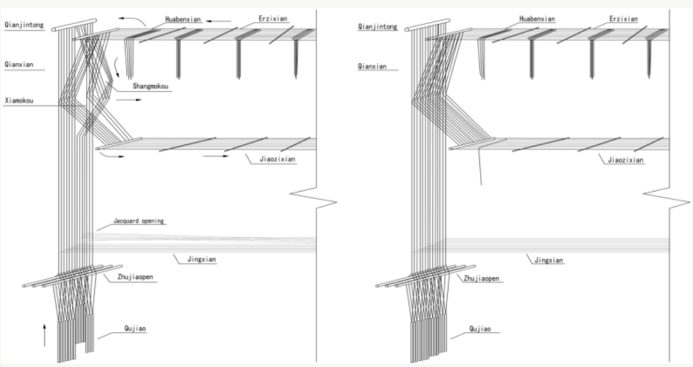
| Principle schematic of the Zhuanggan baffle | Keyframe extraction for the Zhuanggan baffle animation | |
|---|---|---|
| | 50/1050 FPS | 110/1050 FPS |
|  |  |  |

**Table 11 | Hualou opening principal diagram**

| Hualou opening principal diagram | Hualou opening animation keyframe capture | |
|---|---|---|
| | 150/1050 FPS | 275/1050 FPS |
|  |  |  |

**Zhuanggan (撞杆) blocking section**. The Zhuanggan Blocking Section is the area where the weaver controls the stopping and starting of the Kou during the weaving process. This section consists mainly of the Jiaozhu, Jiaozhu cord, the left side of the Zhuanggan, baffle, baffle cord, baffle slot, and Louzhu crossbeam. The Jiaozhu and Jiaozhu cord are securely fixed together, as are the Jiaozhu cord and the baffle. The baffle is attached to the baffle cord, while the baffle slot is fixed to the left side of the Zhuanggan. The baffle cord is connected to the Louzhu crossbeam.

When downward pressure is applied to the Jiaozhu, its α end remains stationary as a pivot, while the β end exerts a downward force. The Jiaozhu is linked to the Jiaozhu cord, which also generates a downward force when pressure is applied to the β end of the Jiaozhu. The Jiaozhu cord also interacts with the baffle. When the Jiaozhu cord is pushed downward, the baffle moves down and locks into the baffle slot, stopping the operation of the latitude tightening mechanism.

Since the baffle cord is fixed to the Louzhu crossbeam and has elastic properties, when the pressure on the aforementioned components is released, the baffle is lifted upward, allowing it to disengage from the baffle slot. This action enables the latitude-tightening mechanism to resume its movement, as illustrated in Table 10.

**Hualou (花楼) opening mechanism**. The "Hualou" refers to the jacquard shedding mechanism operated by the Jacquard worker during the weaving process. This mechanism primarily consists of several components: Qianjintong, Huabenxian, Erzixian, Jiaozixian, Qianxian, Zhujiaopen, and Qujiao. Specifically, Qianjintong and Qianxian are fixed in place, while Huaben and Mingxian are securely joined. The Mokou, formed by Mingxian, is connected to Qianxian, which is also fixed to both the Meridian and Qujiao. The two ends of Zhujiaopen are anchored to the rear of the machine, effectively separating Qianxian.

During the jacquard process, the bound Huabenxian must be unraveled and drawn towards the Mokou section to form the required Qianxian. When a backward force is applied at the Mokou, Qianxian, which is interconnected with Erzixian, generates an upward lifting force. This upward movement of Qianxian is also linked to the Meridian; as Qianxian rises, the Meridian simultaneously ascends, creating a jacquard opening. Qianxian and Qujiao are also connected, thus when Qianxian is elevated, Qujiao also exerts an upward lifting force.

When the force on the aforementioned components is released, the gravitational effect on Qujiao generates a downward force, causing all existing jacquard openings to close, except for the utilized Huabenxian that enters the Jiaozixian to initiate the next cycle. All components thus return to their original positions, as illustrated in Table 11.

**Loom restoration display effect**. Following the digital restoration and repair, the overall structure of the Yunjin Dahualou Loom has been

**Fig. 7 |** Restoration effect drawing (perspective view) of the Yunjin Dahualou Loom.

**Fig. 8 |** Restoration effect drawing (Side view) of the Yunjin Dahualou Loom.

**Fig. 9 |** Restoration effect drawing (Local view) of the Yunjin Dahualou Loom.

accurately depicted, enabling views from multiple angles. By adjusting the textures of wood and bamboo, along with the lighting effects, the materials' authenticity is effectively conveyed on screen. The detailed representation of the wood and bamboo grain further enhances the realism of the display. The digitally restored components of the Yunjin Dahualou Loom highlight its intricate structure and features. Dynamically simulating the loom's operational principles provides a clearer understanding of its functionality. Overall, the digital restoration and repair of the Yunjin Dahualou Loom not only visually recreates the artifact but also preserves and showcases every detail, allowing the public to engage with this unique cultural heritage more authentically and comprehensively, as illustrated in Fig. 7, Fig. 8, and Fig. 9.

**Table 12 | Evaluation system for the restoration effect of the Yunjin Dahualou Loom**

| Target layer | Indicator layer | Relationship with target layer |
| --- | --- | --- |
| Yunjin Dahualou Loom Restoration effect | Overall shape and structure(u1) | Positive correlation |
| | Detailed structure (u2) | Positive correlation |
| | Material restoration and repair Material restoration and repair(u3) | Positive correlation |
| | Working principle(u4) | Positive correlation |

**Table 13 | Interpreting the matrix assignment meanings**

| Assigning relative importance (ai / aj) | Symbolic meaning |
| --- | --- |
| 1 | ai and aj are equally important. |
| 3 | ai is slightly more important than aj. |
| 5 | ai is more important than aj. |
| 7 | aj is significantly more important than ai. |
| 9 | Compared to aj, ai is extremely important. |
| 2, 4, 6, 8 | The median value of the mentioned proximity judgments. |
| countdown | aij = 1/ aij |

## Establishment of a comprehensive evaluation system

### Theory of comprehensive evaluation

This work integrates the AHP and Fuzzy Comprehensive Evaluation methods to conduct a thorough assessment of the restoration effects of the Yunjin Dahualou Loom[56,57]. To reduce the influence of subjectivity on the evaluation results, experts in the relevant field with appropriate knowledge and experience were selected to conduct the assessment. This approach enhances the objectivity and reliability of the evaluation outcomes.

### Defining evaluation metrics and scales

Evaluation metrics $U$ refer to the evaluation of different factors affecting the evaluation object[58]. $U$ is defined as $U = [u_1, u_2, u_3, u_4 \ldots u_n]$, where $u_n$ refers to the subset of items in project evaluations. Evaluators obtain information about the evaluation object and assign corresponding evaluation scales $V$ to the metrics in $U$. The overall scale used in project evaluations is denoted as $V$, and $v_n$ represents each evaluation metric within this set, i.e., $V = [v_1, v_2, v_3, v_4 \ldots v_n]$.

### Determining weights

The AHP method employs a systematic approach to calculate the weights of indicators[59,60]. The process begins by establishing a hierarchical structural model and identifying the indicators for each level[61]. Next, pairwise comparison matrices were developed using a scale of pairwise comparisons to assign values to the indicators at each level. The maximum eigenvalue and consistency index of the judgment matrix are then calculated, followed by a consistency test based on the test coefficient. If the consistency test is passed, the weights for the indicators at each level can be determined, represented as $a = (a_1, a_2, a_3, a_4 \ldots a_n)$.

### Constructing a fuzzy comprehensive evaluation matrix

Using a five-level evaluation scale, each evaluation indicator is assessed within the context of the project. The coefficients for all indicators are then gathered and organized to construct the following $R_i$ fuzzy evaluation matrix:

$$R_i = \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & & \vdots \\ r_{m1} & \cdots & r_{mn} \end{bmatrix}$$

### Fuzzy comprehensive evaluation

The target vector $Z$ is estimated through the numerical values of each indicator in the fuzzy comprehensive evaluation, $Z = (A \cdot B)$. Based on the principle of maximum membership, the evaluation result for the digital restoration effect of the Yunjin Dahualou Loom is obtained.

### Evaluation of digital restoration effects of the Yunjin Dahualou Loom

**Determining the evaluation item set**. The digital restoration process for the Yunjin Dahualou Loom must take into account its form, structure, materials, and working principles. Consequently, the restoration effect of the loom is established as the target layer. Based on these considerations, the evaluation criteria were organized into a criteria layer, which includes the overall form, detailed structure, material restoration and repair, and working principles. This framework allows for a comprehensive assessment of the restoration effects of each criterion, as illustrated in Table 12.

### Constructing the judgment matrix

AHP assigns values to rank the importance of indices[62]. Five experts with knowledge of ancient loom construction and restoration were invited to evaluate the importance of each index by assigning values. A higher value signifies greater importance, while a reciprocal value indicates lower importance. Specific values are detailed in Table 13. Once the scores were assigned, a judgment matrix for the indices was constructed.

By organizing the scoring results of each expert, the judgment matrix $K$ can be obtained. $K_1$ refers to the judgment matrix obtained from pairwise comparisons under the indicators $(u_1, u_2, u_3, u_4)$, while $K_2$ pertains to the indicators $(u_{11}, u_{12}, u_{13}, u_{14})$ arranged in sequence. Similarly, $K_5$ corresponds to the judgment matrix derived from pairwise comparisons based on the indicators $(u_{41}, u_{42}, u_{43}, u_{44})$. As the five experts assigned scores to the importance of these layers of indicators, the following judgment matrix was obtained:

$$\boldsymbol{K}_1 = \begin{bmatrix} 1 & 1.667 & 2 & 1.25 \\ 0.6 & 1 & 2 & 0.667 \\ 0.5 & 0.5 & 1 & 0.5 \\ 0.8 & 1.5 & 2 & 1 \end{bmatrix} \tag{1}$$

$$\boldsymbol{K}_2 = \begin{bmatrix} 1 & 1.667 & 2.5 & 1.429 \\ 0.6 & 1 & 2 & 0.667 \\ 0.4 & 0.5 & 1 & 0.5 \\ 0.7 & 1.5 & 2 & 1 \end{bmatrix} \tag{2}$$

$$\boldsymbol{K}_3 = \begin{bmatrix} 1 & 1.429 & 2 & 1.667 \\ 0.7 & 1 & 2 & 0.4 \\ 0.5 & 0.5 & 1 & 0.5 \\ 0.6 & 2.5 & 2 & 1 \end{bmatrix} \tag{3}$$

$$K_4 = \begin{bmatrix} 1 & 1.429 & 2 & 1.25 \\ 0.7 & 1 & 1.667 & 0.5 \\ 0.5 & 0.6 & 1 & 0.333 \\ 0.8 & 2 & 3 & 1 \end{bmatrix} \tag{4}$$

$$K_5 = \begin{bmatrix} 1 & 1.429 & 1.667 & 1.25 \\ 0.7 & 1 & 1.429 & 0.4 \\ 0.6 & 0.7 & 1 & 0.333 \\ 0.8 & 2.5 & 3 & 1 \end{bmatrix} \tag{5}$$

**Calculating weight coefficients for each index.** The indices were ranked by weight importance in the following order: $u_1$, $u_4$, $u_2$, and $u_3$. Specific weight coefficients for various indicators are presented in Table 14. Table 15 shows the Average Random Consistency Index (*RI*) values.

**Consistency check.** Inconsistent conclusions can occur during pairwise comparisons of indicators. To address this issue, a consistency check should be conducted on the judgment matrix to validate the rationality of the indicator weights. It's important to note that the weights derived from the AHP method may contain a degree of subjectivity[63]. To make the data more accurate and reliable, a consistency check should be performed on the judgment matrix, as shown in formulas (6) to (8).

$$\lambda_{\max} = \frac{\sum_{i=1}^{m} \frac{A_w}{w}}{m} \tag{6}$$

$$CI = \frac{(\lambda_{\max} - m)}{(m-1)} \tag{7}$$

$$CR = \frac{CI}{RI} < 0.1 \tag{8}$$

where $\lambda_{\max}$ represents the maximum eigenvalue; $w$ is the arithmetic mean of each index's normalized values; $A_w$ is the weight of each index; $m$ is the number of indices; CI is the consistency index; CR is the test coefficient; RI is the average random consistency index. From the table, $\lambda_{\max} = 4.0$ and CI = 0.01. Since RI = 0.89 and CR = 0.0115 < 0.1, it passes the consistency test. According to this calculation method, the results are $CR_2 = 0.0078 < 0.1$, $CR_3 = 0.0564 < 0.1$, $CR_4 = 0.0176 < 0.1$, and $CR_5 = 0.0317 < 0.1$, all of which pass the consistency test.

**Table 14 | Integrated weights of various indicators**

| Indicator Name | Weight coefficient | Weight order |
|---|---|---|
| Overall shape and structure(u1) | 0.33578 | 1 |
| Detailed structure (u2) | 0.2077 | 3 |
| Material restoration and repair(u3) | 0.13724 | 4 |
| Working principle(u4) | 0.3193 | 2 |

**Table 15 | Average Random Consistency Index**

| n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| RI | 0 | 0 | 0.52 | 0.89 | 1.12 | 1.26 | 1.36 | 1.41 | 1.46 |

### Comprehensive evaluation of the restoration effect

**Establishing a fuzzy comprehensive evaluation matrix.** To evaluate the restoration effect of the Yunjin Dahualou Loom, a five-level scale was utilized, represented as $V = [v_1, v_2, v_3, v_4, v_5]$, where $V$ = [very poor, poor, average, good, very good][64,65]. A questionnaire survey method was employed to assess various loom indicators, enhancing the accuracy and objectivity of the evaluation of the digital restoration effect. The collected data was systematically organized[66,67]. The evaluation results of the digital restoration effect of the Yunjin Dahualou Loom are presented in Table 16.

Based on the data obtained from Table 15, the following evaluation matrix can be obtained:

$$R = \begin{bmatrix} 0.05 & 0.044 & 0.168 & 0.37 & 0.368 \\ 0.05 & 0.05 & 0.118 & 0.433 & 0.349 \\ 0.047 & 0.034 & 0.14 & 0.452 & 0.327 \\ 0.072 & 0.034 & 0.097 & 0.312 & 0.49 \end{bmatrix} \tag{9}$$

**Fuzzy comprehensive evaluation.** Fuzzy comprehensive evaluation can be calculated as $Z = A \cdot R$:

$$Z = [0.33578 \;\; 0.2077 \;\; 0.13724 \;\; 0.3193] \begin{bmatrix} 0.05 & 0.044 & 0.168 & 0.37 & 0.368 \\ 0.05 & 0.05 & 0.118 & 0.433 & 0.349 \\ 0.047 & 0.034 & 0.14 & 0.452 & 0.327 \\ 0.072 & 0.034 & 0.097 & 0.312 & 0.49 \end{bmatrix} = [0.06 \;\; 0.04 \;\; 0.13 \;\; 0.37 \;\; 0.40] \tag{10}$$

The evaluation system for the digital restoration of the Yunjin Dahualou Loom utilizes five indicators to assess the restoration effect: very poor, poor, average, good, and very good. Based on the final calculation result (Z) from the fuzzy comprehensive evaluation, the membership degrees for each category are as follows: 6% for very poor, 4% for poor, 13% for average, 37% for good, and 40% for very good. Following the principle of maximum membership degree, the digital restoration effect of the Yunjin Dahualou Loom was rated as "very good."

## Conclusion

This work presents a comprehensive digital preservation method that integrates the preservation of both the tangible and intangible cultural heritage of the Yunjin Dahualou Loom through digital modeling techniques. This approach has enabled the digital reconstruction of the loom's form, structure, materials, and working principles. Using the established evaluation system for digital reconstruction, the restoration effect of the Yunjin Dahualou Loom was assessed. The results demonstrate that the digitally reconstructed loom accurately reflects the structure, materials, and operational principles of the original artifact, successfully achieving both the overall form and the dynamic aspects of its craftsmanship. However, the digital restoration of the Yunjin Dahualou Loom using 3D digital technology still falls short of accurately simulating the physical friction and tension effects present in a real-world environment. Building on this study, future research will aim to enhance the model to more closely replicate the

**Table 16 | Evaluating the digital restoration effects of the Yunjin Dahualou Loom**

| Target layer | Indicator layer | Very poor (v1) | Poor (v2) | Average (v3) | Good (v4) | Very good (v5) |
|---|---|---|---|---|---|---|
| Restoration effect | Overall shape and structure(u1) | 0.05 | 0.044 | 0.168 | 0.37 | 0.368 |
| | Detailed structure (u2) | 0.05 | 0.05 | 0.118 | 0.433 | 0.349 |
| | Material restoration and repair (u3) | 0.047 | 0.034 | 0.14 | 0.452 | 0.327 |
| | Working principle(u4) | 0.072 | 0.034 | 0.097 | 0.312 | 0.49 |

physical operational dynamics of the loom. With ongoing advancements in heritage research and the emergence of new technologies, further breakthroughs in the comprehensive digital preservation of both cultural and intangible heritage are anticipated.

The Yunjin Dahualou Loom represents a significant aspect of China's rich traditional textile culture and serves as an important physical artifact for studying the social, economic, cultural, and artistic developments of its time. By employing 3D digital technology for its reconstruction, the risks of natural deterioration during long-term preservation and potential damage during exhibitions and research are significantly minimized. The digitally reconstructed loom model can be rendered with high precision and showcased online, providing the public with a more intuitive understanding of traditional Chinese textile culture. This approach facilitates the effective protection and transmission of both tangible and intangible cultural heritage.

## Data availability

The key data generated or analysed during this study are included in this published article.

## Abbreviations

AHP analytic hierarchy process

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## Author contributions
Hongyu Li: Conceptualization, methodology, supervision; Jinyu Zhang: Drafting the manuscript, software operation; Weili Peng: Investigation and data collection; Xin Tian: Data organization; Jin Shi: Validation and editing. All authors read and approved the final manuscript.

## Competing interests
The authors declare no competing interests.

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