Textile & Leather Review

ISSN 2623-6281 | www.tlr-journal.com | 10.31881/TLR

The Optimization of Functional Textile Structures and Their Aesthetic Performance Based on Digital Weaving Technology

Wan Chen

How to cite: Chen W. The Optimization of Functional Textile Structures and Their Aesthetic Performance Based on Digital Weaving Technology. Textile & Leather Review. 2026; 9:4600-4627. https://doi.org/10.31881/TLR.2026.4600

How to link https://doi.org/10.31881/TLR.2026.4600

Published:27 April 2026

This work is licensed under a Creative Commons Attribution-ShareAlike 4.0 International License

The Optimization of Functional Textile Structures and Their Aesthetic Performance Based on Digital Weaving Technology

Wan Chen

Nanhai Academy of Art, Haikou University of Economics, Haikou 570100, Hainan, China
13322023067@163.com

Article
https://doi.org/10.31881/TLR.2026.4600
Published 27 April 2026

ABSTRACT

The rapid development of intelligent manufacturing and digitalization has promoted the wider application of digital weaving technology in the textile industry, while the simultaneous optimization of functional performance and aesthetic quality in textile structures remains a major challenge. This study aims to address this issue by integrating multi objective optimization algorithms with digital weaving processes to develop a design method that enhances both mechanical and aesthetic properties of fabrics. Using polyester and cotton blended yarns as the research materials, the study applies parameterized digital weaving, genetic algorithms, and particle swarm optimization to adjust key structural variables including yarn density, weaving angle, and fiber blending ratio. The fabrics produced under the optimized design are evaluated through standardized mechanical, comfort related, and aesthetic tests. The results show notable improvements in tensile strength and breathability, a reduction in bending stiffness that reflects enhanced flexibility, and measurable gains in color uniformity, texture finesse, and tactile comfort when compared with a traditionally woven control sample. These findings confirm that the coordinated adjustment of structural parameters, particularly the interaction between yarn density and a 45 degree twill weave, plays a central role in achieving a balanced enhancement of functionality and aesthetic performance. The study concludes that the proposed design framework based on digital weaving provides an effective approach for the development of high performance textiles with improved aesthetic appeal, supporting advanced manufacturing, personalized customization, and potential applications in areas such as sportswear and medical textiles.

KEYWORDS
digital weaving technology, functional textile structures, structural optimization, aesthetic performance, intelligent manufacturing

INTRODUCTION

As global manufacturing transitions towards intelligent and digital models, the textile industry faces dual challenges of technological innovation and market demand. The emergence of digital weaving technology has brought about revolutionary changes, particularly in the design and application of functional textiles[1][2]. Functional textile materials not only serve basic wearability but also meet specialized demands such as antibacterial, breathable, and waterproof properties[3]. However, existing functional textile structures are often focused on a single function, and their integration of structural optimization with aesthetic performance is limited, which restricts their application in high-end markets[4,5]. Therefore, achieving a balance between functionality and aesthetics remains a core challenge in the textile field.

Current design methods for functional textile structures can be broadly classified into two categories: one based on traditional weaving techniques and the other utilizing modern numerical simulation and optimization algorithms for structural design[6]. Traditional weaving techniques are simple, low-cost, and easy to operate but lack flexibility and diverse functionality, particularly when it comes to balancing functionality and aesthetics[7]. Although modern numerical simulation technologies and optimization algorithms offer more possibilities, their complexity and high computational costs limit their practical application in production[8]. Furthermore, most existing research focuses on improving material functionality while neglecting aesthetic performance, resulting in insufficient market competitiveness[9]. Although some scholars have attempted to optimize designs through intelligent weaving technology, research on enhancing aesthetic performance while optimizing functionality remains insufficient. Therefore, how to enhance the aesthetic effect of textiles while optimizing functionality remains an unresolved issue.

The innovation of this study lies in the proposal of a functional textile structure optimization method based on digital weaving technology, achieving dual improvements in both functionality and aesthetics. The specific innovations include: first, digital weaving technology, constructing an innovative multi-functional fabric design framework that optimally integrates fabric structure and function through a digital weaving process, overcoming the limitations of traditional techniques; second, structural optimization, optimizing functional textiles with a focus on aesthetics, ensuring functionality while enhancing aesthetic performance to meet the demands of the high-end market; and third, intelligent design, integrating artificial intelligence and digital design to enhance the customization ability of textiles, optimizing the design process through smart algorithms to improve efficiency and precision, and promoting the development of personalized customization.

This research is of significant theoretical and practical value. From a theoretical perspective, this study proposes a multi-dimensional optimization framework based on digital weaving technology, providing new insights for the field of textile design and advancing research on the integration of functionality and aesthetic performance. From a practical perspective, the innovative methods proposed in this study offer new technical pathways for the development of high-end functional textiles, with broad application prospects in intelligent manufacturing and personalized customization. By organically combining functionality and aesthetics, this research provides theoretical foundations and technical support for the technological transformation and market expansion of the textile industry, driving high-quality industry development.

Related Works

Application Scenarios and Challenges

As an important research area in the textile industry, functional textiles have evolved from simply meeting basic wearability needs to developing intelligent, high-performance, and multifunctional materials with technological advancements[10,11]. Modern functional textiles are widely used in fields such as healthcare, sports, and aerospace, with significant potential, especially in the development of smart textiles and high-performance materials[12]. For instance, in the sports sector, textiles need not only good breathability and moisture absorption but also antibacterial and waterproof properties to suit various complex sporting environments[13]. In healthcare, smart textiles can enable functions such as health monitoring and drug release, providing patients with real-time health monitoring and treatment[14]. Despite the great potential of functional textiles in various fields, achieving a balance between functionality and aesthetics remains a significant challenge in their design.

Currently, textile design mainly focuses on enhancing a single function, while optimizing multiple functions and aesthetic performance remains an unresolved issue. Most existing functional textile design methods concentrate on optimizing physical properties such as wear resistance, tensile strength, and flexibility[15,16]. However, these methods often neglect aesthetic requirements, which leads to a lack of market competitiveness. Although research into intelligent and multifunctional textiles has increased in recent years, systematic design addressing both functional and aesthetic requirements remains underexplored. Existing datasets primarily evaluate single functions, and there is a lack of publicly available resources that simultaneously consider functionality and aesthetic performance, posing significant challenges to multidimensional textile optimization.

Overview of Mainstream Methods

The design methods for functional textiles can generally be divided into traditional craftsmanship and modern optimization algorithms. Traditional craftsmanship involves adjusting yarn arrangements and weaving techniques through experience to enhance fabric strength, comfort, and protective performance[17]. However, when faced with complex functional requirements and aesthetic balance, traditional methods fall short, offering insufficient flexibility and diversity, especially in the design of high-performance textiles.

Modern optimization algorithms have gradually become core tools in the design of functional textiles. Techniques such as genetic algorithms and particle swarm optimization enable researchers to optimize various functions of fabrics, such as water resistance, breathability, and wear resistance, to meet different application needs[18,19]. However, these methods often rely on extensive computation and simulations, resulting in high computational costs and limited practical application in large-scale production, especially when high aesthetic standards are required.

Aesthetic design has recently become a hotspot in textile research, focusing on aspects such as fabric appearance, texture, and color. While modern design methods, such as computer-aided design (CAD) and digital weaving technologies, offer optimization techniques, existing methods typically optimize only a single aesthetic factor, ignoring the coordination of different aesthetic elements[20,21]. Although some research has attempted to combine aesthetics and functionality in design, these methods have failed to effectively consider the synergistic optimization of both aspects. How to organically integrate functionality and aesthetics remains a major challenge in design.

Most Similar Research

Among existing studies, several have made progress in the design and optimization of functional textiles. For example, some studies have proposed optimization methods based on digital weaving technology, using computer simulations to optimize fabric structures and improve their functionality[22,23]. Some studies have employed numerical optimization techniques to adjust fabric weaving structures, enhancing properties such as durability and comfort[24]. However, most of these studies have focused on functional optimization and have not explored the integration of aesthetic design. Therefore, while these studies have achieved significant results in enhancing functionality, there remains a significant gap in optimizing the aesthetics and overall performance of textiles.

In contrast to these studies, the approach proposed in this paper, which integrates digital weaving technology with structural optimization, focuses on the dual enhancement of functionality and aesthetics. By digitally designing and optimizing the fabric structure, this study not only considers the physical properties of textiles but also systematically addresses aesthetic performance, particularly in terms of texture, color, and tactile feel, filling the gap in existing research.

Summary and Research Gaps

Despite some progress in the design and optimization of functional textiles, there remains a lack of in-depth exploration of the concurrent optimization of functionality and aesthetics[25]. Most existing research focuses on enhancing the functionality of textiles, with insufficient consideration of aesthetic performance. Particularly in high-end markets, consumers' aesthetic demands for textiles are increasing, and balancing functionality with aesthetic performance has become a pressing issue in textile design. Therefore, this study aims to fill this gap by using digital weaving technology and intelligent optimization algorithms to achieve dual optimization of functionality and aesthetics, and proposes a comprehensive optimization design framework. Unlike existing studies, this paper not only focuses on enhancing functionality but also systematically explores aesthetic design, particularly through innovative design of fabric texture, color, and tactile feel, to meet the modern market's demand for high-performance and aesthetically pleasing products. Through these innovations, this research provides new theoretical support and technical pathways for textile design, advancing the technological progress of textile design.

METHODOLOGY

Problem Formulation

The optimization objectives in functional textile design typically involve multiple dimensions, requiring consideration of both functionality (e.g., strength, flexibility, breathability) and aesthetic performance (e.g., texture, color, tactile feel). This study optimizes both functionality and aesthetics through digital weaving technology, proposing a comprehensive design framework and defining the research problem in mathematical terms.

First, the optimization variables for functional textile design are defined as x , where each x_i represents the design parameters of the fabric, such as yarn density, weaving angles, and material selection[26]. The objective is to adjust these design parameters x to optimize the functional metrics of the fabric, such as tensile strength and breathability.

In constructing the objective function, functionality and aesthetic performance are treated as two primary optimization goals[27]. Functional metrics and aesthetic metrics represent the fabric's physical properties and aesthetic effects (such as appearance, texture, and tactile feel), respectively. These two metrics are combined through a weighted sum to form the overall objective function. The goal of this study is to maximize this integrated objective function, achieving the optimal balance between functionality and aesthetics.

To ensure the feasibility of the design results, several constraints are defined. The range of design variables is constrained by production process feasibility and physical boundaries, such as yarn density and fabric thickness[28]. Additionally, both functionality and aesthetic metrics need to meet minimum requirements. For example, tensile strength must reach a certain standard, and color difference and texture effects should meet the basic aesthetic requirements of the market.

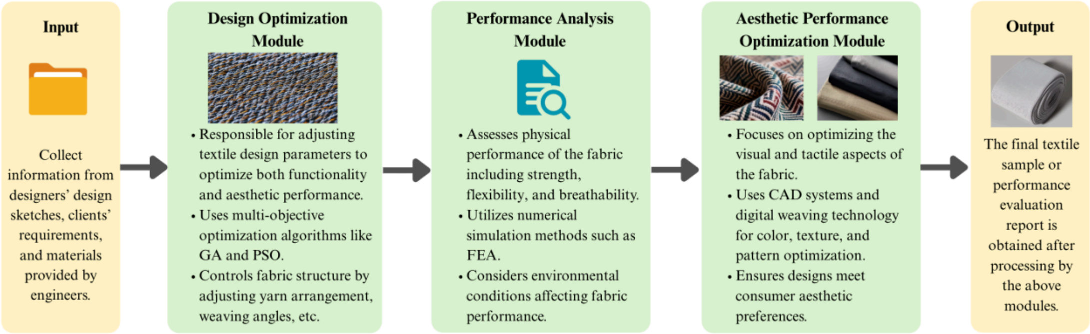
In summary, this study achieves the dual optimization of functionality and aesthetics by adjusting design parameters x , while ensuring the design meets production process and cost constraints, providing theoretical support for subsequent computational methods and experimental validation.

Overall Framework

The textile design framework proposed in this study aims to optimize both functionality and aesthetic performance through digital weaving technology. The overall architecture consists of three core modules: the design optimization module, the performance analysis module, and the user-perceived quality optimization module. To maintain scientific neutrality and ensure objective quantification, the broad concept of "aesthetics" in textile design is specifically defined and measured throughout this study's methodology as "user-perceived quality."

First, the design optimization module is responsible for inputting design parameters and performing multi-objective optimization, adjusting the fabric structure to meet both functional and aesthetic requirements. This module uses digital weaving technology to optimize functional metrics such as strength, breathability, and comfort by adjusting parameters like yarn arrangement and fabric weaving methods. The performance analysis module then evaluates the physical performance of the optimized fabric to ensure it meets design requirements, such as tensile strength and flexibility, while calculating the corresponding performance data. Finally, the user-perceived quality optimization module focuses on the fabric's sensory design, utilizing CAD technology to objectively optimize the fabric's texture, color uniformity, and tactile feel, ensuring the fabric's appeal in both visual and tactile aspects.

The core goal of the entire framework is to achieve a balance between functionality and aesthetics. By optimizing design parameters and evaluating results, the fabric is able to meet the multiple demands of practical applications. The framework diagram illustrates the relationship between the data flow and modules, clearly showing the flow of input and output data, as well as how the modules work together to achieve the final optimization objective. A feedback mechanism is triggered if evaluation results fall below predefined thresholds. For example, if the mechanical strength drops below the original baseline or the user-perceived quality score falls below 3.0/5.0, the system automatically reverts to the design module for iterative parameter adjustment until these constraints are satisfied. Through this framework, the design process can effectively integrate multidimensional requirements, providing a comprehensive optimization solution for textile production.(See figure 1)



Collect information from designers' design sketches, clients' requirements, and materials provided by engineers.

- Responsible for adjusting textile design parameters to optimize both functionality and aesthetic performance.
- Uses multi-objective optimization algorithms like GA and PSO.
- Controls fabric structure by adjusting yarn arrangement, weaving angles, etc.

- Assesses physical performance of the fabric including strength, flexibility, and breathability.
- Utilizes numerical simulation methods such as FEA.
- Considers environmental conditions affecting fabric performance.

- Focuses on optimizing the visual and tactile aspects of the fabric.
- Uses CAD systems and digital weaving technology for color, texture, and pattern optimization.
- Ensures designs meet consumer aesthetic preferences.

The final textile sample or performance evaluation report is obtained after processing by the above modules.

Figure 1. Integrated textile design framework for multi-objective optimization of functionality and aesthetics through digital weaving

Module Descriptions

The framework of this study consists of the design optimization module, performance analysis module, and aesthetic performance optimization module, each playing a crucial role in optimizing both functionality and user-perceived quality. Below is a detailed description of each module.

Design Optimization Module

Motivation:

The design optimization module serves as the core of the system, utilizing advanced multi-objective algorithms to adjust fundamental textile parameters. By overcoming the single-function limitations of traditional methods, it establishes the essential structural foundation required for subsequent functional and visual enhancements.

Principle:

This module uses multi-objective optimization algorithms, such as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO), to find the optimal balance between multiple design objectives. Through digital weaving technology, the fabric structure can be precisely controlled by adjusting parameters such as yarn arrangement and weaving angles, specifically targeting structural integrity and fundamental mechanical properties such as strength and flexibility.

Implementation:

This module optimizes design parameters through a CAD system and numerical optimization algorithms. The specific steps include: inputting initial design parameters, utilizing optimization algorithms for multi-objective optimization, adjusting the design scheme, outputting optimized results, and passing them to other modules for further analysis and validation.

Performance Analysis Module

Motivation:

The core task of the performance analysis module is to assess the physical performance of the fabric and ensure it meets basic functional requirements such as strength, flexibility, and breathability. Even after the design optimization is completed, the performance in real-world applications must still be validated to ensure product feasibility and stability.

Principle:

This module employs numerical simulation methods, such as Finite Element Analysis (FEA), based on textile principles, to simulate and evaluate the fabric's mechanical performance. It includes metrics such as tensile strength, bending resistance, and wear resistance, evaluating the fabric's physical performance under strictly controlled baseline laboratory conditions to ensure reproducible functional validation.

Implementation:

The performance analysis module first receives the output from the design optimization module and uses FEA to construct a digital model of the fabric, performing multi-dimensional performance simulations. The performance data is fed back to the design optimization module for further adjustments, ensuring that the fabric's physical properties meet the predetermined standards.

User-Perceived Quality Optimization Module

Motivation:

As the market's demand for textile aesthetics increases, this module is dedicated exclusively to elevating the fabric's visual and tactile properties. It focuses on the precise coordination of tactile feel, texture, and color to ensure strong market competitiveness.

Principle:

This module uses a CAD system in conjunction with digital weaving technology to optimize the fabric's color, texture, and structure. By simulating the fabric's appearance, it ensures that the user-perceived quality of the fabric not only meets design standards but also aligns with consumer aesthetic preferences.

Implementation:

The user-perceived quality optimization module inputs the fabric's design parameters and aesthetic requirements, then uses digital weaving technology to optimize the weaving method, color matching, and texture. The optimized design is shared with the design optimization and performance analysis modules through a feedback mechanism, ensuring the final product strictly meets the visual and tactile design standards.

Summary

These three modules work in close collaboration. The design optimization module adjusts basic structural parameters, the performance analysis module ensures physical reliability in practical applications, and the aesthetic module focuses on visual and tactile appeal. Through their integrated action, this study provides a highly efficient and comprehensive textile design optimization framework.

Objective Function & Optimization

In the design of functional textiles, optimization objectives typically involve multiple dimensions, requiring consideration of both the fabric's functionality (such as strength, flexibility, breathability) and its user-perceived quality (such as texture, color, and tactile feel). This study establishes a mathematical model to perform multi-objective optimization of the design parameters, aiming to achieve the optimal balance between functionality and aesthetics.

Objective Function

The design parameter vector is denoted as $x = (x_1, x_2, ..., x_n)$, where each x_i represents a design parameter of the fabric, such as yarn arrangement density, weaving angles, and material selection. The optimization goal is to maximize both functionality and user-perceived quality, and the objective function $f(x)$ is expressed as a weighted combination of multiple objective functions:

$$f(x) = \lambda_1 f_1(x) + \lambda_2 f_2(x) \tag{1}$$

where $f_1(x)$ represents the functionality metric, indicating fabric properties like strength and breathability; $f_2(x)$ represents the aesthetic metric, indicating properties like appearance, tactile feel, and color; and λ_1 and λ_2 are the weighting coefficients used to balance the two objectives.

Functionality Metrics

The functionality metric $f_1(x)$ focuses on the fabric's physical properties, such as tensile strength, flexibility, and breathability. The functionality objective function is defined as:

$$f_1(x) = w_1 S(x) + w_2 T(x) + w_3 P(x) \tag{2}$$

where $S(x)$ represents tensile strength, $T(x)$ indicates flexibility, and $P(x)$ is the breathability metric. w_1 , w_2 , w_3 are the weighting coefficients. Each performance metric is calculated as follows:

$$S(x) = f_1(x_1, x_2, ..., x_n) \tag{3}$$

where $S(x)$ is related to yarn density, weaving angles, and other design parameters.

$$T(x) = f_2(x_1, x_2, ..., x_n) \tag{4}$$

where $T(x)$ is related to yarn elasticity and fabric structure.

$$P(x) = f_3(x_1, x_2, ..., x_n) \tag{5}$$

where $P(x)$ is related to yarn material and fabric density.

User-Perceived Quality Metrics

The user-perceived quality metric $f_2(x)$ primarily focuses on the fabric's appearance, texture, color, and tactile feel. The aesthetic objective function is defined as:

$$f_2(x) = a_1 C(x) + a_2 W(x) + a_3 D(x) \tag{6}$$

where $C(x)$ represents color effects, $W(x)$ indicates texture effects, and $D(x)$ represents tactile effects. a_1, a_2, a_3 are the corresponding weighting coefficients.

$$C(x) = f_4(x_1, x_2, ..., x_n) \tag{7}$$

where $C(x)$ is related to yarn color, weaving density, and other factors.

$$W(x) = f_5(x_1, x_2, ..., x_n) \tag{8}$$

where $W(x)$ is influenced by weaving angles, yarn thickness, etc.

$$D(x) = f_6(x_1, x_2, ..., x_n) \tag{9}$$

where $D(x)$ is related to fiber materials and fabric density.

Constraints

To ensure the feasibility of the design results, several constraints are established, covering functionality, production processes, and cost requirements. The constraints are as follows:

$$g_i(x) \leq 0, \quad i = 1, 2, ..., m \tag{10}$$

where $g_i(x)$ represents the constraint on the design parameters x . For example, the tensile strength must exceed a certain threshold:

$$g_1(x) = S(x) - S_{\min} \leq 0 \tag{11}$$

Other constraints include breathability, color difference, texture effects, etc.

Additionally, the range of design variables x is defined as:

$$x_{\min} \leq x_i \leq x_{\max}, \quad i = 1, 2, ..., n \tag{12}$$

These ranges reflect the physical limitations of textile design, such as yarn density, fabric thickness, etc.

Optimization Model

The final optimization problem can be expressed as:

$$\max_{x} f(x) = \lambda_1 f_1(x) + \lambda_2 f_2(x) \tag{13}$$

subject to:

$$g_i(x) \leq 0, \quad x_{\min} \leq x_i \leq x_{\max} \tag{14}$$

By adjusting the design parameters x , this study aims to maximize the objective function $f(x)$ for functionality and aesthetics while satisfying all constraints.

Optimization Methods

This study employs GA and PSO to solve the above optimization problem. These algorithms can effectively handle multi-dimensional, multi-objective optimization problems, making them suitable for the complex design space in textile design. The optimization steps include initializing the population or particles, evaluating fitness, updating design parameters, and continuing the process until the predefined convergence criteria are met (detailed hyperparameters are provided in Section Experimental Materials and Equipment).

EXPERIMENT AND RESULTS

Experimental Design and Methods

Experimental Materials and Equipment

In this study, polyester fiber (PET) and cotton fiber were selected as the yarn materials to compare their performance in functionality and aesthetics. Polyester fiber, known for its high strength and wear resistance, is suitable for applications with high mechanical performance requirements, while cotton fiber, renowned for its excellent breathability and comfort, is ideal for applications with high demands on touch and aesthetics[29]. All yarns used had a fineness of 1.5 dtex and were woven using a blended method. The experimental equipment is divided into three categories, as shown in Table 1.

Table 1. Experimental Materials and Key Equipment List

Category	Name/Model	Main Functions and Parameters
Weaving Equipment	Digital Weaving Machine (Model DT-200)	Programmable control of yarn density (5–50 ends/cm), weaving angle (0°–90°), and fabric structure
Design Software	Computer-Aided Design System (CAD: TextileDesign Pro)	Fabric structure simulation, parameter optimization, and aesthetic effect preview
Performance Testing Equipment	Tensile Testing Machine (Instron 5967)	Tensile strength testing according to ASTM D5035
	Air Permeability Tester (FX3300)	Breathability testing according to ISO 9237
	Color Difference Meter (Color i7)	Color difference measurement (ΔE) according to CIELAB standard
	Bending Stiffness Tester (Handle-O-Meter)	Flexibility testing according to ASTM D1388
	Martindale Abrasion Tester	Abrasion resistance testing according to ISO 12947

Note: All tests were conducted under standard laboratory conditions (temperature 20±2°C, relative humidity 65±4%) to ensure the comparability and reproducibility of the results.

Design Parameters and Optimization Settings

This experiment selected three key design variables that significantly impact both fabric functionality and aesthetics: yarn arrangement density (5–50 ends/cm), weaving angle (0° plain weave, 45° twill, 60° satin), and yarn material (polyester/cotton blend ratio). The impact mechanisms and optimization goals of each parameter are summarized in Table 2.

Table 2. Key Design Parameters and Their Impact Mechanisms

Parameter	Impact Mechanism	Optimization Goal
Yarn Arrangement Density	Higher density enhances mechanical interlock between yarns, improving strength but potentially reducing flexibility and breathability	Balance strength and comfort
Weaving Angle	Angle changes alter yarn interlacing, affecting stress distribution, pore continuity, and surface texture	Co-enhance mechanical performance and aesthetic expression
Yarn Material	Polyester contributes to strength and durability, while cotton enhances breathability and tactile comfort	Achieve synergistic effects between functionality and aesthetics

To find the optimal parameter combination under multi-objective constraints, this study utilized Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) for automatic optimization. The algorithms were based on the objective functions and constraints established in Section Objective Function & Optimization. Through iterative updates of populations (GA) or particle positions (PSO), the algorithms search for designs that simultaneously maximize functional metrics (tensile strength, breathability, flexibility) and aesthetic metrics (color, texture, tactile feel). During the optimization process, weaving angle and yarn density were identified as the most sensitive variables, and their collaborative optimization was key to achieving the balance between functionality and aesthetics. To ensure the computational reproducibility of this study, the specific algorithmic hyperparameters for both GA and PSO were carefully configured based on preliminary testing and standard engineering optimization practices. The detailed settings are summarized in Table 3. Specifically, a linear decreasing inertia weight strategy was employed for PSO to balance global exploration and local exploitation. For both algorithms, the optimization process was set to terminate either when the maximum number of iterations (200) was reached or when a predefined convergence criterion was met, namely, when the change in the multi-objective fitness value remained less than 10^{-4} for 20 consecutive iterations.

Table 3. Hyperparameter configurations for GA and PSO

Algorithm	Parameter	Value / Setting
GA	Population Size	100
GA	Maximum Generations	200
GA	Crossover Probability (P_c)	0.85
GA	Mutation Probability (P_m)	0.05
GA	Selection Method	Tournament Selection (Size = 3)
PSO	Swarm Size (Population)	50
PSO	Maximum Iterations	200
PSO	Inertia Weight (w)	Linear decrease from 0.9 to 0.4
PSO	Cognitive Constant (c_1)	1.5
PSO	Social Constant (c_2)	1.5
Common	Convergence Criteria	Fitness improvement $< 10^{-4}$ over 20 consecutive iterations

Performance Testing and Evaluation Methods

To comprehensively assess the performance of the optimized fabric in terms of both functionality and aesthetics, this study conducted systematic performance testing based on international standards, covering four major dimensions: mechanical performance, comfort, durability, and aesthetic characteristics. The details of the testing items, methods, and evaluation goals are summarized in Table 4.

Table 4. Fabric Performance and User-Perceived Quality Testing Methods

Testing Category	Testing Item	Testing Method and Equipment	Evaluation Goal
Mechanical Performance	Tensile Strength	Standard tensile testing machine (Instron 5967), tested according to ASTM D5035	Measure the maximum tensile force of the fabric, verifying if mechanical properties are improved by the optimization design
Comfort	Breathability	Air permeability tester (FX3300), tested according to ISO 9237	Evaluate air permeability, reflecting the fabric's comfort in applications such as sports and healthcare
Flexibility and Durability	Bending Stiffness (Flexibility)	Bending stiffness tester (Handle-O-Meter), tested according to ASTM D1388	Characterize fabric softness, with lower values indicating better flexibility
	Abrasion Resistance	Martindale abrasion tester, tested according to ISO 12947	Assess the fabric's durability under repeated friction
User-Perceived Quality	Color Uniformity	Color difference meter (Color i7), measured according to CIELAB standard (ΔE value)	A smaller ΔE indicates higher color consistency and stability
	Texture Effects	Image processing technology combined with blind evaluation by three textile experts (1–5 rating scale)	Qualitative analysis of fabric surface uniformity and texture finesse
	Tactile Comfort[30]	Standardized sensory tests (10 participants, 1–5 rating scale) or tactile evaluation instruments	Quantify fabric skin-friendliness and softness

Note: All tests were conducted under standard laboratory conditions (temperature 20±2°C, relative humidity 65±4%) to ensure the comparability and reproducibility of the results.

Data Analysis and Verification

The test results of each optimized design were subjected to statistical analysis, using methods such as mean values and standard deviation to compare the performance of different design schemes. Statistical significance differences in functionality and aesthetics between optimization schemes were verified using t-tests or analysis of variance (ANOVA). The experimental results were compared with theoretical optimization results to verify the actual effectiveness of the optimization method.

Fabric Samples and Experimental Results

In this section, we present the schematic diagrams of the optimized and control fabric samples, and compare their performance in terms of functionality and aesthetics using experimental data.

Sample Description

This study established two fabric samples: the control group and the optimized group, to compare the differences in functionality and aesthetics between traditional weaving methods and the digital weaving optimization strategy proposed in this study.

The control group adopted the traditional plain weave technique, with fixed design parameters: yarn arrangement density of 20 ends/cm, weaving angle of 0° (plain weave), and a polyester/cotton blend ratio of 50:50. The optimized group, based on the multi-objective optimization framework established in Chapter 3, used GA and PSO to search for the optimal solution in the parameter space. The final design parameters for the optimized group were: yarn arrangement density of 32 ends/cm, weaving angle of 45° (twill), and a polyester/cotton blend ratio of 60:40.

Both groups used 1.5 dtex polyester/cotton blended yarns, with fabric dimensions of 30 cm × 30 cm, woven in the same temperature and humidity environment (20±2°C, 65±4% RH) to ensure consistency in experimental conditions and the comparability of results.

It is important to note that the performance improvement of the optimized group was not solely due to the change in weaving angle from plain weave to twill, but rather a result of the synergistic optimization of yarn density, weaving angle, and material blend ratio. The core advantage of digital weaving technology lies in its ability to precisely and repeatedly implement such multi-variable coupling complex structures, whereas traditional methods are limited in simultaneously adjusting multiple parameters to achieve a global optimal state.(See figure 2)

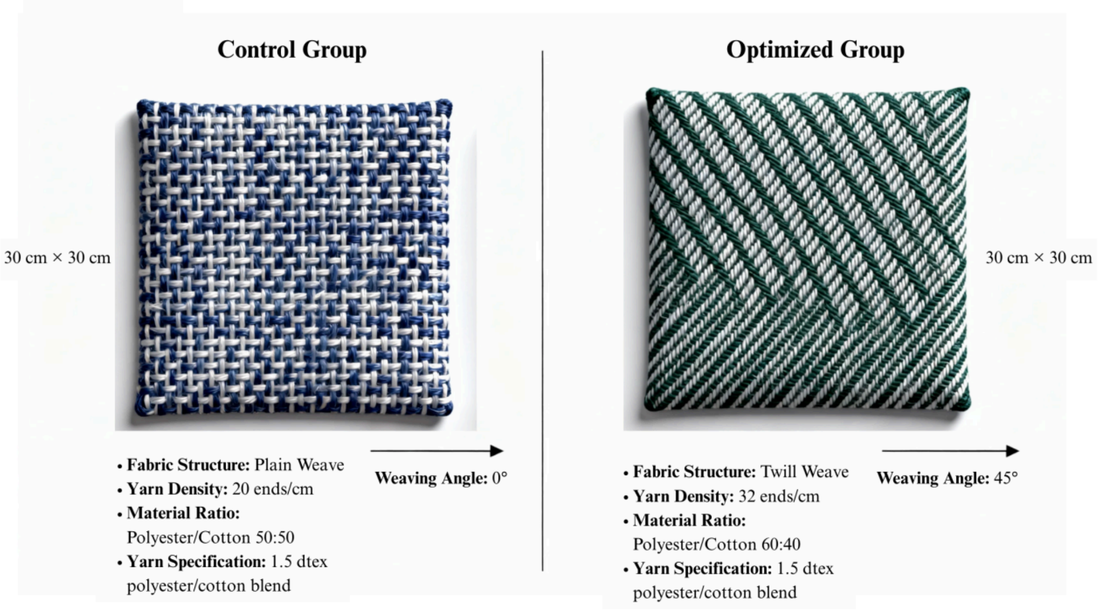


Figure 2. Schematic Diagrams of Optimized and Control Fabric Samples

Functionality Data

To quantitatively evaluate the effectiveness of the optimized design, we compared key functionality metrics between the optimized and control groups, focusing on tensile strength, flexibility (represented by bending stiffness), and breathability. The performance test results of the two groups are summarized in Table 5.

Table 5. Comparison of Functional Metrics Between Optimized and Control Groups

Performance Metric	Control Group (Traditional Design)	Optimized Group (Digital Weaving Optimization)	Change (%)
Tensile Strength (MPa)	2.1 ± 0.1	2.5 ± 0.1	+19.0%
Bending Stiffness (N/mm)	4.2 ± 0.2	3.4 ± 0.2	−19.0%
Breathability (mm/s)	3.5 ± 0.2	4.0 ± 0.2	+14.3%

Note: Data is presented as mean ± standard deviation (n = 5).

Control Group Parameters: Yarn density 20 ends/cm, 0° plain weave, PET/Cotton = 50:50;

Optimized Group Parameters: Yarn density 32 ends/cm, 45° twill, PET/Cotton = 60:40.

As shown in Table 5, compared to the control group, the optimized group demonstrated significant improve-ments in both tensile strength and breathability. Tensile strength increased from 2.1 MPa to 2.5 MPa, a 19.0% increase; breathability improved from 3.5 mm/s to 4.0 mm/s, a 14.3% increase. At the same time, the bending stiffness of the optimized fabric decreased by 19.0% (from 4.2 N/mm to 3.4 N/mm), indicating a significant improvement in flexibility, making the fabric softer to the touch.

These results confirm that through digital weaving technology combined with multi-objective optimization algorithms to adjust yarn density and weaving angle, the fabric's comfort and performance can be effectively improved without sacrificing mechanical properties, making it more suitable for applications that require high strength, breathability, and tactile feel, such as high-end sportswear and functional medical textiles.

Aesthetic Evaluation Results

To systematically evaluate the user-perceived quality of the fabrics, this study quantitatively compared the optimized and control groups based on three aesthetic dimensions: color uniformity, texture effects, and tactile comfort. Color uniformity was measured by the color difference meter (ΔE value according to the CIELAB standard); the lower the ΔE, the better the color consistency and stability. Texture effects were evaluated qualitatively by three textile experts based on surface uniformity and finesse (1-5 rating scale). Tactile comfort was assessed through standardized sensory tests (10 participants) or tactile evaluation instruments (1-5 rating scale). The aesthetic evaluation results of the two groups are compared in Figure 3, with specific data shown in Table 6.

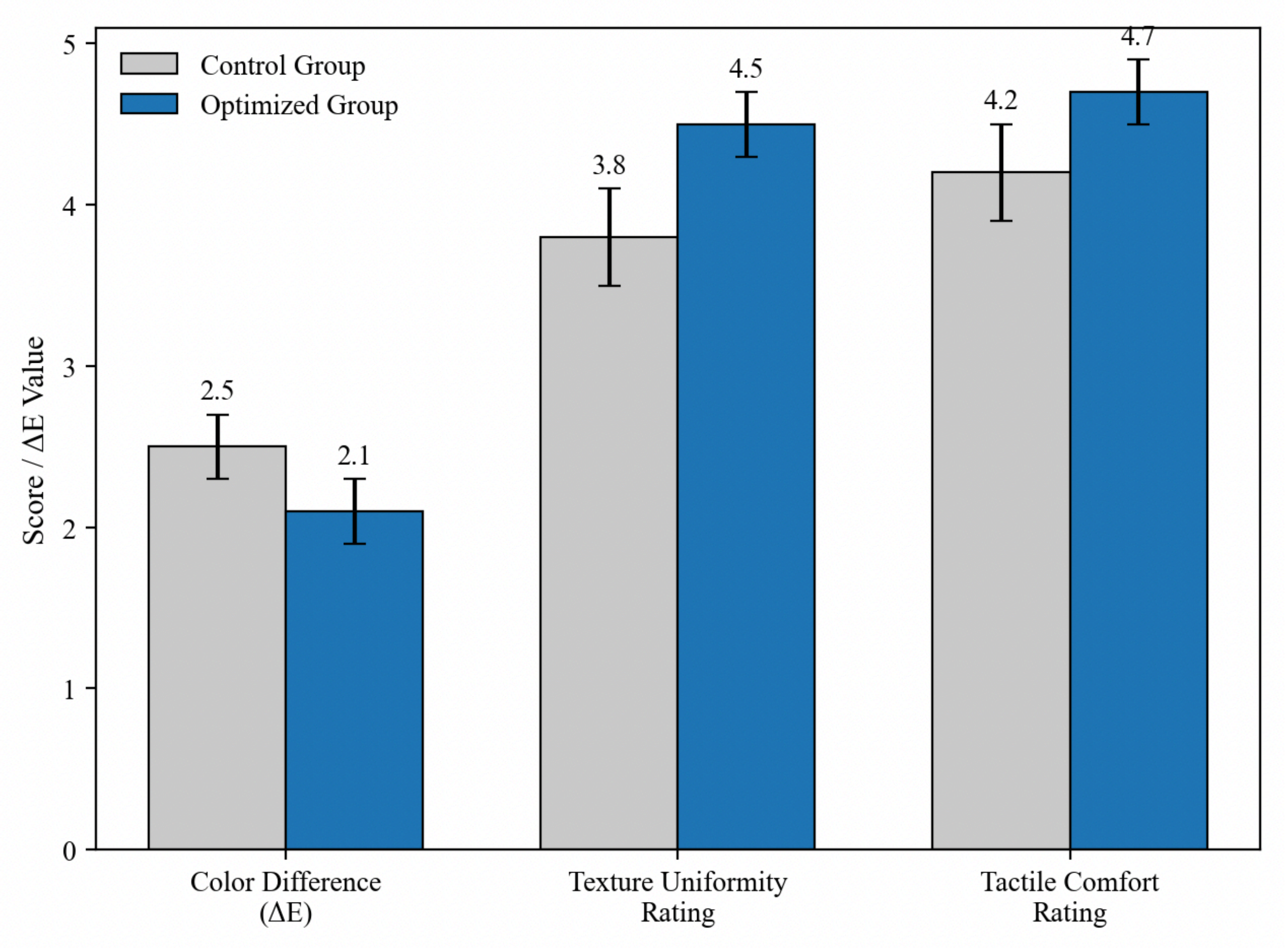


Figure 3. Comparison of scores on various indicators between the control group and the optimized group

Table 6. Comparison of User-Perceived Quality Metrics Between Optimized and Control Groups

Aesthetic Metric	Control Group (Traditional Design)	Optimized Group (Digital Weaving Optimization)	Improvement (%)
Color Difference ΔE (CIELAB)	2.5 ± 0.2	2.1 ± 0.2	−16.0%
Texture Uniformity Rating (1-5 scale)	3.8 ± 0.3	4.5 ± 0.2	+18.4%
Tactile Comfort Rating (1-5 scale)	4.2 ± 0.3	4.7 ± 0.2	+11.9%

As shown in Table 6 and Figure 3, the optimized group outperformed the control group in all aesthetic metrics. Specifically, the ΔE value of the optimized fabric decreased from 2.5 to 2.1, a reduction of 16.0%, indicating significant improvements in color uniformity and stability. In terms of texture performance, the average rating for the optimized group increased from 3.8 to 4.5, an improvement of 18.4%, demonstrating that digital weaving optimization effectively enhanced the surface uniformity and finesse of the fabric. Additionally, the tactile comfort rating improved from 4.2 to 4.7, a 11.9% increase, reflecting the enhanced softness and skin-friendliness of the optimized fabric.

These results collectively demonstrate that the digital weaving optimization method proposed in this study not only significantly improved the fabric's functional performance but also achieved systematic improvements in aesthetic dimensions such as color, texture, and tactile comfort. This makes the fabric more aligned with the high-end market's comprehensive requirements for product appearance and comfort.

Results Analysis and Discussion

In this section, we delve into the advantages of the optimized design based on experimental results and discuss the comprehensive impact of design parameters such as yarn density and weaving angle on fabric performance. Through a comparison with traditional methods and a sensitivity analysis, we further demonstrate the potential of digital weaving technology in textile design.

Collaborative Optimization Mechanism Analysis

Based on the parameter sensitivity heatmap (Figure 4), this study found a significant synergistic effect between yarn density and weaving angle. Increasing yarn density improves tensile strength (due to increased friction and load-bearing yarns), but it also leads to an increase in bending stiffness and a harder tactile feel. This contradiction can be mitigated by optimizing the weaving angle: when a 45° twill weave is used, the yarn float length increases, and the interlacing points are more evenly distributed, resulting in a more uniform distribution of tensile stress and effectively releasing bending stress through a local sliding mechanism. This results in a significant reduction in bending stiffness while maintaining a high level of strength. The twill structure thus provides greater deformability, macroscopically improving both flexibility and tactile feel.

Figure 4 further shows that, under the 45° twill weave, the fabric achieves an optimal balance between tensile strength (2.5 MPa) and tactile comfort score (4.7). This verifies the key role of weaving structure in coordinating mechanical and user-perceived quality.

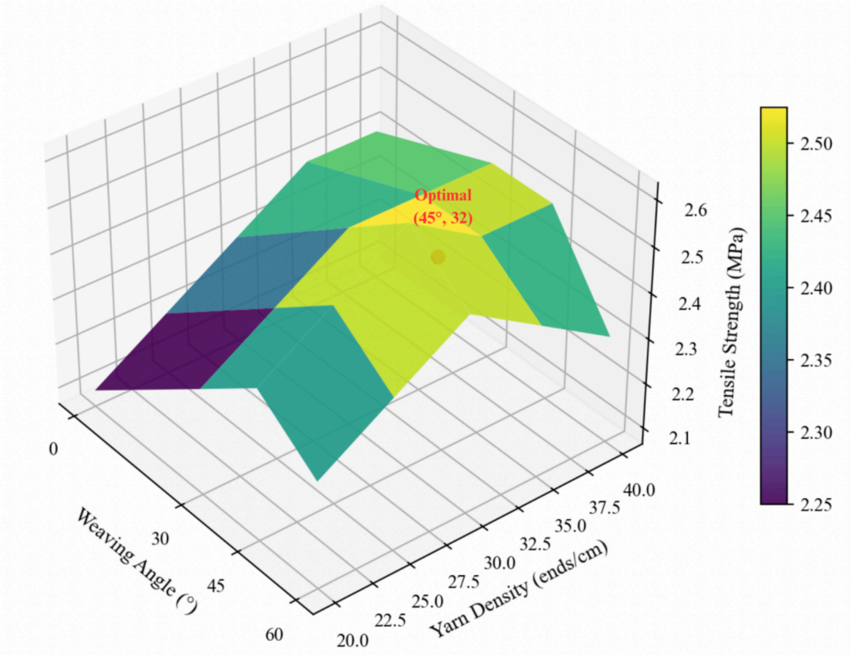


Figure 4. Collaborative optimization of yarn density and weaving angle for tensile strength, with peak performance at 45° twill

In summary, yarn density dominates basic mechanical strength, while the weaving angle governs flexibility and surface properties by adjusting the spatial configuration of yarns. The synergy between the two is the core structural mechanism for achieving integrated enhancement of both functionality and aesthetics, providing theoretical support for intelligent textile design.

Comparison with Traditional Methods

This study systematically compared the optimized digital weaving design with the traditional weaving control group in terms of functionality, aesthetics, and statistical significance.

In terms of functionality, the optimized group had a tensile strength of 2.5 MPa, a 19.0% increase compared to the control group (2.1 MPa) ($p = 0.003$). The breathability was 4.0 mm/s, an increase of 14.3% compared to the control group (3.5 mm/s) ($p < 0.05$), which was due to the enhanced mechanical interlocking from the increased yarn density and the continuous pore channels formed by the 45° twill weave.

In terms of aesthetics, the optimized group showed a 16.0% improvement in color uniformity ($\Delta E = 2.1$ vs. $\Delta E = 2.5$) ($p < 0.05$); the texture rating increased from 3.8 to 4.5 (+18.4%); and the tactile comfort rating increased from 4.2 to 4.7 (+11.9%), indicating that the optimization significantly improved fabric surface uniformity, smoothness, and softness.

All these differences were confirmed to be statistically significant through independent sample t-tests (see Table 7), including tensile strength ($p = 0.003$), breathability ($p < 0.05$), color difference ΔE ($p < 0.05$), and texture rating ($p < 0.05$), thus eliminating the impact of random variation.

Table 7. Statistical Test Results of Performance Differences Between Optimized and Control Groups

Performance Metric	p-value	Significance
Tensile Strength (MPa)	0.003	Significant
Breathability (mm/s)	<0.05	Significant
Color Difference ΔE (CIELAB)	<0.05	Significant
Texture Uniformity Rating (1–5 scale)	<0.05	Significant
Tactile Comfort Rating (1–5 scale)	<0.05	Significant

Note: All tests were based on two-tailed independent sample t-tests, with a significance level of $\alpha = 0.05$.

The results show that digital weaving optimization significantly outperforms traditional methods in both functionality and user-perceived quality, confirming its effectiveness and application potential in high-quality textile development.

Parameter Sensitivity Discussion

To identify the key design parameters affecting the overall performance of the fabric, this study conducted a systematic sensitivity evaluation of yarn density, weaving angle, and material selection based on heatmaps (Figure 5) and correlation analysis. The results show that the weaving angle is the most sensitive variable for regulating the balance between fabric functionality and aesthetics, with significant impacts on multiple performance metrics.

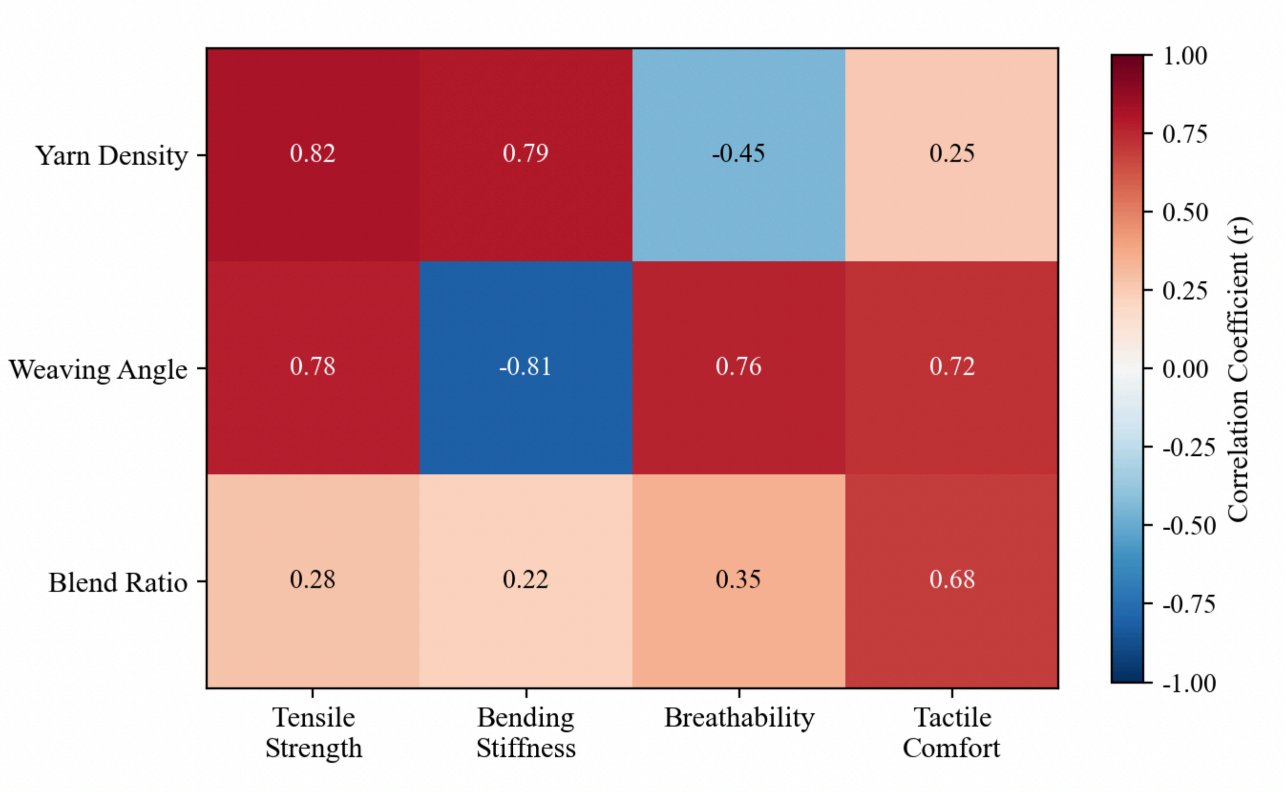


Figure 5. Parameter sensitivity heatmap showing correlation coefficients between design variables and fabric performance metrics

As shown in Figure 5, the weaving angle has a strong correlation with fabric tensile strength, bending stiffness, and breathability ($|r| > 0.75$). When the weaving angle increased from 0° (plain weave) to 45° (twill), the tensile strength increased from 2.1 MPa to 2.5 MPa (+19.0%) due to the more even distribution of yarn interlacing points in the twill structure, reducing stress concentration during loading. Bending stiffness decreased from 4.2 N/mm to 3.4 N/mm (-19.0%), corresponding to a significant improvement in flexibility, due to the increased yarn float length in the twill structure, which allows greater local sliding. Breathability increased from 3.5 mm/s to 4.0 mm/s (+14.3%) due to the continuous pore channels formed by the twill structure, which facilitate better airflow. In contrast, yarn density mainly affects tensile strength ($r \approx 0.82$) and bending stiffness ($r \approx 0.79$), with a relatively weaker effect on breathability ($r \approx -0.45$). Material selection (polyester/cotton blend ratio) primarily affects tactile feel and moisture absorption, with a lower sensitivity to mechanical properties ($r < 0.30$). Therefore, the significant 19.0% improvement in tensile strength observed in the optimized group (60:40 ratio) is predominantly driven by the structural optimization of weaving angle and yarn density, rather than the minor 10% shift in the raw material composition.

It is noteworthy that there is a significant interaction effect between weaving angle and yarn density (p_interaction < 0.05). At higher yarn densities, using a 45° twill weave significantly improves breathability and flexibility while maintaining high strength, indicating that their synergistic optimization is a crucial method for achieving multi-functional integration.

In conclusion, the weaving angle is the key control parameter connecting fabric structure to performance. By changing the spatial configuration of yarns, it directly affects mechanical performance, permeability, and surface aesthetics. The results suggest that in the design of textiles aimed at integrating functionality and aesthetics, optimizing the weaving angle should be prioritized, and its collaboration with yarn density should be fine-tuned to achieve the optimal solution under multiple constraints.

Discussion

This study, by combining digital weaving technology with multi-objective optimization algorithms, has achieved a synergistic enhancement of functional textile structures in both mechanical properties and user-perceived quality. The experimental results demonstrate that the optimized fabric shows a 19.0% and 14.3% improvement in tensile strength and breathability, respectively, while bending stiffness is reduced by 19.0%. Furthermore, user-perceived quality metrics, including color uniformity, texture finesse, and tactile comfort, also show significant simultaneous optimization. Crucially, while the optimization shifted the PET/Cotton ratio from a 50:50 baseline to 60:40, parameter sensitivity analysis confirms this material change has minimal correlation with mechanical strength ($r < 0.30$). The 19.0% strength enhancement is thus dominantly driven by the digitally optimized structural parameters, specifically yarn density ($r \approx 0.82$) and weaving angle ($\mid r \mid > 0.75$). Conventionally, increasing yarn density to improve strength inevitably compromises porosity and breathability. However, our digital optimization model reconciles this physical contradiction through mesoscopic structural decoupling rather than uniform densification. Specifically, while increased local yarn density enhances mechanical interlocking for overall strength, the optimized 45° twill weave strategically adjusts yarn float lengths and the spatial distribution of interlacing points. This precise topological arrangement creates localized load-bearing zones to withstand tensile stress, while simultaneously preserving open pore structures (micro-ventilation channels) in adjacent areas. Consequently, stress uniformity and breathability are synergistically improved without sacrificing mechanical integrity. This balance between functionality and aesthetics is achieved through the weaving angle, which plays a crucial role in controlling the performance-aesthetic equilibrium.

However, this study has certain limitations. Firstly, because our multi-objective framework optimizes material ratios concurrently with structural parameters, it inherently couples these variables. Although statistical analysis isolates their respective contributions, future studies should include strict single-variable control groups to empirically validate the algorithm's isolated effect. Secondly, the experimental materials were limited to conventional polyester/cotton blends. Additionally, sensory evaluations relied partly on subjective testing, necessitating the development of more objective quantification systems. Finally, the relatively high computational cost of the algorithms currently limits real-time design applications.

This method has significant application potential across various fields. In sports apparel, it could be used to customize mechanical and breathability performance for different scenarios; in medical textiles, it could combine with biomaterials to unify comfort and functionality; furthermore, this framework can be integrated with flexible electronics technology to provide aesthetically and functionally optimized fabric substrates for wearable devices. These applications reflect the practical value and cross-disciplinary adaptability of this method.

Future work can be expanded in three areas: first, integrating composite and smart fibers and validating the model's robustness under dynamic environmental conditions (e.g., varying temperature and humidity) to enhance functional diversity; second, developing deep learning-based aesthetic automatic evaluation models to improve the objectivity and intelligence of the design feedback loop; third, optimizing algorithm efficiency by introducing parallel computing and surrogate models to promote the application of this method in real-time design and large-scale manufacturing. Through these improvements, digital weaving technology is expected to drive textile design towards the integration of “performance-aesthetics-intelligence.”

CONCLUSION

This study addresses the key issue of the difficulty in simultaneously optimizing functionality and aesthetics in the field of functional textiles, proposing and validating a multi-objective design optimization method based on digital weaving technology. By integrating parametric modeling, multi-objective optimization algorithms, and digital weaving processes, a full-process framework from design to simulation and manufacturing was established, achieving simultaneous enhancement of fabric mechanical properties and user-perceived quality. The main innovations of this study include: the development of a multi-dimensional optimization model that simultaneously covers functionality and aesthetics; the revelation of the core role of weaving angle in balancing fabric strength, breathability, and tactile comfort; and experimental validation of the technical advantages of digital weaving in achieving precise formation of complex structures and controllable performance.

Academically, this study breaks the design paradigm in traditional textile optimization that separates functionality and aesthetics, proposing a cross-performance dimensional collaborative design method that fills the gap in the coupling mechanism between “structure-aesthetics” and the systematic optimization framework. Practically, this method provides direct technical support for developing end-use textiles that combine high performance and aesthetic appeal, especially suitable for fields such as sportswear and medical textiles, which demand both performance and appearance. It also lays the technical foundation for personalized customization and agile manufacturing in the textile industry.

In conclusion, this study provides a feasible digital methodology for the collaborative optimization of functionality and aesthetics in textile design. Looking forward, this framework is expected to integrate deeply with cutting-edge technologies such as flexible electronics and biosensors, pushing textiles from “passive functional carriers” to “active interactive systems.” At the same time, the “data-driven design” paradigm exemplified by this method can provide cross-disciplinary insights for multi-objective optimization of other materials and structural systems. Ultimately, through continuous technological iteration and interdisciplinary integration, digital weaving will not only be a manufacturing tool but also an empowering platform to achieve a high level of integration between fabric performance, aesthetics, and intelligence.

Author Contributions

The authors declare no conflict of interest.

Conflicts of Interest

The author declares no conflict of interest.

Funding

This research received no external funding.

REFERENCES

[1] Glogar M, Petrak S, Mahnić Naglić M. Digital technologies in the sustainable design and development of textiles and clothing-a literature review. Sustainability. 2025; 17(4):1371. doi: 10.3390/su17041371

[2] Abtew MA, Atalie D, Dejene BK, McBee-Black K. Intelligent and electronic textile materials for adaptive apparel: Innovations, functional design, and future directions. Journal of Industrial Textiles. 2025; 55:15280837251346789. doi: 10.1177/15280837251346789

[3] Ghosh J, Rupanty NS, Noor T, Asif TR, Islam T, Reukov V. Functional coatings for textiles: advancements in flame resistance, antimicrobial defense, and self-cleaning performance. RSC advances. 2025; 15(14):10984-11022. doi: 10.1039/D5RA01429H

[4] Zhang Y, Xia X, Ma K, Xia G, Wu M, Cheung YH, Xin JH. Functional textiles with smart properties: their fabrications and sustainable applications. Advanced functional materials. 2023; 33(33):2301607. doi: 10.1002/adfm.202301607

[5] Zhang W, Wang X, Duan J, Zheng Z, Zhang J, Hang G, Liu Z. Recent research advances in textile-based flexible power supplies and displays for smart wearable applications. ACS Applied Electronic Materials. 2024; 6(8):5429-5455. doi: 10.1021/acsaelm.4c00606

[6] Cui C, Nazlina S. Integrating Genetic Algorithms with Biotechnological Insights for the Application of Chinese Traditional Geometric Patterns in Modern Textile Design. Journal of Commercial Biotechnology. 2024; 29(3):364-376.

[7] Dejene BK, Gudayu AD. Exploring the potential of 3D woven and knitted spacer fabrics in technical textiles: A critical review. Journal of Industrial Textiles. 2024; 54:15280837241253614. doi: 10.1177/15280837241253614

[8] Krzywanski J, Sosnowski M, Grabowska K, Zylka A, Lasek L, Kijo-Kleczkowska A. Advanced computational methods for modeling, prediction and optimization-a review. Materials. 2024; 17(14):3521. doi: 10.3390/ma17143521

[9] Krabbe AD, Grodal S. The aesthetic evolution of product categories. Administrative Science Quarterly. 2023; 68(3):734-780. doi: 10.1177/00018392231173677

[10] Pu J, Ma K, Luo Y, Tang S, Liu T, Liu J, Tao X. Textile electronics for wearable applications. International Journal of Extreme Manufacturing. 2023; 5(4):042007. doi: 10.1088/2631-7990/ace66a

[11] Kumar NR. Evolution of Flexible Electronics in Textiles. In Sustainable Finishing Techniques in Textiles. Singapore: Springer Nature Singapore. 2025; pp. 215-240. doi: 10.1007/978-981-96-4860-3_11

[12] Hassabo AG, Elmorsy H, Gamal N, Sediek A, Saad F, Hegazy BM, Othman H. Applications of nanotechnology in the creation of smart sportswear for enhanced sports performance: Efficiency and comfort. Journal of Textiles, Coloration and Polymer Science. 2023; 20(1):11-28.

[13] Cui G, Wang C. Applications and development trends of textile materials in sports: A review. Alexandria Engineering Journal. 2025; 126:491-506. doi: 10.1016/j.aej.2025.04.094

[14] Deng Z, Guo L, Chen X, Wu W. Smart wearable systems for health monitoring. Sensors. 2023; 23(5):2479. doi: 10.3390/s23052479

[15] Azani MR, Hassanpour A. Electronic textiles (E-Textiles): Types, fabrication methods, and recent strategies to overcome durability challenges (washability & flexibility). Journal of Materials Science: Materials in Electronics. 2024; 35(29):1897. doi: 10.1007/s10854-024-13347-0

[16] Althagafy K, Alhashmi Alamer F. Metal-coated textiles in composite materials: advances in manufacturing techniques, properties, and applications. Cellulose. 2025; 1-25. doi: 10.1007/s10570-025-06587-8

[17] Luo Y, Wechkama T. The Longzhou Zhuang Brocade: Evaluation of the Tactile Sensation of Machine-Woven and Handmade Fabrics. Journal of Roi Kaensarn Academi. 2024; 9(9):96-109.

[18] Liu Y, Kim K. An artificial-intelligence-driven product design framework with a synergistic combination of Genetic Algorithm and Particle Swarm Optimization. Soft Computing-A Fusion of Foundations, Methodologies & Applications. 2023; 27(23). doi: 10.1007/s00500-023-09223-4

[19] Liu S, Liu YK, Lo KYC, Kan CW. Intelligent techniques and optimization algorithms in textile colour management: a systematic review of applications and prediction accuracy. Fashion and Textiles. 2024; 11(1):13. doi: 10.1186/s40691-024-00375-x

[20] Wang Y. Modern Design Intelligent Training Assistance Platform based on Lingnan Architectural Image Generation Algorithm. IJSEA International Journal of Science and Engineering Applications. 27.

[21] Ye L. Design and manufacturing of mechanical parts based on CAD and CAM technology. Engineering Research Express. 2024; 6(4):045411. doi: 10.1088/2631-8695/ad8056

[22] Zhao Q. Algorithm Optimization and Innovative Design of Digital Inheritance System for Miao Family Weaving Handicraft in South Sichuan Province. J. COMBIN. MATH. COMBIN. COMPUT. 2025; 127:7171-7195. doi: 10.61091/jcmcc127b-391

[23] Yu B, Fang L, Luo L, Hu X, Shen C. A study on service-oriented digital twin modeling methods for weaving workshops. Machines. 2024; 12(8):542. doi: 10.3390/machines12080542

[24] Perera YS, Muwanwella RMHW, Fernando PR, Fernando SK, Jayawardana TSS. Evolution of 3D weaving and 3D woven fabric structures. Fashion and Textiles. 2021; 8(1):11. doi: 10.1186/s40691-020-00240-7

[25] Schwarz I, Rogale D, Kovačević S, Firšt Rogale S. A multifunctional approach to optimizing woven fabrics for thermal protective clothing. Fibers. 2024; 12(4):35. doi: 10.3390/fib12040035

[26] Mitra A. Application of multi-objective optimization on the basis of ratio analysis (MOORA) for selection of cotton fabrics for optimal thermal comfort. Research journal of textile and apparel. 2022; 26(2):187-203. doi: 10.1108/RJTA-02-2021-0021

[27] He Z, Tran KP, Thomassey S, Zeng X, Xu J, Yi C. Multi-objective optimization of the textile manufacturing process using deep-Q-network based multi-agent reinforcement learning. Journal of Manufacturing Systems. 2022; 62:939-949. doi: 10.1016/j.jmsy.2021.03.017

[28] Abdelmohsen S, Massoud P. A material-based computation framework for parametric design education. Open House International. 2021; 46(3):459-475. doi: 10.1108/OHI-02-2021-0043

[29] Shahid MA, Okyay N, Babaarslan O. A comparative analysis of denim fabric performances from cotton/polyester blended rigid and stretched yarns. Fibers. 2024; 12(10):86. doi: 10.3390/fib12100086

[30] Tadesse MG, Loghin C, Dulgheriu I, Loghin E. Comfort evaluation of wearable functional textiles. Materials. 2021; 14(21):6466. doi: 10.3390/ma14216466