

Robotic and automated integration of drawing-in and reeding techniques: Advancing fabric design innovation, structural precision, and aesthetic–functional performance

Abstract

The rapid digital transformation of textile manufacturing is reshaping conventional weaving processes through the integration of robotics, automation, machine learning, and computational modeling. Within this transformation, drawing-in and reeding constitute critical pre-weaving operations that directly influence warp arrangement, yarn distribution, fabric architecture, structural accuracy, and the resulting aesthetic and functional properties of woven fabrics. However, these operations are frequently treated as separate processes, creating a technological gap in their coordinated optimization and limiting opportunities for precision-oriented fabric engineering.

This study develops and experimentally evaluates an integrated robotic and automated framework for drawing-in and reeding aimed at improving fabric design innovation, structural precision, and aesthetic–functional performance. The framework investigates the interactions between three drawing-in systems straight, point, and skip drafting and three reeding configurations—single, double, and grouped denting. Mathematical and computational modeling is employed to characterize the relationships between drafting and denting parameters and their effects on warp density, yarn distribution, fabric geometry, structural uniformity, surface characteristics, and selected mechanical and dimensional performance indicators. Machine learning-based predictive analysis is further incorporated to identify parameter combinations associated with improved fabric structural outcomes.

The experimental findings indicate that the integrated optimization of drawing-in and reeding can enhance warp distribution accuracy, reed occupancy, fabric structural regularity, and process repeatability while reducing configuration inconsistencies and setup-related variability. The predictive model demonstrates potential for identifying favorable combinations of drafting and denting parameters and for supporting automated process planning and quality prediction. Variations in drawing-in and reeding configurations also contribute to discernible differences in fabric architecture and surface characteristics, providing additional opportunities for controlled aesthetic and functional fabric development.

The proposed framework establishes an integrated pathway for connecting pre-weaving automation with data-driven textile engineering. By combining robotic process execution, computational modeling, and machine learning-assisted decision support, the approach contributes to the development of flexible, precision-oriented, and digitally enabled weaving systems. The findings provide a foundation for intelligent fabric design, predictive process optimization, and the advancement of next-generation textile manufacturing within the broader contexts of Industry 4.0 and Industry 5.0.

Keywords: machine learning, robotic automation, drawing-in, reeding, weaving technology, fabric structure, structural precision, digital textile engineering, predictive modeling, intelligent textile manufacturing, industry 4.0, industry 5.0

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Introduction

The textile and apparel industry are undergoing rapid digital transformation driven by artificial intelligence (AI), machine learning (ML), robotics, machine vision, and cyber-physical production systems. Within Industry 4.0 and the emerging Industry 5.0 paradigm, textile manufacturing is evolving toward intelligent, connected, flexible, and data-driven systems that emphasize precision, adaptability, human–machine collaboration, sustainability, and customization. In weaving, these developments are particularly important because fabric structure and performance depend strongly on the accuracy of warp preparation. Drawing-in and reeding are

fundamental pre-weaving operations that establish the initial spatial organization of warp yarns. Drawing-in defines the longitudinal sequence of warp ends through the heddles, affecting shedding, interlacement, weave repeat, and pattern realization, whereas reeding controls transverse yarn distribution, spacing, alignment, fabric width, and compactness. Although traditionally performed as separate operations, their structural functions are interdependent. Their combined configuration can influence fabric architecture, density, dimensional stability, surface morphology, mechanical behavior, and aesthetic characteristics. Manual drawing-in and reeding remain susceptible to threading errors, uneven yarn distribution, inconsistent dent occupancy, and operator-dependent variability, particularly in

high-density, multilayer, three-dimensional, and complex woven structures. Such deviations may propagate during weaving and reduce structural uniformity and repeatability. Consequently, automation is relevant not only for reducing labor requirements but also for improving process accuracy, consistency, and reproducibility. Advances in robotics, machine vision, sensing, digital modeling, and intelligent control provide opportunities to automate warp preparation with greater precision. ML further enables the identification of nonlinear relationships among yarn, structural, and process variables and can support prediction and optimization. However, most technological developments have considered drawing-in and reeding independently, while their coordinated integration within a unified computational and robotic framework remains comparatively limited. From a textile-engineering perspective, warp distribution and fabric geometry are fundamental determinants of woven-fabric structure. Previous studies established relationships between warp organization, fabric geometry, and structural behavior,^{1,2} while computational and database-assisted approaches demonstrated the potential of digital systems for drafting and structural optimization.^{3,4} Fabric performance is also governed by interactions among weave architecture, yarn properties, density, interlacement, crimp, and compactness. Relative fabric density can therefore serve as a useful descriptor of structural packing. Studies of multilayer and three-dimensional constructions have further shown that controlled architectural modifications can influence mechanical, thermal, comfort, and aesthetic properties.^{5–8} The integration of computational prediction and robotic execution provides a pathway toward intelligent warp preparation. Digital specifications can be analyzed to identify suitable drafting and denting configurations, predicted fabric responses can guide parameter selection, and robotic systems can reproduce the optimized warp arrangement with high repeatability. Accordingly, this study investigates drawing-in and reeding as coupled structural variables rather than independent preparatory operations. Three drawing-in systems straight, point, and skip—are examined in combination with three reeding configurations single, double, and grouped denting to determine their effects on warp distribution, fabric architecture, structural uniformity, surface characteristics, mechanical behavior, dimensional stability, and selected aesthetic–functional properties. The principal contributions are:

1. An integrated framework treating drawing-in and reeding as coupled variables in woven-fabric engineering.
2. Experimental evaluation of their individual and combined effects on fabric structure and performance.
3. Integration of computational modeling, ML-based prediction, and robotic automation for intelligent warp preparation.

Thus, drawing-in and reeding are repositioned from conventional preparatory operations to engineering variables linking digital manufacturing, structural fabric design, and intelligent textile production.^{9,10}

Drawing-In technique

Drawing-in is the process of threading warp ends through heddles according to a predefined drafting plan. The selected draft determines warp sequence and harness organization and consequently affects shedding, interlacement, weave repeat, pattern realization, and fabric architecture. Threading errors may produce structural irregularities, pattern distortion, dimensional instability, and variations in fabric performance. Accordingly, drawing-in can be regarded as a structural-design variable rather than merely a preparatory operation. Straight, point, skip, and combined drafts provide different mechanisms

for organizing warp ends and are particularly relevant to complex, multilayer, and three-dimensional structures.^{2,3,6} Digital drafting further provides structured information for computational analysis and ML, while robotic manipulation can improve yarn positioning accuracy and reduce operator-dependent variability. This enables drafting selection to be directly associated with targeted fabric characteristics.

Reeding technique

Reeding determines the transverse distribution of warp yarns within the reed and therefore affects yarn spacing, ends per unit length, fabric width, alignment, and structural compactness. Variations in denting can modify fabric density, porosity, dimensional stability, mechanical response, and surface characteristics. These effects become particularly important in high-density, multilayer, and complex fabrics, where controlled denting is required to maintain uniform warp distribution. Previous studies demonstrated the influence of denting parameters on woven-fabric structure and performance, including macro-porosity and air permeability in multilayer fabrics.^{4,11,12} Integration with machine vision, sensing, robotic positioning, and process control can improve denting accuracy and repeatability. Reeding therefore represents both a manufacturing-control parameter and a structural-design variable.

Integrated drawing-in and reeding for fabric design innovation

Drawing-in and reeding jointly determine the initial spatial organization of warp yarns. Drawing-in controls longitudinal sequence and harness grouping, whereas reeding establishes transverse spacing and distribution. Their interaction consequently affects weave realization, warp density, fabric geometry, compactness, and surface morphology. Treating both operations as a coupled system allows their interaction to be optimized according to structural and performance requirements. Digital CAD, computational modeling, databases, and simulation can evaluate alternative configurations before physical production.⁴ When combined with predictive analytics and robotic execution, these tools enable optimized digital specifications to be translated into repeatable physical warp arrangements.

Weave structure and advanced textile applications

Woven-fabric performance is governed by the interaction of weave architecture, yarn characteristics, warp and weft density, interlacement, yarn arrangement, and structural compactness. These factors influence crimp, load transfer, dimensional stability, surface morphology, and mechanical behavior.^{1,13} Multilayer, three-dimensional, and engineered woven structures demonstrate the potential of architectural control to achieve specific combinations of elasticity, insulation, durability, dimensional stability, tactile response, and visual effects.^{7,8} Such principles are applicable to technical textiles, composite reinforcement, smart materials, and emerging textile technologies.^{10,14} Within this context, drawing-in and reeding constitute upstream structural parameters that influence the conditions under which advanced woven architectures are produced. Their integration with weave design and AI-assisted prediction can therefore support targeted engineering of aesthetic and functional properties.

Research gap

Previous research has established the importance of warp organization, reeding, weave architecture, yarn distribution, and fabric density in determining woven-fabric structure and performance.

Computational and database-assisted systems have also demonstrated the potential of digital approaches for representing and optimizing weaving parameters.^{3,4} Nevertheless, three methodological gaps remain. First, drawing-in and reeding are generally investigated as separate operations rather than coupled structural variables. Second, limited research has addressed ML-based prediction of their combined effects on fabric characteristics. Third, computational optimization has not been sufficiently linked to robotic execution for repeatable physical warp preparation. This study addresses these gaps by integrating textile structural engineering, computational modeling, predictive analytics, and robotic automation to investigate drawing-in and reeding as interconnected process variables.

Research problem

Although drawing-in and reeding strongly influence warp organization and fabric formation, they are frequently optimized independently. This separation may obscure interactions affecting warp distribution, structural uniformity, repeatability, and fabric performance. The research problem is therefore formulated as follows: How can drawing-in and reeding techniques be jointly analyzed, optimized, and automated to improve structural precision, fabric-design innovation, and the aesthetic–functional performance of woven fabrics?

The study consequently evaluates whether coordinated drafting and denting configurations produce measurable changes in fabric characteristics and whether these relationships can support ML-assisted prediction and robotic automation.

Research objectives

1.8.1. General Objective: The primary objective is to develop and experimentally validate an integrated computational, robotic, and automated framework for analyzing and optimizing drawing-in and reeding to improve fabric-design innovation, structural precision, and aesthetic–functional performance.

Specific objectives: The study aims to

1. Investigate the effects of straight, point, and skip drafting on warp organization, fabric geometry, structural regularity, and selected performance characteristics.
2. Evaluate the effects of single, double, and grouped denting on warp distribution, density, compactness, and surface characteristics.
3. Determine the interaction between drawing-in and reeding and its effects on fabric architecture and structural precision.
4. Develop mathematical and computational models relating drafting, denting, warp density, weave architecture, and fabric properties.
5. Develop and evaluate ML-based predictive models, where supported by the available dataset, to identify parameter combinations associated with targeted fabric characteristics.
6. Integrate robotic and automated process concepts to improve the accuracy, repeatability, and consistency of drawing-in and reeding.
7. Evaluate aesthetic characteristics, including surface uniformity, texture, pattern definition, and visual structure.
8. Assess relevant functional properties, including tensile behavior, dimensional stability, surface characteristics, and porosity.
9. Establish a digital workflow linking fabric design, computational analysis, predictive modeling, and robotic execution.

10. Develop engineering guidelines for coordinating drawing-in and reeding within intelligent weaving systems aligned with Industry 4.0 and the human-centered, adaptive principles of Industry 5.0.

Materials and methods

Materials and fabric preparation

Experimental woven fabrics were produced under controlled laboratory and industrial weaving conditions to evaluate the effects of integrated drawing-in and reeding on fabric architecture, structural precision, and selected aesthetic–functional properties. All specimens were manufactured from 100% combed cotton yarn (14 Tex) from a single material lot. Yarn linear density, twist, tensile properties, and relevant fiber-packing characteristics were maintained within narrow tolerances to minimize material-related variability. Fabric constructions were designed using a boundary-geometry-based approach to consistently represent warp distribution, weave architecture, and relative fabric density. Three representative structures were selected: plain weave (1/1), four-end Z-twill, and five-end Z-satin, providing distinct interlacement and float configurations. Each structure was produced at relative fabric densities of 55–85% to examine the effects of structural compactness in combination with drawing-in and reeding parameters.

All specimens were woven in the grey state using Picanol weaving machinery under standardized conditions. Weaving speed, warp tension, weft insertion, and principal machine settings were kept constant to minimize process-induced variability. Thus, observed differences were primarily associated with the investigated structural variables.

Experimental and computational research framework

An integrated experimental–computational framework was established to examine the relationships among drawing-in, reeding, fabric structure, and performance. The methodology combined textile structural engineering, digital design, computational modeling, machine learning (ML), robotic automation, and experimental validation.

The framework consisted of four sequential stages:

Stage I – Digital Fabric Design and Process Planning: Weave structures, drawing-in systems, reeding configurations, and relative-density levels were digitally specified. Computational procedures defined the required warp sequence, drafting plan, denting arrangement, and principal structural parameters before production.

Stage II – Drawing-In, Reeding, and Automated Execution: The digital specifications were converted into standardized drawing-in and reeding instructions. Robotic and automated procedures were incorporated to improve yarn positioning, heddle alignment, reed occupancy, and warp distribution while enhancing process repeatability.

Stage III – Computational Modeling and ML-Based Prediction: The experimental dataset was structured using drawing-in system, reeding configuration, weave structure, and relative fabric density as input variables and measured fabric characteristics as responses. Where supported by the dataset, ML models were employed to identify nonlinear relationships and predict selected fabric properties. Computational predictions were subsequently evaluated against experimental measurements.

Stage IV – Experimental Validation and Performance Assessment:

Predicted and measured results were compared using appropriate statistical and performance analyses. The validation assessed the significance of the investigated variables and the agreement between computational predictions and experimental observations, providing an objective basis for evaluating integrated drawing-in and reeding configurations and their effects on structural precision and fabric performance.

Experimental variables and design parameters

The experimental design was structured around the coordinated variation of drawing-in, reeding, weave architecture, and relative fabric density. The principal experimental factors were defined as follows Table 1:

Table 1 The principal experimental factors

Factor	Experimental levels
Drawing-in system	Straight, Point, Skip
Reeding configuration	Single, Double, Grouped
Weave structure	Plain (1/1), 4-end Z-twill, 5-end Z-satin
Relative fabric density	55–85%
Yarn material	100% combed cotton
Yarn linear density	14 Tex

The factorial organization of these variables enabled the investigation of both individual and combined effects. Particular emphasis was placed on determining whether the interaction between drawing-in and reeding configurations produced measurable changes in fabric structure and performance beyond the independent contribution of either parameter. The experimental factors were maintained under controlled production conditions to improve the internal validity and repeatability of the experimental comparisons. Where multiple specimens were produced for a given experimental condition, the same machine and material-control procedures were maintained throughout the production sequence.

Mathematical and structural modeling

Mathematical modeling was employed to describe the relationship between warp arrangement, denting configuration, weave geometry, and fabric structural parameters. The modeling framework considered the spatial distribution of warp ends and their interaction with the selected drafting and denting systems. Warp density was characterized according to the relationship between the number of reed dents per unit length and the number of warp ends assigned to each dent:

$$EPC = \frac{\text{times of threads of warp ends per centimeter}}{DPC} EPD \dots\dots\dots (1)$$

The number (times of threads of warp ends per centimeter) is above, where:

EPC, ends per centimeter; **DPC**, dents per centimeter; **EPD**, number of warp ends per dent.

The mathematical relationship provides a quantitative basis for assessing the effects of denting configuration on warp distribution and fabric compactness. It was integrated with the selected weave geometries to establish a consistent structural representation of the experimental fabrics. Relative fabric density (RFD) was used as a compactness descriptor, enabling comparison among weave structures and yarn arrangements while accounting for differences in geometric packing.

Machine learning and predictive modeling: Machine learning (ML) was applied to evaluate the predictive relationships between

processing parameters and selected fabric characteristics. The input variables comprised drawing-in system, reeding configuration, weave structure, and relative fabric density, while experimentally measured structural, surface, mechanical, and dimensional properties were used as target variables. The workflow included data preprocessing, categorical encoding, feature scaling where required, model training, validation, and performance assessment. The dataset was partitioned using a controlled procedure to reduce data leakage and maintain independent evaluation. Supervised models were selected according to dataset characteristics and evaluated using R^2 , RMSE, and MAE, where applicable. Validated models were subsequently used to identify parameter combinations associated with targeted fabric characteristics, supporting data-driven process optimization.

Robotic and automated process integration: The robotic framework translated digital drawing-in and reeding specifications into physical warp-preparation instructions, including yarn sequence, heddle arrangement, reed occupancy, and warp-end distribution. Automation was used to improve positional accuracy, repeatability, and process consistency. The framework also provides a basis for future integration of machine vision and sensing for deviation detection and verification of the executed configuration against the digital specification. The integrated workflow is therefore represented in the following Figure 1:

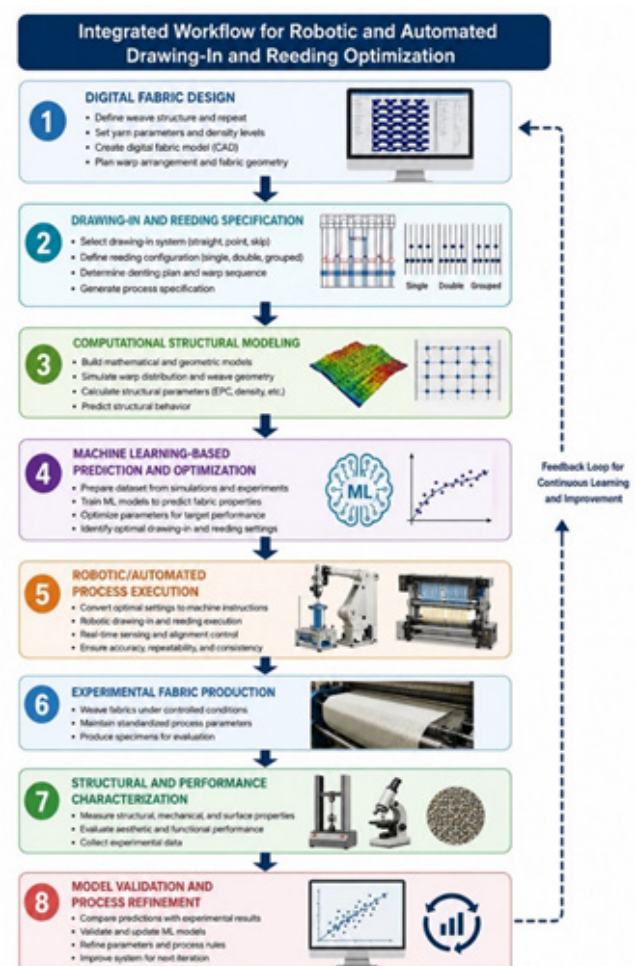


Figure 1 This architecture establishes a feedback-oriented pathway in which experimental measurements can be used to improve subsequent computational predictions and process decisions.

Digital textile engineering using weavepoint®

Digital textile engineering was implemented using WeavePoint® as a virtual environment for fabric design, structural simulation, and planning of drawing-in and reeding configurations before physical production. The software enabled systematic evaluation of alternative weave architectures and structural parameters while linking digital design with experimental manufacturing. WeavePoint® was used to develop and evaluate drawing-in and reeding configurations, simulate weave structures and fabric geometry, analyze warp–weft relationships and structural parameters, and generate a digital dataset containing design and process variables for subsequent predictive analysis.

This digital workflow reduced preliminary experimental trials and facilitated evaluation of interactions among drawing-in, reeding, weave structure, warp density, and fabric geometry. The resulting dataset supported ML-based prediction and parameter selection for targeted structural, aesthetic, and functional characteristics. Accordingly, WeavePoint® functioned as a digital engineering and decision-support tool connecting virtual textile design, structural analysis, experimental production, and data-driven optimization. The approach extends earlier work on digital textile simulation and database-assisted structural engineering^{3,4} toward an integrated ML-supported and robotic framework for intelligent woven-fabric development (Figure 2).

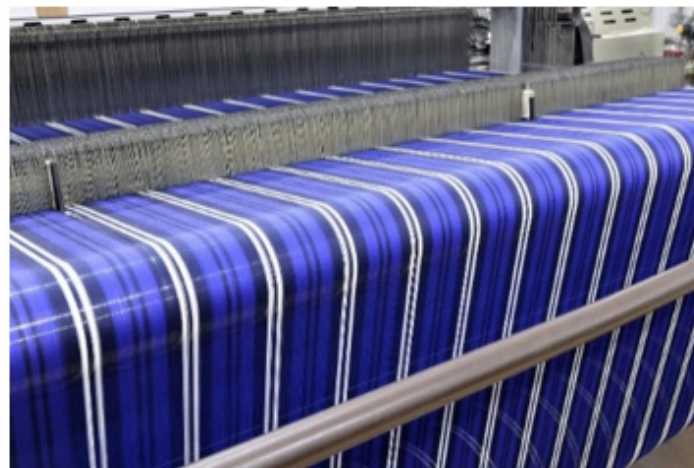


Figure 2 automatic drawing-in process| fabric testing methods| weaving.

Digital textile engineering using WeavePoint®

WeavePoint® was used as a digital textile-engineering environment for fabric design, structural simulation, and planning of drawing-in and reeding configurations before physical production. Alternative weave architectures, patterns, and structural parameters were digitally generated and evaluated to reduce preliminary experimental trials and ensure consistent process planning. The software supported the analysis of warp–weft relationships, fabric geometry, weave structure, drawing-in, reeding, and warp density, while the resulting design and

process data were organized for subsequent predictive analysis. This enabled systematic evaluation of parameter interactions and selection of configurations associated with targeted structural, aesthetic, and functional characteristics. Accordingly, WeavePoint® provided a digital link between virtual fabric development and experimental production, complementing the computational and robotic procedures described in the preceding sections. The approach extends previous work on digital textile simulation and database-assisted structural engineering^{3,4} toward an integrated ML-supported framework for intelligent woven-fabric development.

Single covered yarns

Table 2 Types of single covered yarns

Yarn type	Spandex	Secondary material	Blend ratio	Spandex count (denier)	Secondary count	Final count
Spandex + Cotton	0.5 kg	0.5 kg	50:50:00	40	30/1	~40
Spandex + Polyester	0.5 kg	0.5 kg	50:50:00	40	1/150	~40
Spandex + Viscose	0.5 kg	0.5 kg	50:50:00	40	30/1	~40

Double covered yarns

Table 3 Types of double covered yarns

Yarn type	Spandex (kg)	Material 2	Material 3	Blend ratio	Spandex count	Secondary count	Final count
Spandex + Cotton + Polyester	3-Jan	3-Jan	3-Jan	1:01:01	40	40/1	~40
Spandex + Polyester + Viscose	3-Jan	3-Jan	3-Jan	1:01:01	40	1/120	~40
Spandex + Viscose + Cotton	3-Jan	3-Jan	3-Jan	1:01:01	40	40/1	~40

These yarn systems improve elasticity & structural integrity, consistent with multilayer fabric studies (Elnashar & Dubrovski, 2008; Elnashar & Bashkova, 2014).

Production of double woven Fabrics: Fabric design was based on:

- Denting systems
- Elastic weft yarns (spandex)
- Weave structure
- Stretch behavior

Fabric design plan

Table 4 Fabric design plan

Binding type	First structure*	Second structure**	Total samples	Fabric width
Type 1	14 samples	14 samples	14	1.5 m
Type 2	14 samples	14 samples	14	1.5 m
Type 3	14 samples	14 samples	14	1.5 m
Type 4	14 samples	14 samples	14	1.5 m
Type 5	14 samples	14 samples	14	1.5 m
Type 6	14 samples	14 samples	14	1.5 m
Type 7	14 samples	14 samples	14	1.5 m
Type 8	14 samples	14 samples	14	1.5 m
Control Sample	—	—	112	—

Weaving system and manufacturing requirements

The experimental fabrics were produced on industrial Picanol/Sulzer rapier looms equipped with electronically controlled Jacquard shedding and dual warp beams at a textile manufacturing facility in El-Mahalla El-Kubra, Egypt. Warp and weft tension, loom speed, shedding, beat-up, yarn feeding, and environmental conditions were controlled to ensure process repeatability and specimen consistency. The programmable weaving system enabled accurate implementation of predefined drawing-in and reeding configurations and provided a digital interface for process planning, automated execution, and structural optimization. This configuration facilitated systematic modification and monitoring of weaving parameters in relation to fabric-performance requirements.^{3,9}

Fabric structural configurations

Two representative multilayer woven structures were developed to investigate the interaction between drawing-in, reeding, and fabric architecture.

Structure I (*)

- Upper layer: Plain weave (1/1)
- Lower layer: Plain weave (1/1)
- Interconnecting layer: 5-end satin binding

Structure II (**)

- Upper layer: Spider weave
- Lower layer: Plain weave (1/1)
- Interconnecting layer: 5-end satin binding

The structures were selected to provide different interlacement frequencies, yarn mobility, layer interactions, and binding conditions. These characteristics influence warp crimp, fabric compactness, dimensional stability, surface morphology, and aesthetic appearance. Their combination with elastomeric yarns further enables assessment of the interaction between material behavior and structural design, particularly deformation and recovery.^{6,15}

Research procedures and experimental methodology

Experimental workflow

The methodology integrated digital textile engineering, automated drawing-in and reeding planning, robotic implementation, machine-learning prediction, and experimental validation. Drawing-in and reeding were treated as coupled structural variables rather than independent preparation operations.

The workflow comprised:

- A. Selection of straight, point, skip, and broken drafting configurations.
- B. Selection of single, double, and grouped denting.
- C. Digital modeling and generation of preparation plans.
- D. Automated/robotic implementation of warp positioning and reed occupancy.
- E. Fabric manufacturing under controlled conditions.
- F. Structural, mechanical, surface, and functional characterization.
- G. Statistical analysis of process–property relationships.
- H. Machine-learning prediction and optimization.
- I. Experimental validation of selected configurations.

This workflow established a digital-to-physical closed loop linking design, manufacturing, measurement, prediction, and model refinement.^{16,17}

Integrated structural analysis of drawing-in and reeding

Drawing-in and reeding were analyzed as an integrated structural system. Drawing-in determines the longitudinal organization and heddle sequence of warp ends, whereas reeding controls their transverse distribution, density, and alignment.

The investigated variables included:

Drawing-in: straight, point, skip, and broken drafts.

Reeding: single, double, and grouped denting.

Their combined effects were evaluated through warp distribution, ends per dent, reed occupancy, dent spacing, warp density, relative fabric density, weave geometry, structural regularity, and dimensional stability.

Mathematical relationships among drafting sequence, dent spacing, ends per dent, warp density, and relative fabric density were used to connect digital preparation parameters with the resulting woven architecture.^{4,15}

Machine learning and experimental validation

A machine-learning framework was developed to relate drawing-in and reeding parameters to structural, mechanical, aesthetic, and functional properties. Experimental fabrics produced from cotton, polyester, and blended yarn systems constituted the physical dataset.

The principal input variables were:

Drawing-in sequence

Ends per dent
Reed count
Dent spacing
Relative fabric density
Weave structure
Yarn characteristics

The data were organized into process/structural inputs and measured fabric responses to identify nonlinear relationships and predict performance. Candidate configurations were subsequently evaluated against predefined objectives and validated using independently manufactured specimens. The resulting digital-to-physical optimization loop supports a transition from trial-and-error development to predictive woven-fabric engineering.^{16,17}

Fabric manufacturing and sample preparation

All specimens were manufactured under standardized controlled conditions. Warp systems were prepared according to digitally generated drawing-in and reeding plans, with controlled warp distribution, reed occupancy, and yarn tension. The resulting fabrics were produced using the predefined structural configurations and conditioned before testing.

This protocol minimized uncontrolled variation and provided a consistent basis for evaluating relationships among warp preparation, woven architecture, and fabric performance.¹

Characterization and measurement techniques

The fabrics were characterized in terms of structural, mechanical, surface, and functional properties.

Structural characteristics

Measurements included warp and weft density, warp-to-weft density ratio, ends per dent, reed occupancy, relative fabric density, and structural regularity.

Mechanical characteristics

Mechanical response was assessed through tensile strength, elongation at break, elastic recovery where applicable, and dimensional stability.

Surface and aesthetic characteristics

Surface evaluation included texture, smoothness, pattern definition, visual uniformity, and surface regularity to establish relationships between structural configuration and aesthetic–functional quality.^{7,13}

Digital design, CAD simulation, and robotic process planning

CAD-based textile engineering was integrated with digital simulation and robotic process planning to establish a design-to-manufacturing workflow. The digital environment was used to model woven structures, simulate drawing-in and reeding alternatives, analyze yarn distribution and structural geometry, generate automated preparation plans, and support machine-learning datasets.

This approach enabled alternative configurations to be evaluated before physical production, thereby reducing unnecessary experimental iterations and improving process repeatability. The

resulting digital representation connects fabric-design parameters with machine-executable instructions and supports digitally connected manufacturing consistent with Industry 4.0 and Industry 5.0 principles.^{3,9}

Performance evaluation and data acquisition

Fabric performance was evaluated through mechanical, aesthetic, and functional indicators.

Mechanical performance

Tensile strength, elastic recovery, and dimensional stability were used to assess load-bearing capacity, deformation, recovery, and structural integrity.²

Aesthetic performance

Surface smoothness, texture uniformity, pattern definition, visual consistency, and surface regularity were evaluated to determine the effects of warp distribution and reed occupancy on visual and tactile quality.¹

Functional performance

Drape, air permeability, flexibility, abrasion resistance, and wear resistance were considered as functional indicators.^{4,7}

All measurements were stored in a structured digital database linking drawing-in, reeding, weave structure, yarn characteristics, manufacturing conditions, and measured fabric properties.

Statistical analysis and intelligent predictive modeling

The experimental data were analyzed using descriptive statistics, correlation analysis, multivariate analysis, and machine-learning methods. These analyses were used to determine relationships among drawing-in, ends per dent, reed count, dent spacing, weave structure, relative fabric density, and fabric responses.

Validated predictive models were subsequently used to evaluate alternative drawing-in/reeding combinations and identify configurations satisfying specified structural, mechanical, aesthetic, and functional objectives. Machine learning therefore served as a predictive and decision-support tool for intelligent textile process optimization.^{4,15}

Methodological contribution

The proposed methodology establishes an integrated digital–robotic–intelligent textile-engineering framework linking structural design, drawing-in, reeding, digital simulation, weaving, characterization, and predictive optimization.

The principal methodological contribution is the treatment of drawing-in and reeding as coupled structural variables. Their combined effects on warp distribution, reed occupancy, yarn alignment, fabric geometry, surface characteristics, and functional performance are evaluated within a unified framework.

This closed-loop architecture enables experimental knowledge to be returned to the digital environment for model refinement and improved prediction. It consequently provides a basis for predictive and adaptive woven-fabric engineering, supporting CAD/CAM, automation, robotics, digital databases, machine learning, and intelligent process control while reducing reliance on conventional trial-and-error development.

Results and discussion

The results demonstrate that the coordinated interaction of drawing-in and reeding substantially influences woven-fabric architecture and associated structural, surface, mechanical, aesthetic, and functional properties. Their control of warp distribution affects yarn alignment, inter-yarn interaction, crimp, compactness, and surface morphology.

Integration of digital design, simulation, and automated process planning enabled these variables to be evaluated before manufacturing, thereby improving process consistency and reducing unnecessary experimental iterations.

Statistical evaluation of surface characteristics

ANOVA showed that weave structure and relative fabric density significantly affected surface mean deviation (SMD) under the investigated conditions, whereas their effects on the coefficient of friction were not statistically significant.

The SMD response reflects the influence of weave geometry, yarn crimp, warp distribution, and fabric compactness on the surface profile. In contrast, friction depends on a broader combination of fiber and yarn characteristics, surface morphology, finishing, contact pressure, measurement direction, and interacting surfaces. Thus, structural parameters are particularly important for surface morphology, whereas friction requires simultaneous consideration of structural and material variables.

Directional behavior of surface roughness

Surface measurements exhibited clear anisotropy between warp and weft directions, with generally higher SMD values in the warp direction. This behavior is associated with differences in yarn spacing, interlacement, distribution, and mechanical restraint.

Accordingly, surface roughness should be evaluated directionally rather than through a single isotropic parameter. Drawing-in and reeding therefore represent important directional variables for controlling both the magnitude and distribution of surface roughness.

Influence of drawing-in configuration

Drawing-in substantially affected warp organization, shed geometry, yarn interaction, and structural regularity. Straight, point, skip, and broken drafts generated distinct warp architectures through differences in yarn sequencing and grouping.

Straight drafting provided regular warp distribution; point and broken drafts introduced controlled grouping and directional variation; and skip drafting modified local yarn spacing and interaction during shedding. Electronically controlled Jacquard shedding further enabled complex threading arrangements.

Thus, drawing-in functions as a structural design variable, rather than merely a preparatory operation. Its accurate digital definition and automated execution can improve warp-positioning precision, repeatability, structural control, and design flexibility.

Effect of weave geometry on surface roughness

Surface roughness was strongly associated with interlacement frequency, yarn crimp, float length, and local yarn restraint. Plain weave, characterized by frequent interlacement, produced greater yarn undulation and surface irregularity. Twill provided an intermediate response, while satin, with longer floats and lower interlacement frequency, generally produced a smoother surface.

Therefore, increased interlacement tends to increase yarn crimp and surface irregularity, whereas longer floats favor surface smoothness. Weave geometry should consequently be incorporated into intelligent optimization of tactile and visual properties.

Synergistic effect of drawing-in and reeding integration

Coordinated drawing-in and reeding produced measurable improvements compared with independent parameter selection. Under the investigated conditions, the optimized configurations showed:

Approximately 15–20% improvement in tensile strength.

Improved surface smoothness through more uniform warp distribution.

Enhanced pattern definition and structural regularity.

Improved flexibility and drape.

Greater resistance to deformation and structural degradation.

These findings confirm that drawing-in and reeding exert interdependent structural effects. Drawing-in establishes warp sequence and heddle organization, whereas reeding controls lateral positioning and density. Their coordinated adjustment therefore modifies the overall warp geometry and its interaction with the weft.

Contribution of digital textile design and computational process planning

CAD-based design and digital simulation enabled alternative weave architectures, drawing-in sequences, and reeding configurations to be evaluated before manufacturing. The main benefits were:

Reduced physical experimentation.

Early identification of unsuitable configurations.

Lower preliminary material consumption.

Improved process repeatability.

Faster comparison of structural alternatives.

Greater design flexibility.

Generation of data for predictive modeling.

The digital environment therefore provides a direct link among fabric design, structural analysis, process planning, and automated manufacturing, while generating datasets suitable for machine-learning prediction.

Implications for intelligent textile design

Coordinated drawing-in and reeding provide simultaneous benefits for textile engineering and fabric design. Precise warp organization can improve structural stability and mechanical response while influencing surface quality, pattern definition, visual consistency, and tactile behavior.

Digital modification and automated execution expand the design space for multilayer, elastic, technical, and function-oriented woven structures, reducing dependence on empirical development.^{6,9}

The resulting process data can support future robotic weaving systems in which machine-learning models identify suitable drawing-in/reeding combinations according to specified fabric properties, design objectives, and manufacturing constraints.

Influence of drawing-in systems on fabric structure and performance

The experimental results confirmed that drafting configuration influences warp organization, shed formation, yarn interaction, and fabric behavior.

Straight draft: Straight drafting provided uniform warp distribution, balanced geometry, and consistent load transfer. Its regular heddle sequence supports dimensional stability and manufacturing repeatability, making it appropriate for fabrics requiring predictable structural behavior.

Point draft: Point drafting generated symmetrical warp organization and greater potential for geometric and decorative effects. Directional reversal supports controlled repetition and visual balance, making it suitable for applications emphasizing pattern organization and aesthetic expression.

Skip draft: Skip drafting increases separation between selected warp ends and modifies their interaction during shedding. This configuration can facilitate yarn movement and reduce excessive warp-to-warp contact, particularly in dense or structurally complex fabrics.

Overall, drafting selection provides a means of balancing structural integrity, manufacturing efficiency, and aesthetic performance, while its associated structural parameters can serve as inputs for predictive models.^{4,15}

Overall interpretation and engineering implications

The results establish drawing-in and reeding as interconnected structural variables governing warp distribution, reed occupancy, yarn alignment, fabric geometry, and compactness. Their effects extend from warp preparation to the final surface, mechanical, aesthetic, and functional properties of the fabric.

Digital textile engineering strengthens this approach by enabling drafting, denting, and structural configurations to be simulated before manufacturing. This reduces experimental iterations, improves process consistency, and accelerates exploration of design alternatives.

The combined experimental and digital datasets provide a basis for machine-learning models linking process configurations with fabric-performance responses. When coupled with automated or robotic execution, such models can support adaptive control according to predefined performance targets.

Accordingly, the integration of optimized drawing-in, coordinated reeding, digital simulation, robotic process planning, and intelligent data analysis provides a pathway toward improved structural precision, manufacturing repeatability, aesthetic quality, and functional performance.

The proposed framework supports the transition from conventional trial-and-error development toward predictive, data-driven textile manufacturing, particularly for multilayer, elastic, technical, and high-performance woven structures. It also provides a technological basis for integrating robotics, artificial intelligence, and digital engineering within Industry 4.0 and Industry 5.0 environments.^{14,18}

Finally, each drawing-in configuration defines a specific heddle-threading sequence governing shed formation, warp movement, interlacement, and fabric geometry. Drafting can therefore be regarded as a fundamental structural design parameter in intelligent weaving and predictive textile-engineering systems.

$$H(n) = f(n, r) \dots \dots \dots (2)$$

Where:

$H(n)$: heddle frame number

n : warp end index

r : repeat of the design

Reeding systems and their influence on fabric structural performance

Reeding (denting) is a critical structural-control operation that determines warp-end spacing, transverse distribution, density, alignment, and fabric compactness, thereby influencing surface morphology, mechanical response, dimensional stability, porosity, and aesthetic quality. Its effect is intrinsically coupled with drawing-in: drawing-in defines the longitudinal ordering and heddle sequence of warp ends, whereas reeding establishes their transverse arrangement. Consequently, woven architecture results from the coordinated interaction of both operations rather than from either parameter independently.

Previous studies have demonstrated that coordinated threading and reeding can affect structural stability, mechanical behavior, and visual characteristics, particularly in complex and multilayer fabrics.^{1,2,7} Accordingly, reeding should be considered an active structural-design variable within performance-oriented and digitally assisted fabric development.

Single denting

Single denting, with one warp end per dent, provides high positional control and uniform transverse yarn distribution. It promotes regular spacing, balanced tension, surface uniformity, and dimensional consistency, making it suitable for fine and technically engineered fabrics requiring precise construction.

Its standardized geometry also facilitates digital representation, automated planning, and robotic execution, making it a useful reference configuration for process databases and predictive reeding models.^{1,2}

Double denting

Double denting places two warp ends in each dent, increasing local compactness while reducing the number of threading positions. It provides a practical balance between structural stability, warp compactness, and preparation efficiency, particularly for medium-density fabrics.

Its performance depends on appropriate matching of ends per dent with yarn characteristics and target fabric density. The standardized configuration is also readily incorporated into digital planning and automated manufacturing systems.^{2,3,9}

Group denting

Group denting assigns variable numbers of warp ends to selected dents, enabling controlled spatial changes in yarn spacing and density. This configuration provides greater flexibility for localized density gradients, surface relief, decorative effects, and multilayer or elastic structures. Variations in local density can affect surface morphology, porosity, air permeability, flexibility, thermal behavior, deformation, and elastic recovery, depending on yarn characteristics and weave geometry.⁵⁻⁸ Therefore, group denting should be selected according to defined structural and functional objectives rather than solely for decorative effects.

Integrated reeding and drawing-In

The combined drawing-in–reeding system provides multidimensional control of woven architecture. Drawing-in determines warp sequence and heddle organization, while reeding controls lateral spacing, ends-per-dent distribution, and local density. Their coordinated adjustment influences:

- Warp and weft density
- Relative fabric density and compactness
- Yarn alignment and porosity
- Surface morphology and pattern definition
- Dimensional stability and mechanical integrity
- Air permeability and thermal behavior

The interaction is particularly important for density-dependent properties such as porosity and air permeability, while uniform warp distribution supports consistent load transfer and structural stability.^{2,4}

Digital–robotic process integration

Within the proposed framework, drawing-in and reeding are represented as coupled digital process variables, including warp-end sequence, ends per dent, reed occupancy, yarn density, and target fabric architecture. CAD and digital simulation enable alternative configurations to be generated and evaluated before manufacturing, while robotic systems provide accurate and repeatable implementation. The resulting experimental data can be linked to their corresponding digital configurations to train machine-learning models that predict relationships among preparation parameters, fabric architecture, and performance. Thus, CAD/simulation provides the planning layer, robotics the execution layer, and machine learning the prediction and optimization layer, supporting structural precision, customization, repeatability, and reduced trial-and-error development.^{10,18}

Engineering significance

The three reeding systems provide distinct structural functions: single denting emphasizes positional uniformity, double denting balances compactness with preparation efficiency, and group denting enables controlled spatial variation in density and yarn spacing. When integrated with appropriate drawing-in configurations, these systems define a flexible design space for controlling fabric geometry, compactness, surface morphology, mechanical behavior, and functional performance. Their integration with digital simulation, robotic execution, and machine-learning optimization provides a foundation for intelligent woven-fabric engineering and performance-driven process selection.

Overall interpretation

Reeding is therefore not merely a warp-separation operation but a fundamental structural-design parameter. Its coordinated selection with drawing-in enables controlled manipulation of warp distribution, fabric density, surface characteristics, mechanical response, and functional behavior. This integrated approach supports the development of digitally designed and intelligently manufactured woven fabrics with improved structural precision, repeatability, and application-specific performance.

The denting function may be expressed as:

$$D = \frac{E}{R} \dots\dots\dots(3)$$

Where:

- D: ends per dent
- E: total warp ends
- R: number of reed dents

Theoretical relationship

The integration between drawing-in & reeding can be expressed as:

$$T_f = f(H(n), D, \rho_w, \dots\dots\dots(4)$$

Where:

- F_s : fabric structure
- ρ_w : warp density

Integration between technical & design aspects: The analysis confirms that successful textile design is determined by the synergy of geometric and mechanical factors, where:

Geometric relationships: Thread arrangement, heddle sequence, and warp spacing directly influence pattern formation and structural consistency.

Mechanical interactions: Yarn tension, friction, and deformation govern the stability, drape, and functional performance of the fabric.

Coordinating drawing-in & reeding techniques, supported by digital simulations, ensures that both technical precision and aesthetic quality are achieved. This integration fosters innovative fabric designs with enhanced structural integrity, visual clarity, and functional properties.

Mathematical interpretation: Warp density relationship

$$pw = \frac{E}{W} = \dots\dots\dots(5)$$

Where:

- W: fabric width

Fabric Tightness Factor

$$T_f = pw \times D = \dots\dots\dots(6)$$

This indicates that fabric compactness increases with both warp density and denting concentration.

Functional analysis of the reeding technique

Structural significance of reeding

Reeding (denting) is a fundamental warp-preparation operation that determines the transverse distribution, spacing, local density, fabric width, compactness, and structural regularity of warp ends. By acting as a geometric reference during beat-up, the reed transfers the planned warp arrangement into the woven structure. Variations in ends per dent and dent occupancy therefore modify lateral warp geometry and fabric architecture.

Accordingly, reeding should be considered a design-controllable structural parameter that complements drawing-in by controlling transverse warp organization relative to its longitudinal sequence.^{2,12}

Engineering role in fabric formation

Accurate reeding promotes warp alignment, tension balance, structural uniformity, and dimensional consistency, supporting

reproducible realization of the intended weave architecture. Its interaction with drawing-in, weave geometry, yarn characteristics, and fabric density can influence tensile behavior, flexibility, porosity, air permeability, thermal response, dimensional stability, and surface.^{4,7} The combined drawing-in–reeing configuration is particularly relevant to multilayer, three-dimensional, elastic, technical, and function-oriented woven structures, where conventional uniform warp distribution may restrict structural and aesthetic flexibility.^{3,5,6}

Digital and robotic implementation

Within an intelligent textile-manufacturing framework, reeding can be digitally represented through warp-end sequence, heddle allocation, ends per dent, reed occupancy, spatial distribution, and target warp density. These parameters can be computationally evaluated with the corresponding drawing-in configuration and converted into machine-executable process instructions. Linking these digital configurations with experimentally measured fabric responses provides a structured dataset for machine-learning-assisted prediction and optimization. The resulting models can identify relationships between warp-preparation parameters and target fabric properties, enabling progressive refinement of process configurations. Thus, reeding functions simultaneously as a physical preparation operation, a digital process variable, and an optimization parameter within robotic weaving systems.^{9,14}

Functional and engineering implications

The coordinated integration of drawing-in, reeding, digital simulation, automated execution, and predictive modeling provides multidimensional control of woven-fabric architecture. This approach supports improved structural precision, process repeatability, and performance-oriented design while reducing dependence on empirical trial-and-error development. The methodology is particularly suitable for advanced woven structures requiring controlled density, flexibility, surface morphology, mechanical response, or functional performance, and provides a technological basis for intelligent manufacturing consistent with Industry 4.0 and Industry 5.0 principles.

Fabric density relationship: Warp density is determined as a function of reed configuration and can be expressed as:

$$\text{Ends per cm (EPC)} = \text{Dents per cm} \times \text{Ends per dent} \dots \dots \dots (7)$$

This relationship highlights the direct influence of denting arrangement on fabric compactness and structural characteristics.

The comparative results demonstrate that no single reeding system is universally optimal; its suitability depends on the required balance among structural precision, compactness, flexibility, permeability, mechanical performance, aesthetic complexity, and manufacturing efficiency. The results further show that reeding performance is strongly coupled with the selected drawing-in system. Because drawing-in controls the longitudinal arrangement of warp ends while reeding determines their transverse distribution, different drafting sequences can produce distinct structural outcomes with the same denting configuration. Thus, final fabric architecture is governed by the combined drafting $\times$ denting configuration.

Implications for robotic and intelligent reeding

Within a digital–robotic manufacturing framework, reeding configurations can be digitally defined using reed count, dent spacing, ends per dent, dent occupancy, spatial distribution, and target fabric density, and linked to the corresponding drawing-in and weave parameters. This digital representation enables alternative configurations to be computationally evaluated and experimentally validated. The resulting process–property relationships can subsequently support machine-learning models for predicting suitable reeding configurations according to specified structural and performance targets.

Optimized reeding configuration

Accordingly, reeding can be transformed from a conventional preparation operation into a digitally defined and computationally optimizable structural variable. Its integration with automated drawing-in and robotic weaving provides a basis for adaptive systems capable of selecting process configurations according to targeted fabric properties. Overall, the engineering role of reeding extends beyond warp insertion into the reed to programming the transverse architecture of the fabric. Combined with drawing-in, digital design, and intelligent optimization, it can contribute to structural precision, aesthetic differentiation, functional performance, and manufacturing efficiency, supporting next-generation woven-fabric production within Industry 4.0 and human-centered Industry 5.0 environments.

Comparative engineering interpretation

The comparative evaluation demonstrates that the investigated reeding systems occupy different positions within the structural-performance design space. Their principal engineering characteristics can be interpreted as follows Table 5.

Table 5 Comparative engineering interpretation

Reeding configuration	Primary structural effect	Principal performance advantage	Main design application
Single denting	Uniform yarn separation	Maximum positional precision and regularity	Fine and precision woven fabrics
Double denting	Increased yarn packing	Balance between stability and productivity	Medium-density woven fabrics
Multiple denting	High structural compactness	Increased rigidity and load-bearing capability	Technical and structurally rigid fabrics
Skip denting	Controlled structural opening	Increased permeability and flexibility	Lightweight and ventilated fabrics
Group denting	Local density variation	Enhanced texture and design differentiation	Decorative and multilayer fabrics
Variable denting	Spatially adaptive density	Localized functional optimization	Smart and functionally graded fabrics

Comparative and intelligent interpretation of reeding systems

The comparative results indicate that no single reeding system is universally optimal; its suitability depends on the required balance among structural precision, compactness, flexibility, permeability, mechanical performance, aesthetic complexity, and manufacturing

efficiency. Reeding performance is also strongly coupled with the drawing-in system: drawing-in determines the longitudinal warp sequence, whereas reeding controls its transverse distribution. Consequently, final fabric architecture is governed by the combined drafting $\times$ denting configuration. Within a digital–robotic framework, reeding can be encoded through reed count, dent spacing, ends per dent, dent occupancy, spatial distribution, and target fabric density,

together with drawing-in and weave parameters. These variables can be computationally evaluated and experimentally validated to establish process–property relationships for machine-learning-based prediction and optimization.

Thus, reeding can be transformed from a conventional preparation operation into a digitally defined structural variable that

is computationally optimized and automatically implemented. Its integration with drawing-in, digital simulation, and robotic weaving supports adaptive selection of process configurations according to targeted fabric properties, contributing to structural precision, aesthetic differentiation, functional performance, and manufacturing efficiency within Industry 4.0 and human-centered Industry 5.0 environments.

Table 6 Classification of reeding systems and their functional characteristics

Reeding system	Ends per dent	Structural effect	Functional impact	Typical applications
Single Denting	1	Uniform yarn distribution	High precision, smooth surface	Fine fabrics
Double Denting	2	Balanced compactness	Improved strength and stability	Medium-weight fabrics
Multiple Denting	>2	High density structure	Increased thickness and strength	Heavy textiles
Skip Denting	Variable	Open structure	Enhanced permeability and lightness	Technical textiles
Group Denting	Variable	Ribbed / textured effect	Aesthetic enrichment	Decorative fabrics
Variable Denting	Variable	Controlled structural variation	Tailored functional performance	Smart textiles

Integrated optimization of drawing-in and reeding

Coordinated optimization of drawing-in and reeding is essential for controlling woven-fabric architecture and structural performance. Drawing-in defines the longitudinal arrangement of warp ends, while reeding controls their transverse spacing and density. Their combined effect governs warp–weft interlacement, compactness, dimensional stability, alignment, and structural integrity. Poor coordination can produce non-uniform warp distribution, local density variations, irregular geometry, and reduced pattern definition, whereas optimized configurations improve structural homogeneity, dimensional stability, surface regularity, and manufacturing reproducibility.^{3,17,18} These effects are particularly significant in multilayer and three-dimensional fabrics, where drafting and denting influence interlayer binding, pore formation, and structural connectivity.^{5,6} Within intelligent manufacturing, drawing-in and reeding parameters can be digitally encoded and correlated with measured fabric properties to support machine-learning-assisted optimization. This enables predictive identification of process configurations for specified structural, aesthetic, and functional requirements.

Design innovation and intelligent textile engineering

Structural rhythm and visual pattern formation

Controlled drawing-in sequences generate distinct structural rhythms and visual patterns by modifying warp interlacement, continuity, and directionality. Drawing-in therefore functions as a design variable as well as a warp-preparation operation.^{4,13}

Digital drawing-in sequences combined with controlled reeding configurations allow structural rhythms to be systematically programmed and translated into machine-executable parameters.

Structural harmony and geometric balance

The coordinated relationship between threading and denting establishes geometric balance and structural uniformity. Accurate warp alignment improves pattern definition, surface regularity, dimensional stability, and mechanical consistency.^{3,7}

Digital modeling enables these characteristics to be evaluated before production, allowing aesthetic geometry and engineering requirements to be optimized concurrently.

Matrix-based structural design and computational textile engineering

A matrix-based representation can describe the interactions among drawing-in, reeding, density, and weave parameters using discrete process variables and corresponding fabric responses. This facilitates systematic exploration of complex structures, including multilayer, three-dimensional, elastic, textured, and functionally graded fabrics.^{9,10} Integration with CAD simulation and machine learning supports identification of process–property relationships and advances textile design toward predictive, performance-oriented engineering.

Industrial and technological implications

The integration of automated drawing-in, robotic warp preparation, digitally controlled reeding, CAD-based planning, and intelligent manufacturing can improve positional accuracy, repeatability, preparation efficiency, and material utilization.^{3,9} Digital process specifications can also be transferred from virtual design environments to automated manufacturing, establishing a continuous information pathway from fabric concept to machine-executable production. Combined with advanced materials and sustainable strategies, this approach supports high-performance and function-oriented textiles within Industry 4.0 and human-centered Industry 5.0.¹⁴

Discussion of experimental findings

The results confirm that fabric performance is governed by the interaction of geometric, structural, material, and process variables. Warp distribution, density, weave architecture, drawing-in, and reeding determine fabric geometry, while yarn properties, tension, friction, and interlacement influence mechanical and surface behavior.^{1,2} The integrated approach improved structural precision by coordinating longitudinal and transverse warp organization rather than optimizing preparation parameters independently.¹⁸ Digital modeling further supported evaluation of alternative configurations before production, reducing trial-and-error and improving process-planning efficiency.^{3,9} These principles are particularly relevant to multilayer, textured, elastic, and structurally complex fabrics requiring balanced aesthetic, structural, and functional performance.^{5,6}

Summary of principal findings

Structural performance

Integrated drawing-in and reeding improved warp-distribution regularity, structural precision, reproducibility, and dimensional

stability, with particular relevance to multilayer fabrics requiring reliable interlayer connectivity.⁴

Aesthetic performance

Controlled structural planning enhanced surface texture, visual rhythm, geometric balance, and pattern definition, demonstrating that aesthetic characteristics can be systematically engineered through warp-preparation parameters.^{7,15}

Functional performance

The coordinated configuration of drawing-in and reeding provides a basis for tailoring tensile behavior, elasticity, dimensional stability, flexibility, air permeability, thermal response, and durability through the combined effects of yarn properties, weave architecture, density, and warp organization.^{4,7}

Digital, robotic, and intelligent manufacturing implications

The study establishes a link between textile structural engineering and intelligent manufacturing by representing drawing-in and reeding as digital process variables suitable for simulation, experimental validation, and machine-learning datasets. This provides a foundation for predictive process–property models and future transfer of optimized configurations to computer-controlled preparation and weaving systems, supporting closed-loop manufacturing with reduced

dependence on trial-and-error.

Overall research findings

The findings establish integrated drawing-in and reeding as a unified approach for controlling woven-fabric architecture and performance. Their coordinated configuration enables systematic control of warp organization, density, compactness, surface morphology, and structural integrity, while digital modeling and predictive analysis provide a basis for data-driven optimization. Overall, the integration of textile structural engineering, digital design, robotic execution, and predictive modeling provides a pathway toward precise, flexible, and adaptive woven-fabric manufacturing aligned with the objectives of Industry 4.0 and emerging Industry 5.0 paradigms.

Reeding (Denting) systems

Definition and function: Reeding controls warp spacing, fabric width, and density:

EPC= (Dents per cm) × (Ends per dent)

(7)

This relationship highlights the direct impact of denting configuration on fabric compactness and uniformity.

Principal types of reeding systems

Table 7 Classification of reeding systems and their characteristics

Reeding system	Ends per dent	Structural characteristics	Functional impact	Typical applications
Single Denting	1	Uniform yarn spacing	High precision, low friction	Fine cotton, silk fabrics
Double Denting	2	Balanced structure	Improved strength and efficiency	Apparel fabrics
Multiple Denting	≥3	Dense and compact	Increased thickness and durability	Denim, canvas
Skip Denting	Variable	Open structure	High permeability, decorative effects	Leno, mesh fabrics
Group Denting	Variable	Ribbed/textured	Enhanced aesthetics and patterning	Decorative textiles
Variable Denting	Variable	Irregular distribution	Customized functional performance	Technical textiles

Drawing-in and tying methods

Table 8 Classification of drawing-in methods

Method	Description	Advantages	Limitations	Applications
Hand Drawing	Manual threading	High flexibility	Time-consuming	Complex fabrics
Semi-Automatic	Assisted threading	Improved consistency	Equipment required	Medium-scale
Automatic Tying	Fully automated	High efficiency	High cost	Large-scale production

Analytical perspective

The analytical comparison demonstrates a transition from operator-dependent weaving preparation to digitally controlled and automated execution. Manual drawing-in remains appropriate for prototypes, small-batch production, and highly customized structures, but its dependence on operator skill may increase variability and limit repeatability and productivity in complex or large-scale warp systems.

Automated drawing-in improves warp-end positioning, threading accuracy, repeatability, and preparation efficiency, supporting reliable and scalable weaving preparation.^{3,9} Similarly, accurate reeding controls transverse warp distribution, density, alignment, and compactness, while digital control reduces manual variability and improves structural consistency.^{2,4,16} Accordingly, drawing-in and reeding can be considered digitally programmable manufacturing variables. Their digital representation facilitates integration with CAD modeling, automated planning, robotic execution, and data-driven process optimization.

Integrated engineering perspective

The findings establish drawing-in and reeding as coupled engineering variables governing the longitudinal and transverse organization of the warp system. Their interaction influences fabric density, yarn alignment, interlacement, compactness, dimensional stability, and surface morphology. Joint optimization therefore provides more comprehensive control of fabric architecture than independent adjustment of either operation. Digital textile platforms enable alternative configurations to be modeled and evaluated before production, while experimental characterization supplies feedback for subsequent optimization. This approach is particularly relevant to complex, multilayer, elastic, and function-oriented fabrics.^{6,10,16} The resulting process–structure–performance data also provide a foundation for machine-learning prediction and robotic process control. With sufficiently expanded datasets, predictive models could recommend drawing-in and reeding configurations according to specified structural, aesthetic, and functional targets, supporting adaptive weaving-process optimization.^{19–33}

Conclusions

This study demonstrates that integrated optimization of drawing-in and reeding provides an effective approach for controlling woven-fabric architecture and performance. Treating both operations as a coupled system improves control of warp distribution, alignment, compactness, structural regularity, and surface morphology, while supporting the development of complex, multilayer, elastic, and function-oriented fabrics. The results confirm that coordinated drafting and denting enhance structural consistency, dimensional stability, and manufacturing reproducibility. Statistical analysis showed that weave architecture and relative fabric density significantly affect surface roughness (SMD), whereas their effects on the coefficient of friction were not statistically significant under the investigated conditions. This indicates that roughness is strongly associated with weave geometry and interlacement, while friction depends on additional yarn, fiber, surface, and testing factors. Comparative results further showed that satin structures exhibited smoother surfaces than plain-weave structures, attributable primarily to differences in interlacement frequency, yarn crimp, and float geometry.

A major outcome is that drawing-in and reeding should be optimized jointly rather than independently, because their combined configuration determines the spatial organization of the warp system and consequently affects density, geometry, compactness, surface regularity, and mechanical behavior.

From a technological perspective, the study establishes a foundation for integrating digital textile engineering, CAD modeling, automated process planning, robotic execution, and machine-learning-assisted optimization. Digital process representation allows alternative configurations to be evaluated before production, while experimentally derived process–structure–performance relationships provide a basis for predictive modeling.

The proposed framework therefore supports a transition from experience-based preparation toward data-driven and predictive weaving. Future closed-loop systems could optimize process parameters computationally, convert them into robotic preparation instructions, experimentally validate the resulting fabric, and update predictive models using the acquired data.

Overall, the integration of drawing-in, reeding, digital design, robotic execution, and predictive modeling offers a pathway toward greater precision, repeatability, design flexibility, and resource efficiency while reducing dependence on manual trial-and-error. This integrated architecture is consistent with the objectives of Industry 4.0 and emerging human-centered Industry 5.0 manufacturing.

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Conflicts of interest

There are no conflicts of interest.

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