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Digital Sustainability of Intangible Cultural Heritage: The Example of the "Wu Leno" Weaving Technique in Suzhou, China

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Abstract: Digital technology can be used to enable the living preservation and heritage innovation of the intangible cultural heritage of Chinese traditional textile skills for sustainable development. Taking the "Wu Leno" weaving technique in Suzhou as the research object, we first elaborated on the origin, development, and evolution of "Wu Leno" through documentary research and case study methods. Second, considering the inheritance of the Leno weaving technique, we used digital technology to establish the pattern. The study showed that a digital database and virtual reality technology can be used to build a loom model and create a simulation library to realize innovative applications and interactive experiences in apparel design. The study also showed that the digital database and the interactive technology of virtual reality can provide practical pathways and explore experiences for the preservation, inheritance, cross-border communication, and sustainable innovation development of Suzhou "Wu Leno" weaving techniques in modern times.

Keywords: intangible cultural heritage; Leno weaving technique; digitalization; sustainable development; innovative application

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1. Introduction

On 17 October 2003, UNESCO promulgated the Convention for the Safeguarding of Intangible Cultural Heritage (ICH) and defined the concept of ICH. Since UNESCO adopted the Convention for the Safeguarding of the ICH in 2003, 676 elements corresponding to five regions and 140 countries have been included on its lists of ICH [1]. With the development of science and technology and given the popularity of the Internet, big data, information technology, and intelligence, more and more people are paying attention to the digital preservation and heritage research of ICH. Digital technology can promote the sustainable development and innovation of ICH protection and inheritance. Thus, it is important to make full use of these means to increase scientific and technological support.

Suzhou is located on the southern riverfront of the Yangtze River and is rich in ICH resources. These include many textile ICH techniques, such as Suzhou embroidery, Kesi, and other traditional weaving techniques, which have been included in the representative list of national ICH. Since 2016, the "Wu Leno" weaving technique has been listed in the fourth batch of representative items of ICH in Jiangsu Province. Leno is a type of silk fabric with a light texture in which the warp threads twist with each other and intertwine with the weft threads to form patterned holes, giving the surface a striped or floral distribution. It is suitable for making summer dresses, embroidery embellishments, screens, lamps, and related decorations. Therefore, it is considered a high-grade fabric that can be widely used in daily life, and its practical value is significant.

This paper proposes the use of modern digital technology to promote the protection and inheritance of traditional roving crafts and the innovative design of patterns to further broaden the application scenarios of traditional intangible cultural heritage, to realize immersive and interactive experiences, and to promote sustainable development of ICH.

2. Review of Literature

2.1. Study on the Weaving Skills of Leno Fabrics

Academic research on the Leno weaving process has mostly focused on traditional Chinese silk [2–5] or dyeing and weaving patterns [6–9]. Jiu Zhou and Xi Peng [10] analyzed the characteristics and interrelationships of the various types of jacquard fabrics and constructed a genealogy of the organization of jacquard fabrics in ancient China according to their evolution. Ziqi Wang [11], Hailong Li [12], and other specialized works [13–16] also focused on silk or dyeing and weaving techniques, as well as related patterns from historical evolution and technological innovation. Specific research on the Leno weaving process has mainly been carried out by Hang Hang and Yarong Wang [17], with guiding significance and reference value for the study of the evolution of ancient Chinese Leno fabrics. Hongjiang Hao and Weidong Yu [18] discussed the historical evolution of Hang Leno weaving equipment and techniques, as well as folklore phenomena and inheritance. The study on the preservation and heritage status [19] of Suzhou Leno weaving techniques, which are facing endangerment, expresses the importance and urgency of their protection and puts forward suggestions for their protection, heritage, and development.

2.2. Study on the Digitization of ICH

In recent years, research on the digitization of ICH has mainly focused on methods of protection [20–24], inheritance, and development [25–30]. Hong Ding [31] designed the digital protection and development system of intangible cultural heritage, including how to effectively protect it and promote the continuous development of the domestic local economy. Lufang Zhang [32] proposed a virtual experience system for bamboo weaving, considering its digital protection, inheritance, and development. Yulie Wang and other scholars [33] discussed how to realize the application of virtual reality technology, digital interaction technology, new media, and other technologies in the display of cultural resources in museums. Besoain Felipe [34] digitized 30 pieces from nine local museums to provide an experience that represents the main artisan work of the local region.

2.3. Development of Digital Technology and Textile Weaving

As the scope of digital technology has expanded in the field of cultural heritage, more and more studies [35–39] on the combination of textiles and digitalization have been published. YiLing Zhou [40] proposed building a digital protection platform for textiles of ICH. Arayaphan Watsaporn [41] aimed to digitize the ancient fabric of the Museum and develop technology to visualize cultural resources on a digital platform, thus providing a virtual museum services website for collaboration and sharing collections online. Gururajan Arunkumar [42] digitized color images of stained fabrics, and the pixel values in the color and intensity planes of these images were probabilistically modeled as a Gaussian Mixture Model (GMM).

Through the analysis of existing research, it can be seen that the digitalization of ICH is diversifying, but the operability characteristics of traditional ICH processes, including textile weaving skills, have not been thoroughly explored and demonstrated. In terms of display and communication, digital media is still the main means. Digital technology has great potential in the development of traditional textile technology, and it requires further research and application.

3. Research Area and Methods

3.1. Overview of Leno Fabric

3.1.1. Leno Fabric Traceability

Leno did not originally refer to a variety of silk but to a net used by ancient ancestors as a bird catcher. In order to explore the origin and development of Leno fabrics, a large number of relics of Leno fabrics were found during visits and research of textile collections and restored replicas in museums in Jiangsu Province, Henan Province, Hubei Province, Hunan Province, and other places. The earliest Suzhou Leno Fabric can be traced back to about 6000 years ago. The wild fabric was excavated at the Neolithic site of Cao Shoe Mountain in Suzhou, Jiangsu Province (Figure 1) [43], and collected in Suzhou Cao Shoes Mountains Archaeological Site Park. The Yang Shao site was then unearthed containing re-colored Leno fabric from more than 5600 years ago in Henan Xing Yang County, Qing Tai Village (Figure 2) [44], which was collected in the China Silk Museum. This was the earliest mulberry silk twisted warp fabric found in history, and it remains the earliest silk fabric found in the world to date. Traces of intricate roving were found on the silk fabric fragments used to wrap the surface of the objects in the tomb of Fu Hao at Yin Xu from the Shang Dynasty in 1300 B.C. [45]. Suzhou Leno Fabric in the pre-Qin period had become an important cultural symbol of status and wealth, as well as a popular fabric for the upper class. The Hubei Jiangling Masan No. 1 Chu tomb excavated in the mid-Warring States held dragon and phoenix tiger embroidery Leno (Figure 3) [46], collected in Jingzhou Museum, which is typical of Leno in the embroidery of silk fabrics. After the Qin and Han dynasties, Leno fabrics became more and more exquisite. Han Dynasty Leno, in addition to plain Leno, has appeared alongside jacquard Leno, especially in Hunan Changsha Ma Wang Dui, excavated during the Han Dynasty. "Diamond pattern Leno" (Figure 4) [47], collected in Hunan Provincial Museum, is the earliest and most complete Leno fabric preserved today.

Figure 1. Rib Ko hemp cloth unearthed from Cao Shoe Mountain in Wu Xian.

Figure 2. A reddish-colored roving fabric excavated from the Yang Shao site in Qing Tai Village, Xing Yang County, Henan.

Figure 3. Embroidered Leno with dragon, phoenix, and tiger patterns.

Figure 4. Lozenge pattern Leno.

3.1.2. Structural Organization

Today's fabric histology applies to the definition of Leno organization. Leno is a weaving method and structure, wherein the fabric wefts parallel each other, while the warp is divided into two groups (twisted warp and ground warp), twisted with each other with the weft interwoven [48]. The twisted fabric was originally a knitted fabric, but especially in today's woven fabric produced under loom fabric conditions, it has increasingly become a knitted fabric. It is a twisted type with at least one axis system in the line of travel of slender objects, strips, ropes, threads, yarns, etc. The twisted warp is a warp thread that changes position back and forth, while the ground warp is a warp thread whose position does not change, thus forming an intertwist crossing and entangling at a certain twist angle to form the fabric. The twist angle of rotation can be 90°, 180°, 270°, and 360°; that is, the generalized twist angle of rotation θ formula is

$$\theta = m\frac{\pi}{2} + 2k\pi = \frac{4k+m}{2}\pi \tag{1}$$

In the formula, m is the number of twisted positions, m = 1, 2, 3, 4; k = 0, 1, 2 . . . for the circle factor, or the number of k turns around the twist. The structure of the rows constituted by different twist rotation angles θ is shown in Figure 5.

Figure 5. Structure of wring-braiding fabric with different twist angles. (**a**) Upper and lower interchange and left and right interchange; (**b**) no top and bottom change and left and right change; (**c**) no change of top and bottom and no change of left and right; (**d**) up and down and left and right.

Slewing structure when k = 0:

m = 1 (90°) is the shifted twist, corresponding to Figure 5a for the reciprocal twist with upper and lower interchange and left and right interchange.
m = 2 (180°) is the undulating twist, which corresponds to Figure 5b for the reciprocal twist with no top and bottom change and left and right change.
m = 3 (270°) is the reset twist, which corresponds to Figure 5c as the reciprocal twist with no change of top and bottom and no change of left and right.
m = 4 (360°) is the loop return twist, which corresponds to Figure 5d for the reciprocal twist of up and down and left and right.

3.1.3. Process Flow of Leno Weaving

The weaving process of Leno is complicated and fine. It can mainly be divided into 12 weaving processes: picking, soaking, winding, twisting, re-twisting, clearing, silk, shaking, twisting, warping, picking flowers, and weaving. It can be further subdivided into different processes according to different warps and weft threads (Figure 6): twisting (re-twisting), shaping, rewinding, and warping six process details; weft threads carry out and silk (initial twisting), twisting (initial twisting), shaping, rewinding, and silk (re-twisting); twisting (re-twisting), shaping, rewinding, and weft winding nine process details. Then, the warp and weft carry out the finishing process of weaving, raw inspection, refining, dyeing, and finished product inspection.

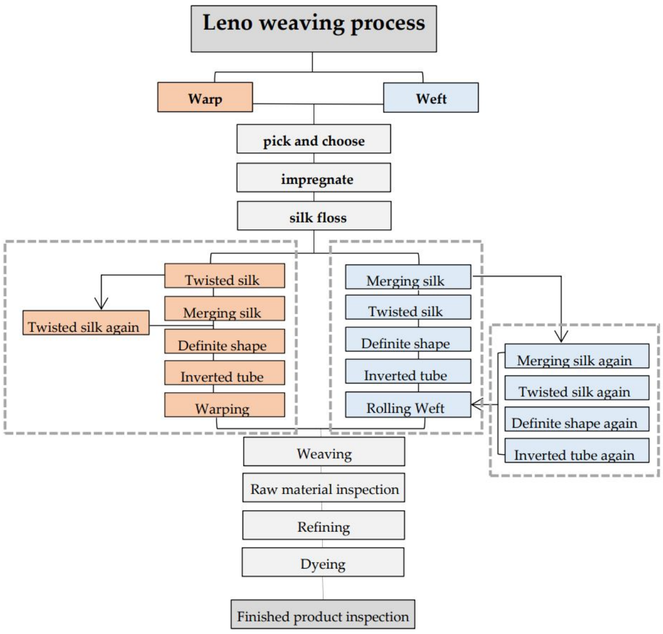
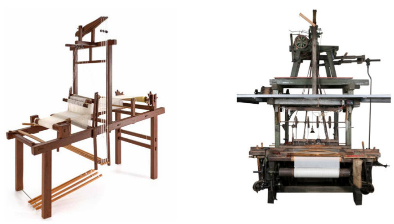


Figure 6. Process flow of Leno weaving.

The most important piece of equipment in the Leno weaving process is the loom. Traditional wooden loom (Figure 7a) structure is complex and of low production efficiency since one to two people can only weave, at most, a few dozen centimeters of fabric per day. In recent years, weaving production efficiency has been improved through the corresponding transformation of the shuttle loom by skilled workers. With modern, advanced, high-speed semi-automatic looms (Figure 7b), one person can operate six looms, producing up to thousands of meters of fabric per day. For example, Suzhou Jin Da Silk Co., Ltd. (Suzhou, China), uses shuttle looms, and the master Liqun Zhu, the inheritor of Leno weaving, even moves the loom onto a live Internet performance space to share sarong skills, science, and clothing systems with Internet users, making the domestic sales of Suzhou Leno fabric jump by 80%.



(a) (b)

Figure 7. Loom: (**a**) wooden loom; (**b**) high-speed and semi-automatic loom.

3.2. Research Methods and Technical Process

For the digital design of roving, the first step was to innovate the composition form of the traditional pattern by digital means and to recreate it with the concept and principle of modern design. The proposed methods for pattern redesign included shape grammar, split grammar, individual pattern extraction recreation, and the continuous pattern composition rule.

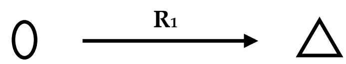
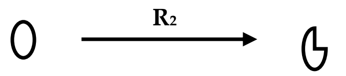
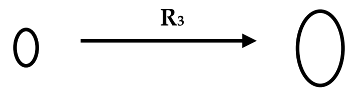
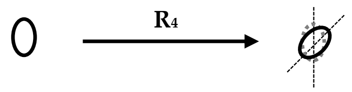
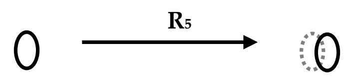
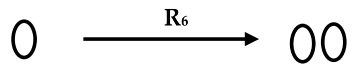
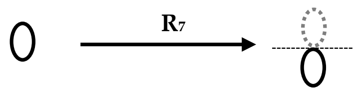
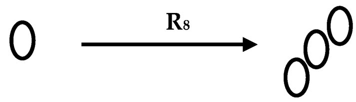
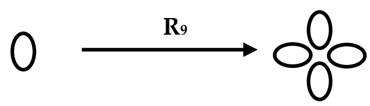
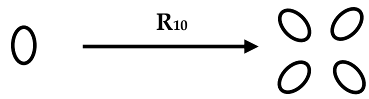
3.2.1. Pattern Generation and Derivation Principle

Digital generation of patterns is mainly combined with shape grammar for pattern inference and derivative design. Shape grammar was proposed by George Stiny and James Gips, and it was first applied in the field of painting and sculpture. Shape grammar is defined as

$$SG = (S, L, R, I) \tag{2}$$

where S denotes a finite set of shapes, L denotes a finite set of symbols, R denotes a finite set of rules, and I denotes an initial shape [49]. Shape grammar usually refers to the method of generating a new figure by recombining and arranging one or more extracted basic graphic elements as a unit, then following the corresponding inference rules. The types of inference rules include modified inference, generative inference, and derivative inference. The main rules are movement, substitution, addition, deletion, scaling, duplication, mirroring, rotation, mis-cutting, circular array, linear array, etc. (Table 1). As shown in Figure 8a, a rhombus was selected as a unit pattern and arranged symmetrically, balanced according to the shape grammar, arranged in a divergent or aggregated manner with central symmetry, or forming a suitable pattern for decoration. In this way, it decorated the chest, back (Figure 8b), shoulders, or hips of a garment with a positioning pattern, etc.

Table 1. List of shape grammar deduction rules.

Regular Shapes R	Rule Features	Rule Name	Method	Schematic
Modifying Rules	Focus on graphic shape genetics to achieve replacement innovation in form	**R_1 = Replacement**	Replace the existing shape of a figure with a part of the shape of another figure	
		R_2 = Add or delete	Add or remove part or all of the morphological curve of the initial shape	
Generative rules	Focus on the variation of graphic shapes to generate new forms	**R_3 = Reduce or enlarge**	Reduce or enlarge part or all of the curve of the initial shape	
		R_4 = Rotate	Angle transformation of the initial shape	
		R_5 = Parallel movement	Translation moves the local nodes of the initial shape in a straight line	
		R_6 = Copy	Copying the initial shape	
		R_7 = Mirror image	Mirroring of the initial shape along horizontal or vertical lines	
		R_8 = Staggered cutting	Displacement proportional to the directed distance from each point of the graph to a line parallel to that direction	
Derivative rules	Focus on combinatorial relationships of shapes to generate innovative combinatorial shapes	**R_9 = Circumferential Array**	Generate multiple shapes of one or more features in a circumferential array around an axis	
		R_{10} = Linear Arrays	One or two or more linear paths in a linear array to generate multiple shapes of one or more features	

Note: R_1, R_2, R_3—indicate different shape grammar derivation rules,  indicates the initial shape.

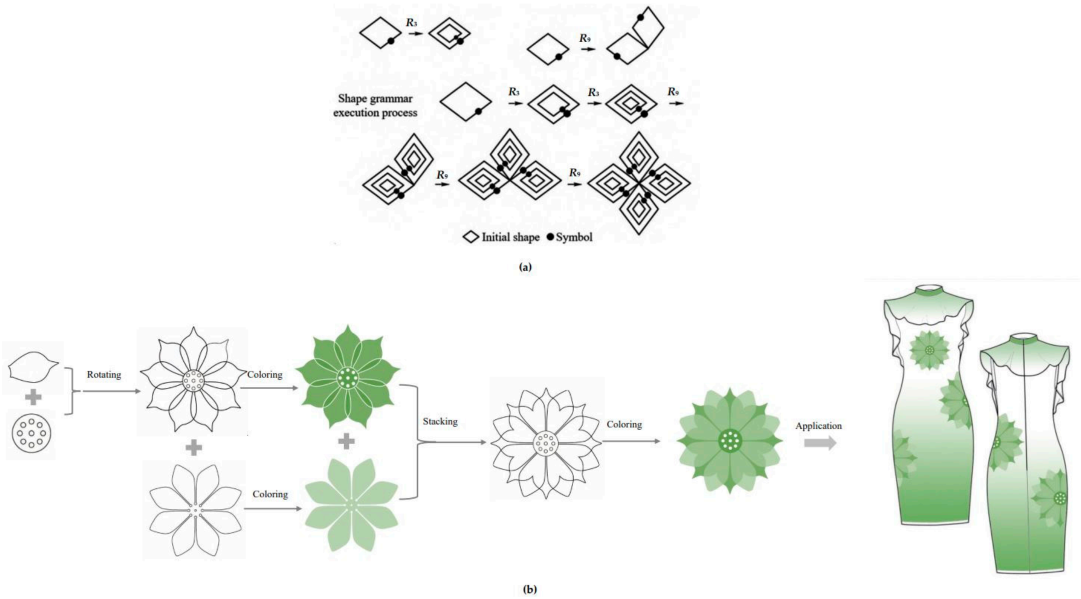


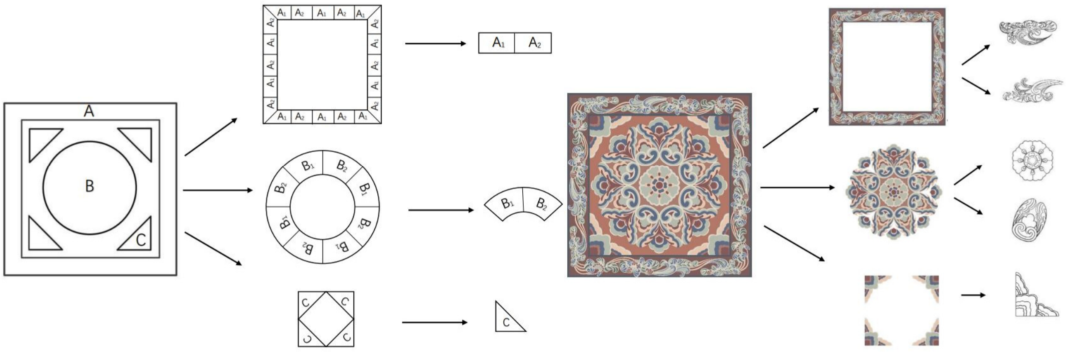
Figure 8. Shape grammar execution process and application example: (**a**) execution process; (**b**) application example.

3.2.2. Individual Pattern Extraction and Reconstruction

A monogram is a pattern composed of a single element and pattern, and the most complex pattern is composed of a single pattern unit or a single pattern that has been derived and deformed. The single pattern can be divided into symmetrical, balanced, and suitable patterns. It is the simplest pattern composition method and the most direct form of pattern application to extract the single element of a Leno fabric pattern for the decoration of clothing. Using the principle of pattern composition in the deconstruction, the elements were split into point-like, a single point, scattered combination, or symmetrical or balanced compositions for layout arrangement. This principle was mainly based on the idea of split syntax to decompose different types of individual patterns. Split syntax refers to the process of decomposing and deconstructing complex and multi-level patterns by decomposing the complete graphic structure into multiple single elements and showing their specific composition forms according to specific syntax and rules [50]. As shown in Figure 9, the circular individual pattern was deconstructed layer by layer, several different levels were fractalized, and the design elements and basic graphic elements of each level were extracted (Figure 9a). Each basic pattern could be used as the original unit pattern of the fabric to re-derive and re-deform according to the shape grammar, completing the digital pattern extraction and re-design process (Figure 9b).

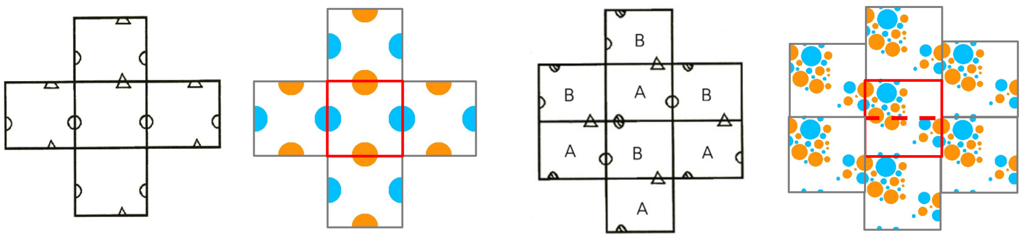
3.2.3. Continuous Pattern Filling and Combination

The prerequisite for the weaving process of patterns on knitted fabrics is the connection of patterns through the plate making process, which occurs mostly in the form of continuous patterns. A continuous pattern is divided into two-sided continuous and four-sided continuous according to the continuous mode. The two-sided continuous is the unit pattern up, down; left, right; diagonal, vertical; or horizontal or diagonal to the infinite repeated extension of the two directions, forming a band and strip decoration (Figure 10). The unit pattern repeated cycle into a strip decorative belt can be repeated in the positive direction (Figure 10a), as well as in the reverse direction. The four-sided continuous pattern unit oriented up, down, left, or right in four directions repeatedly cycle in an infinite extension, and its jointing can be divided into a flat version or a jump version (Figure 10b). At present, a two-sided continuous pattern can be applied to the piece material design of Leno fabric for apparel in collars, cuffs, waists, hems, skirts, and other band parts, using an embroidery process for decorative embellishment (Figure 11a). The formation of a continuous face of the whole pattern decoration, mostly used in the roving of the clothing of the pile material design, is suitable for fabric jacquard or printing (Figure 11b).



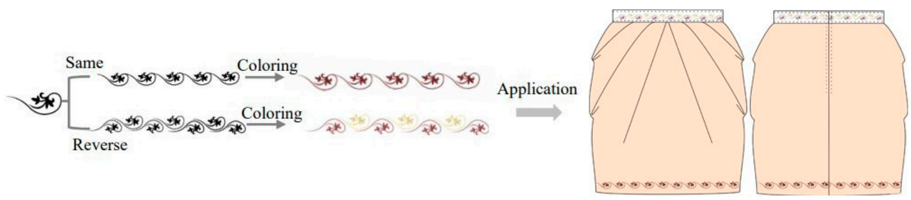
(a) (b)

Figure 9. Schematic diagram of split syntax and an application example: (**a**) execution process; (**b**) application example.

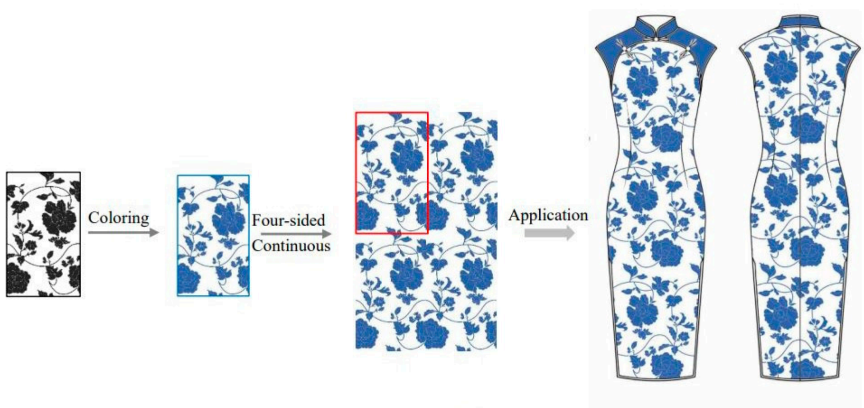


(**a**) (**b**)

Figure 10. Four-sided continuous jointing method schematic: (**a**) flat version; (**b**) jump version.



(a)



(b)

Figure 11. Two-sided continuous and four-sided continuous pattern composition and application examples: (**a**) two-sided continuous; (**b**) four-sided continuous.

4. Digital Sustainability Research Design

4.1. Digital Technology Routes

Through extensive market research, the pattern of the fabric can be digitally collected; the composition style, organization structure, and common colors of the fabric pattern are summarized; and the fabric pattern is vectorized in digital graphic drawing software. The fabric pattern element library, pattern color library, and organization structure library are constructed to realize the digital redesign and re-creation of the fabric pattern with the help of 3D virtual reality. At the same time, a library of clothing and home textile effect models and an interactive experience of different loom principles are developed. From the original pattern collection to the pattern database establishment, the research route to realize the independent synthesis and innovative application of the pattern, and the development of the digital application scheme of the Leno pattern in Figure 12, we can finally bring to life the purpose of digital pattern dissemination. Then, we can develop digital preservation standards for the traditional craft of Leno weaving and implement digital preservation of the traditional craft. This process will allow us to establish a complete database of traditional patterns and craft resources using modern technology, focus on digital empowerment, promote the inheritance and innovative design of Leno weave craft technology and patterns, further broaden the traditional craft inheritance application scenarios, and realize immersive experiences.

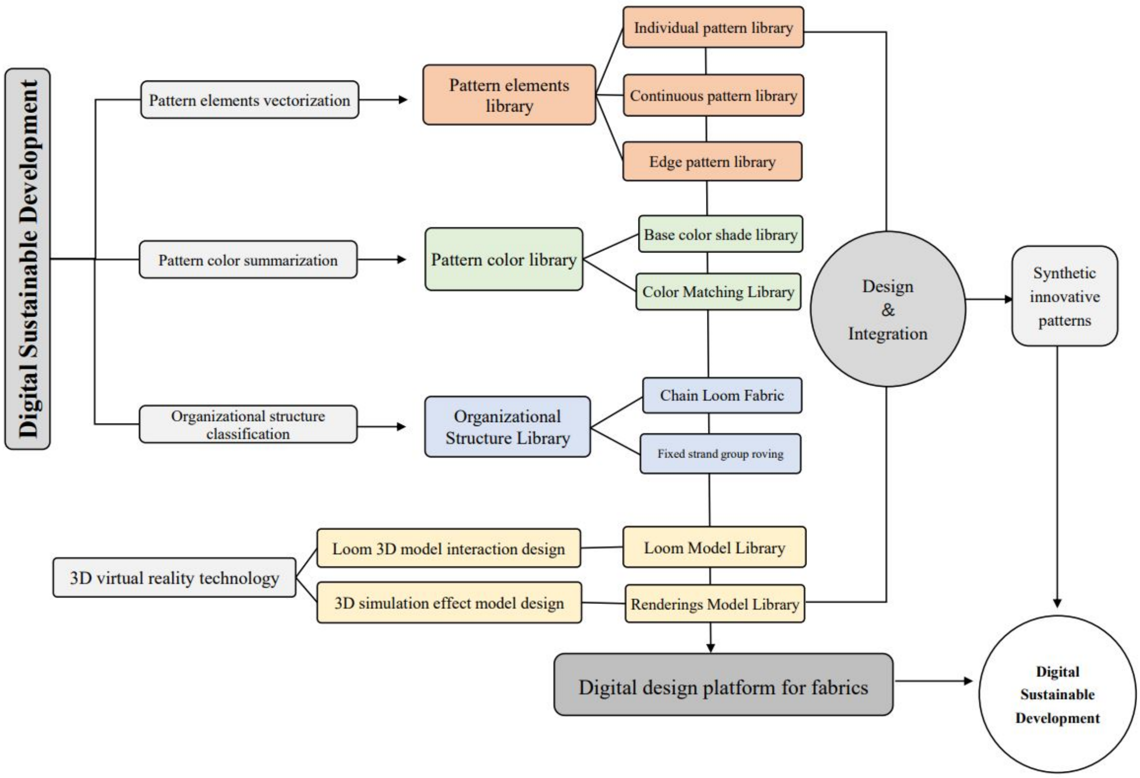


Figure 12. Digital sustainability development research program.

4.2. Establishment of the Digital Resources Library

4.2.1. Construction of the Digital Pattern Element Library

By fractalizing the unit pattern of Chinese traditional Leno patterns and deriving the element shapes, a pattern element library was established, as shown in Figure 13, including an individual pattern library, continuous pattern library, and edge decoration pattern library.

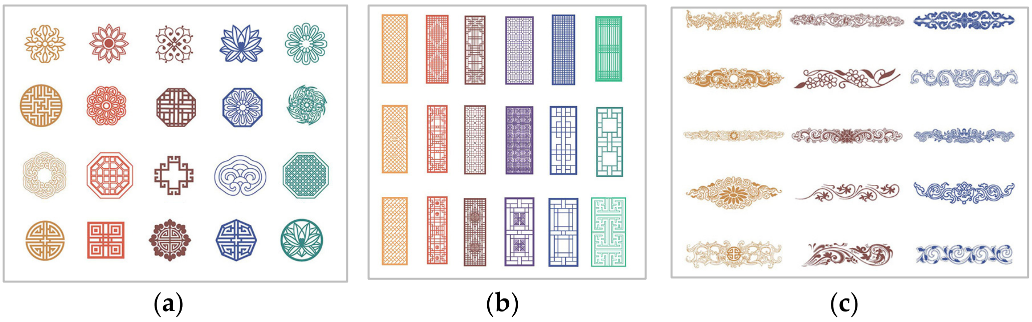
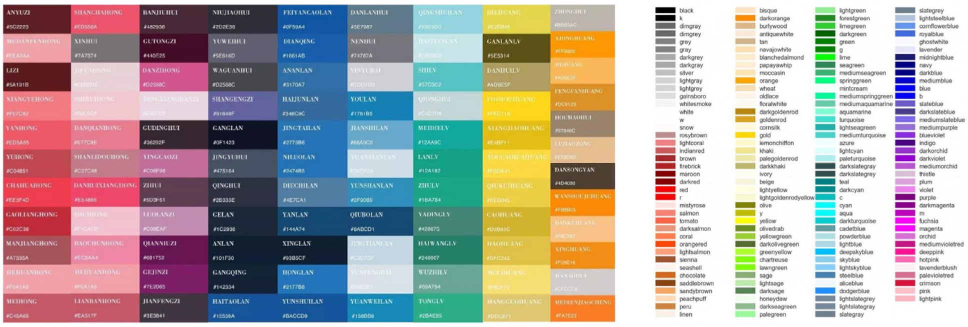


Figure 13. Graphic element library. (**a**) Individual pattern library; (**b**) continuous pattern library; (**c**) edge pattern library.

(1) The central outline of the individual pattern library was mostly round or square and filled with various plants, animals, and figures such as lotus, poinsettia, group flowers, dragons, phoenixes, etc., for decoration (Figure 13a). These can be divided into one-fourth symmetry, one-sixth symmetry, and one-eighth symmetry according to the symmetrical repetition unit. The central element was the visual center and focus of the whole pattern, which played a decisive role in the theme of the pattern.
(2) The continuous pattern library was the basis of the fabric decorative elements. Most of the continuous pattern was filled with geometric patterns such as "ten thousand", "back", and lattice (Figure 13b). These were mostly four-sided continuous patterns, and they could be flat or jump versions. They were rich in variation and rhythm. It was essential to pay attention to any sparse and dense pattern, as well as the area and the main pattern of the coordination relationship.
(3) The border pattern library was the edge of the fabric clothing or home textile decorative embellishment and nested border filling elements. Filling patterns are mainly S–shaped curly grass, twining plant patterns, cloud patterns, or geometric patterns of two-sided continuous patterns (Figure 13c). Furthermore, they can be designed by reconstructing, combining, superimposing, and balancing individual patterns, and play a supporting and embellishing role in the whole picture.

4.2.2. Construction of the Digital Pattern Color Library

In the process of designing the patterns, we considered the color matching of the pattern and the visual and sensory feelings brought by different color matching of the fabric. By sorting and screening the colors of traditional classic fabrics, the most representative color combination scheme was selected, and the pattern color library was established in Figure 14, which could be divided into the base color hue library and the color matching library. Figure 14a shows the hue library, based on the extraction and categorization of the common colors of the classical Leno fabric, which can be used for the filling of the base color of the fabric pattern. Figure 14b depicts the color library that, using the method of sequential gradation of hue, lightness, and purity classification, can be used for a variety of color schemes. When designing the color scheme of the base and flower of the fabric pattern, it is necessary to pay attention to the matching of colors at each level and the contrasting relationship between different parts and levels of the pattern of different processes. In addition, it is necessary to consider the proportion of the configuration of colors of different area sizes and to combine the color presentation characteristics of the fabric to assign colors to the shape and style of the pattern within the category.



(**a**) (**b**)

Figure 14. Pattern color library. (**a**) Color libraries; (**b**) color libraries.

4.2.3. Construction of a Digital Organizational Structure Library

The tissue structure of the fabric was divided into single-layer tissue and heavy tissue according to the presence or absence of weft, then according to the number of twisted warps: into two warps twisted, three warps twisted, and four warps twisted. At the same time, based on whether the pattern included jacquard, it could be divided into plain and flower Leno two, and then the comprehensive structure and warp and weft thread number continued to subdivide. Two warps contained two warps stranded chain Leno, two warps stranded a weft yarn Leno, two warps stranded odd weft Leno, and two warps stranded even weft Leno. Three warps contained three warps stranded flower Leno and three warps stranded horizontal Leno. Four warps contained four warps stranded plain Leno, four warps stranded flower Leno, and four warps stranded horizontal Leno fabric. Though shuttle class Leno fabric is usually divided according to the grain and weft color, it can also be divided into dark flower Leno, weaving gold Leno, and two-color Leno. Non-through shuttle class Leno fabric can be divided into makeup flower Leno and weaving gold makeup flower Leno. According to the standard of the weaving process, it can be divided into categories of tissue structure and built into the tissue structure database (Table 2).

Table 2. Classification of the organizational structure.

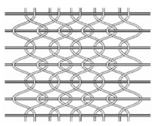
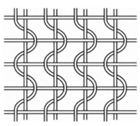
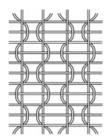
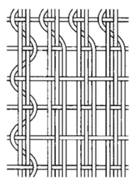
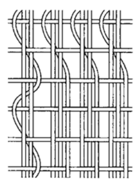
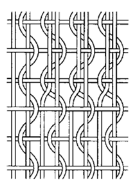
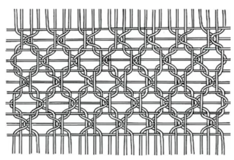
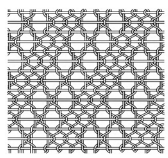
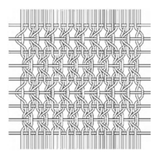
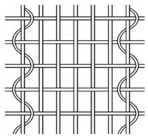
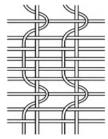
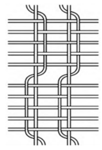
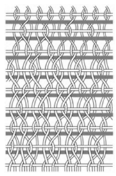
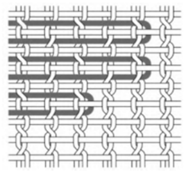
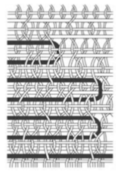
Classification	**Organizational Structure Chart**		
Structure of two-warp-twisted Leno	 Structure of two-warp-twisted Leno	 Two-warp-twisted and one-weft structure	 Even weft Leno
Structure of three-warp-twisted Leno	 Structure of three-warp-twisted figured plain weave Leno	 Structure of three-warp-twisted figured twill weave Leno	 Structure of three-warp-twisted figured hidden pattern Leno
Structure of four-warp-twisted Leno	 Structure of four-warp-twisted Leno	 Structure of four-warp-twisted figured Leno	 Structure of four-warp-twisted Leno

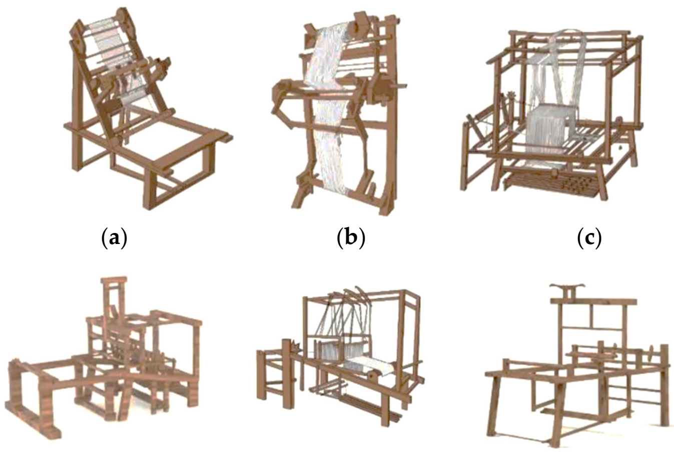
Table 2. *Cont.*

Classification	Organizational Structure Chart			
Structure of vertical/horizontal Leno	 Vertical Leno	 Special horizontal Leno	 Horizontal Leno (five-shuttle Leno)	
Structure of special process roving Leno	 Structure of the dark pattern Leno，the two-color Leno, and the golden Leno	 Structure of the golden makeup flower Leno	 Structure of two-warp-twisted makeup flower Leno	 Structure of four-warp-twisted makeup flower Leno

Note: The table is arranged differently from top to bottom for the number of warp lines, and from left to right for the latitude lines.

4.2.4. Digital Loom Interactive Experience Platform

The loom interactive experience platform design first collated different types of looms, including the oblique loom, vertical loom, multi multi-tip loom, small flower-jacquard loom, large flower-jacquard loom, and Leno weaving loom, while it established the loom restoration model library (Figure 15). The corresponding loom could be selected to simulate weaving loom fabric and provide the virtual interactive non-heritage weaving skills immersion experience, such as weaving, warping, shuttle holding weft, holding reed beating, jacquard bunching, warp splitting, shuttle weft holding, reed beating, etc.



(**a**) (**b**) (**c**)

(**d**) (**e**) (**f**)

Figure 15. Loom model library: (**a**) oblique loom; (**b**) vertical loom; (**c**) multi multi-tip loom; (**d**) small flower-jacquard loom; (**e**) large flower-jacquard loom; (**f**) Leno weaving loom.

In addition to the basic model effects of the main looms, a 3D exploded view was created to allow users to understand the components of the loom structure. The 3D virtual reality looms can be used in museums or online museum displays, where visitors can interactively experience the details of the loom weaving process and the process of weaving grosgrain, as they can with Suzhou Museum's holographic projection 3D weaving machine (Figure 16). First, the loom details appear on screen as a 3D model effect, and the user can slide left and right to view the detailed 360° model. Second, visitors can follow the prompts for loom simulation and an immersion experience. The new media form of establishing digitally simulated looms with dynamic images and interactive virtual reality enables the general audience to achieve a deeper, more intuitive, and vivid understanding of Wu Leno culture through a dynamic digital design method that allows users to participate. It can also fully display and spread the meaning and value of non-heritage culture.

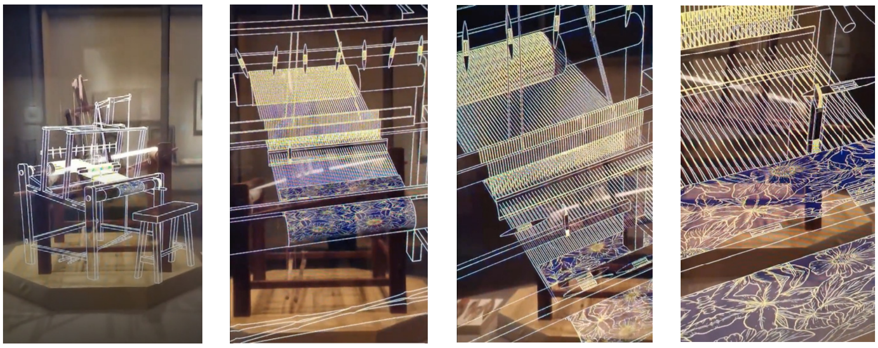


Figure 16. 3D model of a loom and simulation of the weaving process.

4.2.5. Construction of the Digital Effect Model Library

In the digital design of Leno fabric, new interpretations and dissemination of three-dimensional traditional patterns of loom fabric have been developed to expand the scope of product applications in apparel, home textiles, cultural and creative products, interior decoration, public art, and other fields. A more intuitive, three-dimensional display pattern in clothing and clothing applications can be achieved with the help of 3D virtual reality technology to establish a simulation pattern products model library (Figure 17). The model library was established considering its use in clothing products, including pants, skirts, scarves, ties, shoes, hats, bags, home textiles, etc., based on the need for real-time simulation of patterns. Patterns can be scaled up or down to simulate products, and the application effect of the pattern design can be displayed in real-time.

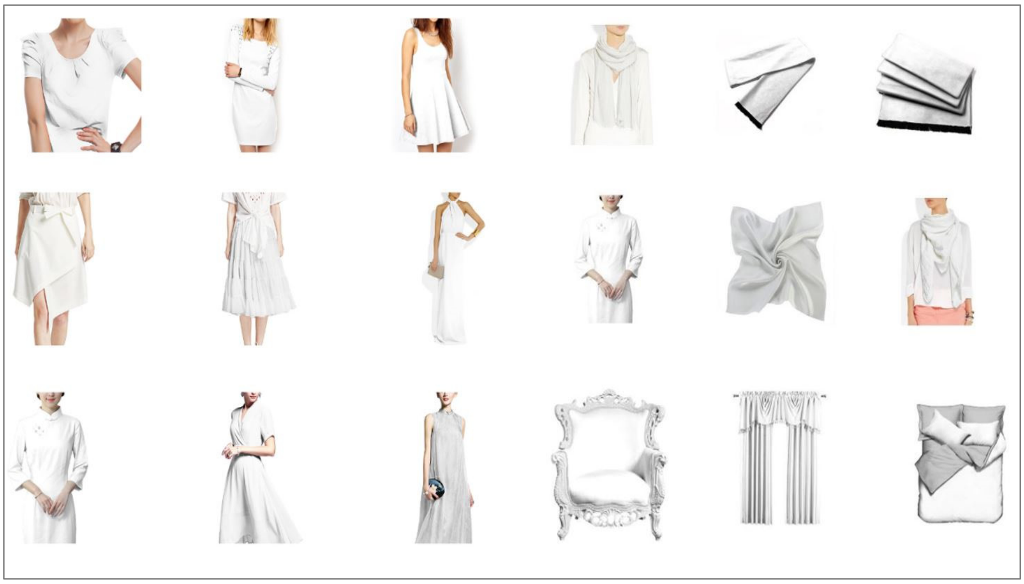
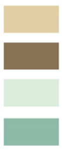
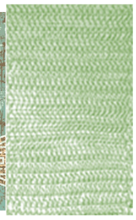
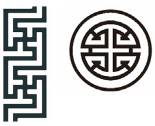
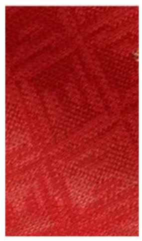
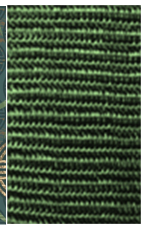


Figure 17. Simulation using the 3D model library.

4.3. Digital Innovation Design and Application Process

The innovative design and application process of Leno fabric includes five major parts: combining elements, color matching, pattern design, organizational structure, weaving fabric samples, and simulating the application effect. The specific digital design and application process are shown in the three cases in Table 3. The first step is to determine the pattern elements of the fabric, select the individual pattern from the pattern element library, and combine different individual patterns, continuous patterns, and edge patterns. In the second step, we select the corresponding base color. The third step, according to the shape grammar and continuous pattern composition rules, is to synthesize a new pattern. The fourth step involves selecting the appropriate four warp twisted roving weave structure from the fabric structure library and using different looms to weave small samples of fabrics. The fifth step determines the Leno fabric pattern simulation on suitable clothing apparel, such as cheongsam, dresses, silk scarfs, etc., to present the simulation application effect, thus achieving the Leno fabric digital design to the digital application process. This study used digital graphic design software to vectorize the patterns and establish a digital pattern library. On this basis, the pattern elements could be freely combined with modern design methods and principles to realize interactive design synthesis. Three-dimensional virtual reality technology was used to complete the digital simulation application of textile products.

Table 3. Digital innovation design and application process.

	Combined Elements	Color Matching	Pattern Design	Organizational Structure	Fabric Samples	Simulation Effects
1						
2						
3						

Note: The table shows the different design solutions from top to bottom and the steps of digital design and application from left to right.

5. Conclusions

In this study, we attempted to explore the visualization and promotion of "Wu Leno" weaving techniques in Suzhou and to promote the digital dissemination and sustainable development of intangible cultural heritage and traditional textile craft culture. At the same time, the use of digital technology to create new intangible cultural heritage content and to create a new environment for display and dissemination was not only in line with the characteristics of the times and new media but also created a new digital experience with contemporary flavor and characteristics.

In conclusion, through interdisciplinary, cross-fertilization research methods, the innovative design application of traditional Chinese intangible cultural heritage weaving techniques using modern digital technology was shown to promote the sustainable development of traditional textile techniques in contemporary times. Thus, its cultural, allegorical, and aesthetic values can be inherited and continued. This study will have far-reaching significance for the promotion and dissemination of Chinese traditional culture.

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