Cultural Politics Reconstruction of Textile Industry Heritage from the Perspective of Marxist Spatial Production Theory: A Case Study of the Modern Cotton Mill Cluster in the Yangtze River Delta

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ABSTRACT This study investigates the cultural-political reconstruction of textile industrial heritage from the perspective of Marxist spatial production theory, taking the modern cotton mill cluster in the Yangtze River Delta as a representative case. To reveal the mechanisms through which capital-driven spatial transformation reshapes production systems and workers' identities, the research integrates historical archives, data from 12 heritage sites, 42 oral histories, ISO 1101-based precision measurement, three-dimensional reconstruction, and digital twin technologies into a comprehensive analytical framework. High-precision spatial acquisition and digital modeling not only enhance the authenticity of industrial heritage restoration but also provide a technical foundation for intelligent infrastructure monitoring and digital information management, where advanced sensing technologies play an increasingly important role. Quantitative analysis shows that the spatial retention rate of the blowing workshop is only 24.5%, while the average retention rate of original production functions is 33.3%, indicating substantial disruption of historical process logic and technological continuity under capital intervention. Based on these findings, a reconstruction strategy integrating process-unit preservation, precision measurement, digital twin restoration, and worker participation is proposed to promote the coordinated regeneration of technological systems and cultural memory. The proposed framework offers a sustainable pathway for balancing industrial modernization with heritage conservation and provides methodological insights for future interdisciplinary research on high-fidelity spatial sensing and intelligent digital management of industrial heritage.

INDEX TERMS textile industrial heritage, spatial production, digital twin, precision measurement, industrial heritage reconstruction

I. INTRODUCTION

THE modern cotton textile industry was central to China's early industrialization, profoundly influencing urban space, social structure, and cultural identity. Leveraging its advantages in port transportation, capital, and labor, the Yangtze River Delta region—centered on Shanghai, Wuxi, and Nantong—emerged as a hub of modern textile industry agglomeration and technological diffusion since the late Qing Dynasty [1,2]. These spinning mills significantly shaped urban expansion and industrial layout in terms of spatial scale, constructing labor relations, gender structures, and technological systems centered around the factory system, thereby giving rise to a distinctive industrial culture [3].

However, during urban renewal, textile industrial heritage is frequently stripped of its physical evidence, reconfigured, and reconstructed, gradually eroding its authenticity [4,5]. In contemporary transformation practices, many projects convert textile factories into cultural and creative parks, art communities, or commercial complexes [6]. While this approach achieves spatial reuse on the surface, it often neglects the technical continuity and spatial structural logic inherent to the textile process system [7,8]. Venues centered on textile processes have been deconstructed into consumer landscapes, with production facilities either relegated to mere decoration or removed entirely to accommodate real estate development interests [9]. This cultural strategy, to some extent, conceals the fundamental tension between production knowledge and spatial politics in the preservation of industrial heritage, and exposes systematic issues in current heritage reconstruction, namely a lack of understanding of production systems, insufficient recognition of technical context, and inadequate retention of process details [10,11].

This issue cannot be fully understood if it is regarded merely as a technical absence or a cultural deviation. According to Marxist spatial production theory, the production of space is a process wherein capital restructures both material environments and social relations. The neglect of the production system, technical context, and process detail is not incidental but is rooted in the logic of capital, which seeks surplus value through spatial reconfiguration. Therefore, the research framework of this paper embeds these deficiencies into the theoretical horizon of spatial production, aiming to reveal how cultural politics and capital power interact to reshape the authenticity and identity of textile heritage.

In this context, it is imperative to identify the mechanisms of capital reconstruction through Marxist spatial production theory and to explore heritage reconstruction pathways that balance production materiality with contemporary cultural demands. This constitutes a key challenge and a theoretical gap in current research on textile industrial heritage [12,13]. At the technical level, equipment distortion, technical discontinuities, and functional disarray have led to the erosion of production semantics and the de-historicization of process knowledge. Understanding of industrial heritage is often limited to architectural form and historical symbolism, lacking comprehensive restoration of production space and labor practices, and failing to effectively incorporate public perspectives [14,15].

At the intersection of Marxist spatial production theory and industrial heritage research, recent scholarship has adopted a critical spatial perspective to examine various regions and cases, highlighting the profound impact of capital, power, and social structure on the reproduction of industrial heritage. Ahn [16] explored the integration of Marxism into urban planning through critical literature analysis and dialogue, illuminating its potential for sustainable and equitable development. Yang [17] employed spatial production theory and multiple methods to analyze the cultural governance and spatial logic of Taipei and Hong Kong during industrial transformation, revealing differences in local government systems. From a comparative China-West perspective, Zhang et al. [18] analyzed policy and institutional differences between Western Europe and China in industrial heritage protection, demonstrating the influence of development levels on practical approaches. In specific urban cases, Qian [19] examined two industrial heritage sites in Hangzhou, analyzing how local governments and real estate capital promoted renewal, resulting in the commercialization of heritage and the weakening of cultural narratives. Song et al. [20] used the Xi'an Jihua 3511 Factory as a case, employing multiple methods to study its functional transformation and governance innovation within a complex landscape. Although these studies enrich the application of Marxist spatial theory in industrial heritage from multiple dimensions, common challenges persist, such as insufficient explanation of the spatial-political dimension and disconnects between historical narratives and actual capital mechanisms.

In the realm of material protection and process restoration for industrial heritage, the application of digital technology and new materials is increasingly a catalyst for innovation in conservation concepts and practices. Lite et al. [21] reviewed the degradation and protection methods for textile cultural relics, emphasizing the potential of antibacterial nanomaterials to delay degradation. Dang et al. [22] categorized China's digitalization practices in world cultural heritage into six levels, elucidating evolutionary features and development trends in data collection, visualization, and application. Building on this, Yao [23] analyzed digital technology applications and key techniques in intangible cultural heritage, noting that digitalization is a key means to promote protection, dissemination, and the practical inheritance of craft knowledge. Zhang et al. [24] reviewed terminology and practices in industrial heritage protection in Belgium, demonstrating its effectiveness in integrating urban development and providing reference points for the coordinated development of textile industrial heritage. Conversely, Rashid et al. [25] examined the Dennys Lascelles wool store, combining emotional value with digital technology, and argued that traditional protection models struggle to adapt to urban change, advocating for an inclusive and dynamic paradigm in industrial heritage protection. In summary, while existing research has introduced various technical innovations, it remains insufficient in addressing social and cultural dynamics, public participation mechanisms, and value diversity. There is an urgent need for deeper theoretical and methodological integration.

To address the dual loss of technological and cultural heritage in the textile industry, this paper develops a comprehensive research framework integrating spatial deconstruction and process analysis, informed by Marxist spatial production theory. The framework focuses on 12 representative spinning mills in the Yangtze River Delta. Through historical data, process lines are reconstructed, while 3D modeling and ISO measurement are used to restore equipment accuracy. Additionally, 42 oral histories from workers are analyzed to explore mechanisms of knowledge dissemination and clarify the relationship between process logic and spatial practice. A capital rheology model is also constructed to reveal the coupling between equipment disposal and space compression. The study proposes a strategy centered on process unit protection, technical group participation, and digital twin restoration to address material, identity, and social challenges in contemporary heritage reconstruction.

The selection of 12 heritage sites was based on the distribution of modern cotton mills across Shanghai, Wuxi, and Nantong, ensuring coverage of various ownership structures, transformation trajectories, and spatial patterns. The 42 oral histories were obtained from workers with diverse roles and years of experience, reflecting different layers of technical knowledge and identity formation. These numbers were chosen for analytical representativeness, capturing the range of industrial practices and cultural memories essential to reconstructing the production system and its political implications across the Yangtze River Delta, rather than strict demographic representativeness.

This study employed purposive sampling within the textile mill cluster of the Yangtze River Delta, selecting 12 heritage sites and 42 oral histories to capture diverse ownership types, transformation trajectories, and spatial forms. Inclusion criteria for sites included the availability of accessible archives or records of process layouts and evidence of formal transformation or reuse after 1990. Sites lacking documentation or where onsite investigation was not feasible were excluded. Interviewees were required to have at least 12 months of production experience, be at least 18 years old, and provide written consent for audio recording and transcription. The sample encompassed diverse occupations, experience levels, and transformation contexts until thematic saturation was reached (interview 42). All interviews were transcribed verbatim and processed in NVivo 12. Two independent coders initially open-coded 20 transcripts to develop a codebook, which was then applied to the entire dataset. Coding consistency was measured, yielding a Cohen's kappa of 0.82 and an intraclass correlation coefficient of 0.79. Discrepancies were resolved through joint discussion.

II. THEORETICAL FOUNDATION AND ANALYTICAL METHOD: SPATIAL PRODUCTION AND CULTURAL POLITICS

UNDER THE LOGIC OF CAPITAL

ANALYSIS OF CAPITAL FLOW MODEL AND SPATIAL COMPRESSION MECHANISM

This subsection clarifies the conceptual framework by distinguishing two interrelated analytical layers. Capital rheology refers to the temporal flow of various forms of capital as they are invested, withdrawn, and reallocated within industrial landscapes. Spatial compression denotes the measurable contraction of process space and functional density resulting from capital rheology that prioritizes profit-driven reconfiguration over process preservation.

The spatial compression function presented below operationalizes capital rheology in geometric and process terms. In this model, each type k of capital is represented as a rheological component with an elasticity coefficient that quantifies its propensity to compress physical process space, and a maintenance cost term capturing the economic trade-off involved in spatial preservation. This mathematical formulation formally links the abstract concept of capital rheology with a quantifiable spatial compression outcome, serving as the empirical basis for measurement and validation.

$$C_t = \sum_{k=1}^{n} \epsilon_k \frac{I_k(t)}{S_k(t)} \tag{1}$$

In Formula (1), C_t represents the total space compression value at time t; $I_k(t)$ is the investment amount of the k-th type of capital in the heritage space; $S_k(t)$ is the corresponding space maintenance cost; and ϵ_k is the elasticity coefficient of the capital type with respect to space compression.

The parameters ϵ, k, α, β, w_n, and θ were set using a combination of corpus metrics and expert assessment. Initial values were derived from archival frequency, standardized asset records, and scores based on an oral history semantic matrix. A panel of 15 technicians, cultural heritage experts, and metrology engineers conducted pairwise comparisons using the analytic hierarchy process (AHP), with agreement ratios below 0.08. The final weights are presented in Table. The empirical coefficient θ was constructed from three indicators: length of service, process familiarity, and operator confidence. The weights were normalized to the range [0, 1] based on AHP results. Model validation was performed using least squares regression, with predicted scores showing a good fit to the spatial conservation rates of the 12 heritage sites. After adjustment, $R^2 = 0.72$. A Monte Carlo sensitivity analysis (1,000 simulations with $\pm 20\%$ weight perturbation) was conducted to verify robustness, demonstrating a stable distribution of model outputs.

In empirical modeling, terrestrial laser scanning and building information modeling (BIM) were used to reconstruct 12 textile heritage spaces in three dimensions. These models were combined with historical asset statements to establish a time series of capital investment and spatial deformation from 1930 to 2020. Results indicate a strong coupling between the frequency of capital intervention and the degree of spatial compression, especially in front-end process areas such as raw material pretreatment and yarn formation, where space occupancy rates decrease rapidly with accelerated capital inflow. This correlation does not imply direct causality in all cases; the interaction is also influenced by regulatory environments, shifts in local governance, and the agency of technical groups involved in heritage transformation. While capital intervention frequency and spatial compression degree often move in tandem, these mediating variables require careful consideration when interpreting results.

Moreover, different forms of capital have distinct effects on spatial compression. Industrial capital primarily targets process compression, whereas commercial capital directly alters the spatial functional structure. In summary, the capital flow model reveals the nonlinear process underlying the spatial transformation of textile industrial heritage. This mechanism demonstrates how capital reduces the integrity of process logic and diminishes the historical semantics embedded in production space, transforming them into resources for spatial reorganization oriented toward economic efficiency. This theoretical perspective helps explain trends of “de-crafting” and “de-identification” in contemporary heritage transformation.

From the Marxist spatial production perspective, the capital rheology model operationalizes the concept of time–space compression by quantifying the elasticity of different capital forms in spatial restructuring. The model parameters embody the logic of capital accumulation, wherein surplus value is pursued through the contraction of process lines and the subordination of historical semantics to economic efficiency. Similarly, the cultural tension function is derived from Lefebvre’s assertion that space is not neutral but contested. This function translates the contradiction between workers’ lived space and the abstract space imposed by capital into measurable variables, revealing how changes in operational paths and process mismatches materialize ideological struggles within heritage spaces. These models thus concretize Marxist theoretical constructs within a technical framework linking capital power to spatial and cultural transformation.

THE RECONSTRUCTION FRAMEWORK OF TEXTILE FACTORY SPACE AND TECHNOLOGY FROM THE PERSPECTIVE OF CULTURAL POLITICS

In regenerating textile industrial heritage, space is not merely a physical entity but also a field for reconstructing capital power and reorganizing cultural memory. Drawing on Lefebvre’s “spatial triad” and Althusser’s theory of ideological state apparatuses, this paper constructs a cultural politics reconstruction model for textile space, analyzing the coupling between process operation and worker identity under spatial compression.

This study divides the textile factory into a series of production units, each corresponding to a specific process space, associated technical functions, and historical context. The “cultural tension function” T is applied to measure the impact of spatial transformation on workers’ cultural identity:

$$T_i = \alpha \cdot d(p_i, p_i') + \beta \cdot \delta f_i \tag{2}$$

In Formula (2), $d(p_i, p_i')$ represents the trajectory distance between the original and modified operation; δf_i is the process mismatch caused by function transfer; α and β are adjustment parameters.

Additionally, a semantic mapping function $M : L \to O$ is constructed whereby language symbols L in workers’ narratives are coupled with process operation behaviors O to quantify the synchronization intensity between linguistic memory and spatial operations. This quantifies the cultural embedding depth of each spatial unit.

During spatial redistribution, principal component analysis integrates spatial compression rate, semantic retention, and process continuity. A multidimensional evaluation index system is established, and a reconstruction priority function is proposed:

$$P_i = w_1 \cdot C_i + w_2 \cdot M_i + w_3 \cdot T_i \tag{3}$$

Formula (3), C_i represents the spatial compression rate; M_i is the semantic embedding degree; T_i is the cultural tension; and w_n is the normalized weight. This function guides the prioritization of spatial preservation and reconstruction strategies for each process area.

The study established a process for converting qualitative narrative materials into cultural tension profiles. Transcripts were segmented into thematic units and annotated according to a coding manual. Coding results were mapped to an ordinal index from 0 (absent) to 3 (strong and repetitive emphasis). Unit scores were summed using weights determined via AHP to form a composite spatial unit score. Validity testing revealed that cultural tension scores were significantly correlated with compression rate (r = 0.65) and functional transposition rate (r = 0.58), demonstrating convergent validity. Receiver operating characteristic (ROC) analysis identified high-tension units as positive categories, with an area under the curve (AUC) of 0.81, indicating acceptable discriminatory performance.

In summary, the model presented herein considers both the spatial functional logic and the workers’ identity structure, enabling the systematic construction of textile heritage from physical regeneration to symbolic restoration within the context of cultural politics.

ANALYSIS OF WORKING-CLASS MEMORY, IDENTITY, AND THE CULTURAL POLITICAL IDENTITY MECHANISM

During the transformation of textile industrial heritage, the historical memory and identity of the working class are often compressed and fragmented by the logic of spatial reconstruction, mapping the practical path, planning intention, and perceptual memory of production space into “job behavior trajectory,” “functional configuration after transformation,” and “cultural identity projection,” respectively. This process constructs a three-dimensional interactive mechanism of workers’ cultural and political identity.

Based on semantic vector extraction from oral histories, this paper establishes a “social memory matrix” M_{ij}, where i represents individual workers and j denotes the spatial memory dimension. This matrix is modeled using fuzzy logic functions and K-means clustering to quantify spatial memory. Implementation involved segmenting and encoding oral history transcripts using semantic role labeling, embedding key process-related terms through word vectorization, and aligning each semantic vector with spatial units reconstructed in the BIM model to ensure correspondence between narrative elements and spatial coordinates. These vectors were normalized into numerical matrices, serving as input for fuzzy logic functions and clustering algorithms. While quantification simplifies the richness of oral narratives—partially sacrificing nuances such as emotional tone and informal expression—this limitation is acknowledged, and results are interpreted accordingly. The “identity displacement function" ΔI_i is further used to measure the extent to which workers' identities change in response to spatial transformation:

$$\Delta I_i = \gamma \cdot \Delta S_i + \lambda \cdot F_i \tag{4}$$

In Formula (4), ΔS_i is the spatial compression rate experienced by individual; F_i is the frequency intensity of the individual's participation in the process; γ and λ are adjustment factors. This function reveals that greater transformation and lower individual participation correspond to a more pronounced decline in sense of identity.

Combining these models, this paper constructs a "space compression–identity dilution" feedback mechanism, whereby the dominance of capital logic directly diminishes the influence of operational experience within the identity structure, leading to the reconstruction of identity and weakening of historical participation. Finally, the "cultural identity strength index" R_i is used to represent an individual's level of identification with the space after transformation:

$$R_i = \theta \cdot T_i \cdot \rho_i \tag{5}$$

In Formula (5), T_i is the intensity of cultural tension; ρ_i is the weight of the technical level of the position within the process chain; and θ is the experience coefficient. The experience coefficient θ reflects the extent to which individual workers have accumulated tacit knowledge through repeated operation of the same process. This coefficient is derived from oral history records and field surveys by coding years of experience, process familiarity, and self-reported operational confidence. A normalized scale from 0 to 1 is applied, with higher values indicating deeper embeddedness of operational memory. This coefficient ensures that the index balances technical weight and cultural tension, preventing overemphasis on structural parameters at the expense of experiential knowledge.

This analytical framework reveals the spatial logic underlying the generation of working-class cultural identity. The participation of original workers in heritage transformation and the preservation of core process space are essential for maintaining their cultural-political identity and historical narrative.

APPLICATION OF PRECISION MEASUREMENT AND DIGITAL MEASUREMENT TECHNOLOGY

The spatial restoration of textile industrial heritage necessitates high-precision restoration of equipment layout and process accuracy to preserve technical logic and historical authenticity. Accordingly, this study adopts the ISO 1101 standard, utilizing a three-coordinate measurement system and a laser tracker to conduct spatial mapping and error analysis of core equipment, and develops a quantitative calibration mechanism for process space. A unified metrology approach is employed for geometric acquisition and process parameter measurement. A terrestrial laser scanner is configured with high-precision angular resolution, achieving an average point density of approximately 200–300 points per square meter. A portable laser tracker is used for static and dynamic coordinate control, with a dynamic sampling frequency of 50 Hz. Micro-displacement sensors record data at 1,000 Hz during roller spacing and actuator response testing. All equipment is calibrated according to national metrology standards. Measurement uncertainty is assessed in accordance with the Guide to the expression of uncertainty in measurement (GUM). After combining the standard uncertainties of individual instruments, the uncertainty for terrestrial scanning and registration is 0.9 mm, and for laser tracker alignment is 0.3 mm. This corresponds to an expanded uncertainty of approximately ± 1.8 mm at a 95% confidence level, with the overall error controlled within ± 2 mm. In the equipment layout analysis, the machine tool reference surface is designated as the reference, the equipment boundary coordinate point set $\{K_i\}$ is obtained through the three-coordinate contact probe, and the deviation value is calculated:

$$\delta_i = \left\| K_i - K_i^{(0)} \right\| \tag{6}$$

In Formula (6), the original design position is denoted as $K_i^{(0)}$, and the equipment offset value is represented as δ_i.

In the space compression evaluation, the centerline spacing d_{ij} of the process equipment is measured and compared with the original design value $d_{ij}^{(0)}$ to define the space retention rate:

$$R = \frac{d_{ij}}{d_{ij}^{(0)}} \tag{7}$$

Additionally, a point cloud model is established through non-contact laser scanning, and spatial volume comparisons are performed in conjunction with BIM. In terms of process parameter restoration, the focus is on detecting the accuracy of the roller spacing setting in the drafting system. A micro-displacement sensor is employed to measure the setting time. If the operation time exceeds the threshold or the setting deviation surpasses the original process tolerance range, it indicates that the empirical process is difficult to restore. The above measurement model confirms the existence of varying degrees of equipment dislocation, compression distortion, and increased operational complexity in the current heritage space, providing a quantifiable and traceable measurement basis for subsequent digital twin modeling and cultural reconstruction.

DIGITAL TWIN AND PROCESS RESTORATION, PROCESS RESTORATION AND CULTURAL CONSTRUCTION

Digital twin technology offers a systematic virtual-reality mapping mechanism for the spatial restoration and process reconstruction of textile industrial heritage. This paper constructs a multi-level digital twin model based on three-dimensional geometry acquisition, dynamic process control, and semantic coding embedding to achieve coordinated reproduction of spatial structure, process path, and cultural semantics.

During the geometric modeling stage, laser scanning and industrial vision technology are utilized to collect point cloud data of textile equipment and build a standardized three-dimensional coordinate system. Error propagation analysis and sampling stability assessments indicate that configuration error can be controlled within ± 2 mm under specified field conditions, corresponding to an expanded uncertainty at a 95% confidence level. The test environment is maintained at 20 ± 2°C and $45\% \pm 10\%$ relative humidity; all instruments are within their calibration period and no older than seven years. This error standard applies to devices with a maximum linear dimension of 10 m or less and is valid using a multi-station scanner and tracker co-registration process. For larger devices or acquisitions outside these environmental conditions, the uncertainty will increase, and the configuration error must be adjusted accordingly.

In the process control layer, a state-space dynamic model is constructed for the spinning and drafting system:

$$\dot{x}(t) = A(t)x(t) + B(t)u(t), \quad y(t) = C(t)x(t) \tag{8}$$

In Formula (8), $\dot{x}(t)$ denotes the internal state of the equipment; $u(t)$ is the operation control input; $y(t)$ is the response output; and matrices $A(t)$, $B(t)$, and $C(t)$ represent the system structure and parameter evolution, enabling precise control of speed, tension, and transmission rhythm.

The virtual operation process is modeled based on discrete event systems, which define the process state set Q, event set Σ, and transfer function δ. This process maps the operation path and timing nodes of yarn formation, creating a process-directed graph and facilitating dynamic simulation of the entire process. At the semantic level, the semantic triple structure (O_i, A_j, V_k) is applied to bind the operation unit O_i, attribute dimension A_j, and parameter value V_k to the IEC 61360 general data dictionary, thereby establishing a connection between the digital twin and the knowledge graph. Unstructured experience is embedded in the operation response deviation adjustment through a fuzzy logic control system to support the reproduction of tolerance in the historical operation path.

In summary, the digital twin model constructed in this study supports physical, logical, and semantic triple modeling while enabling the cognitive embedding of empirical craftsmanship. This framework provides a robust technical foundation for authenticating heritage spaces and reconstructing cultural value. Nevertheless, the application of digital twin technology faces several limitations. The modeling process cannot fully resolve the issue of incomplete operational knowledge, as tacit skills and experiential details often resist codification. Geometric error correction also remains challenging; historical equipment deformation and undocumented modifications result in discrepancies that exceed the tolerance range of standard models. For example, deviations in roller spacing reconstruction demonstrate that even high-resolution sensors cannot capture the operational elasticity of manual adjustments. Addressing these challenges requires further research into adaptive error correction algorithms, integration of oral history coding with real-time simulation, and hybrid restoration strategies that combine digital models with experiential reenactment.

III. EMPIRICAL ANALYSIS: SPATIAL RECONSTRUCTION OF TEXTILE INDUSTRIAL HERITAGE, CULTURAL MEMORY, AND CAPITAL LOGIC

HISTORICAL RESTORATION AND MODERN DECONSTRUCTION OF THE SPATIAL LAYOUT OF TEXTILE FACTORIES

This section analyzes the preservation and variation characteristics of the spatial layout of typical textile factories in the Yangtze River Delta region during heritage transformation through quantitative evaluation.

The analysis focuses on four indicators: spatial retention rate, compression rate, functional transposition rate, and display substitution rate, revealing the reuse logic of process spaces. The display substitution rate refers to the proportion of original process equipment that has been removed and replaced by exhibition elements such as symbolic installations or replicas. The craft area denotes spaces originally dedicated to manual or semi-manual operations, such as carding and blowing, which possess distinctive spatial organization and technical significance. These categories distinguish between spaces preserved for their technical logic and those reconstructed primarily for display purposes. Figure 1 presents the quantitative comparison results for each process area across the four indicators.

As illustrated in Figure 1, space retention is highly dependent on the structural openness and display adaptability of the process area. The weaving area exhibits the highest retention rate (64.8%) due to its independence and suitability for display transformation. In contrast, the retention rate of the blowing workshop is only 24.5%. Conversely, the compression rate in the blowing workshop reaches 68.2%, indicating substantial reconstruction of its original functional space for alternative uses. The functional transposition rates in the dyeing and finishing area and the drawing and spun yarn area are 49.7% and 36%, respectively, signifying significant loss of original technical logic in these process areas.

For the 12 transformed factory spaces, this study systematically organized their current functional distribution, including display, office, and commercial use, while retaining some original functions. The relevant data are summarized in the heat map presented in Figure 2.

Analysis of the functional distribution in 12 typical factories (Figure 2) reveals that the average retention rate of original process functions is 33.3%, with the highest rate at 46.4% in F08 and the lowest at 24.2% in F04. Most factories prioritize display and commercial functions,

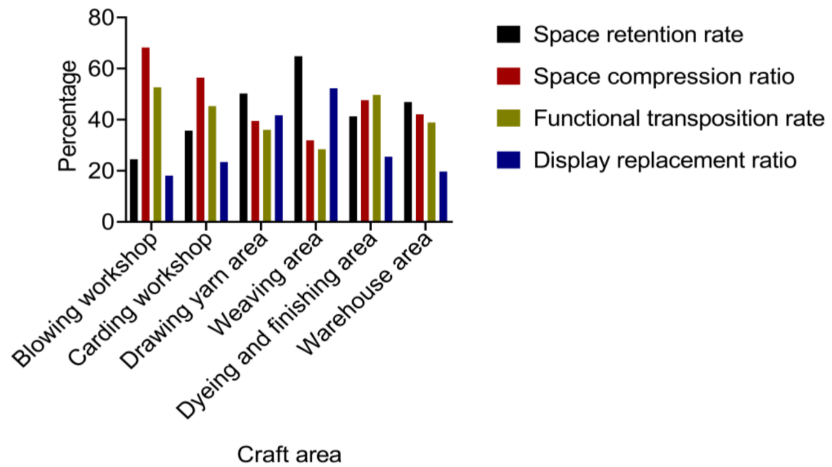

FIGURE 1. Distribution of spatial transformation indicators in each process area

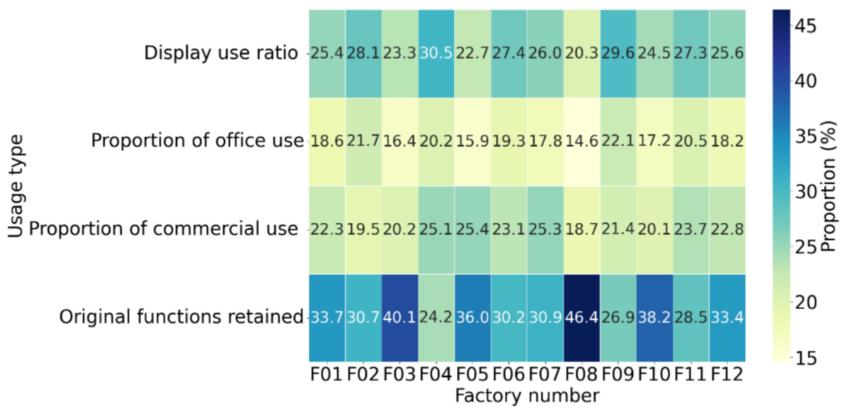

FIGURE 2. Heat map of the distribution ratio of functions used in different factories

followed by office use, indicating a trend toward functional translation driven by the principle of "visibility first," which is positively correlated with the integrity of the building structure.

INHERITANCE STATUS AND IMPACT OF PROCESS OPERATION KNOWLEDGE

To evaluate the status of knowledge inheritance and the regenerative capacity of textile technology, this study constructs a multidimensional index system to compare and analyze typical technology types across four dimensions: cognitive mastery rate, practical reproducibility, parameter error, and operation time, as shown in Figure 3.

(1) Proportion of knowledge mastery and reproduction status of typical textile processes; (2) Mastery of principles and practical operation scores; (3) Measured error statistics of relevant operation parameters; (4) Average time performance for relevant operation steps. The data trends in Figure 3 reveal significant differences in knowledge retention and reproduction capabilities among various processes. The recognition rate for key processes in streamline control reaches 72.5%, with a practical reproduction ability of 58.9%, indicating clear path logic and stable operational feedback. Although the recognition rate for key processes in drafting control is relatively high (68.4%), the retention rate of process knowledge is only 42.8%, highlighting a disconnect between theory and practice. The parameter setting deviation in the temperature control system is prominent, reaching 0.62 mm, and the average time for parameter initialization is 119 seconds, underscoring the system's high dependence on operator proficiency and low level of automation.

The reported value of 0.62 mm refers to the mechanical displacement at the actuator output of the temperature control mechanism, used to adjust the roller gap or thermal element position, rather than temperature units. Displacement is measured at the actuator output by a calibrated micro-displacement sensor and referenced to the roller axis.

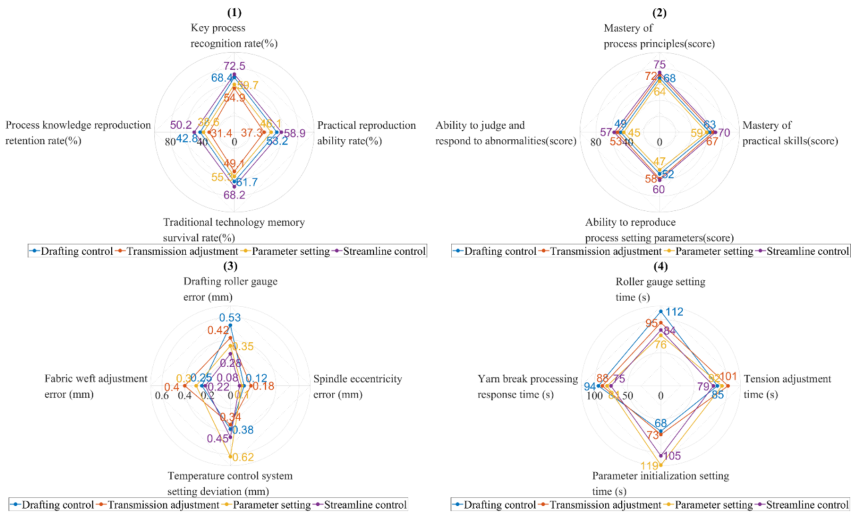

FIGURE 3. Radar chart comparing indicators of each capability dimension of typical textile processes

ANALYSIS OF DIFFERENCES BETWEEN EQUIPMENT ACCURACY RESTORATION AND HISTORICAL EQUIPMENT PARAMETERS

To assess the accuracy of key equipment in the restoration of textile industrial heritage, this study collects mechanical deviation data from core components, including sizing, spinning, carding, and weaving, and compares their operational stability and structural differences; details are presented in Figure 4.

Figure 4 demonstrates that different types of equipment exhibit distinct deviation patterns under dynamic conditions. The maximum deviation of the sizing machine's cylinder temperature control component is 0.45 mm, with a wide fluctuation range, primarily influenced by heat transfer lag and external environmental factors. The dragon tendon component of the spinning machine displays the smallest deviation, ranging from 0.05 mm to 0.23 mm, indicating consistent operational stability. The deviation distribution of other devices, such as the roller gauge adjustment system and the automatic weft-beating system angle synchronization device, is concentrated between 0.11 mm and 0.39 mm, reflecting robust structural constraints on control accuracy. Although modern restoration equipment optimizes structural design, it still exhibits parameter response lag or insufficient control feedback when simulating the original process states.

IMPACT OF CAPITAL FLOW ON THE COMPRESSION OF TEXTILE FACTORY HERITAGE SPACE

This section quantitatively evaluates the spatial compression characteristics of textile factories in the Yangtze River Delta region under varying transformation paths by constructing five capital intervention intensity models. These models cover five major process modules: raw material area, forming area, weaving area, process preparation area, and finished product finishing area. Figure 5 compares the compression rates of these production areas under different levels of capital intervention.

Among the different intervention stages, capital-oriented transformation exerts the greatest influence on spatial compression. The compression rate in the raw material pretreatment area reaches 81.6%, while the yarn formation area and process preparation area record rates of 80.9% and 73.5%, respectively. In contrast, compression rates during small-scale adjustments and low capital intervention stages remain below 40% for most areas, indicating limited scope and pace of transformation.

PRACTICAL APPLICATION AND EFFECT EVALUATION OF DIGITAL TWIN TECHNOLOGY IN PROCESS RESTORATION

To verify the feasibility and stability of the digital twin system in textile process restoration, this study selects typical chemical materials—such as slurry, dye auxiliaries, printing slurry, adhesives, coating liquid, and finishing agent—and monitors their dynamic viscosity changes across ten rounds of simulation operations to evaluate process response consistency. Experimental trends are presented in Figure 6.

According to Figure 6, different materials exhibit distinct rheological stabilities. The adhesive shows significant fluctuations, with viscosity dropping from 22.3 Pa·s to 19.7 Pa·s and then rising to 23.1 Pa·s, indicating high sensitivity to operational cycles. The viscosity of the printing paste peaks at the fourth round (14.1 Pa·s) before declining, reflecting structural susceptibility to disturbance. In contrast, the viscosity of slurry and dye auxiliaries fluctuates minimally, and the finishing agent remains stable between 3.6 Pa·s and 4.1 Pa·s, demonstrating strong material consistency.

A pilot study was conducted at site F08 to implement the proposed measurement modeling and engagement workflow. Multi-station terrestrial laser scanning, registered to portable tracker control points, combined with historical drawings and on-site measurements, generated a Level-of-Detail 3 BIM-based digital twin with semantic tags for ten process units. A drafting system facilitated a restoration

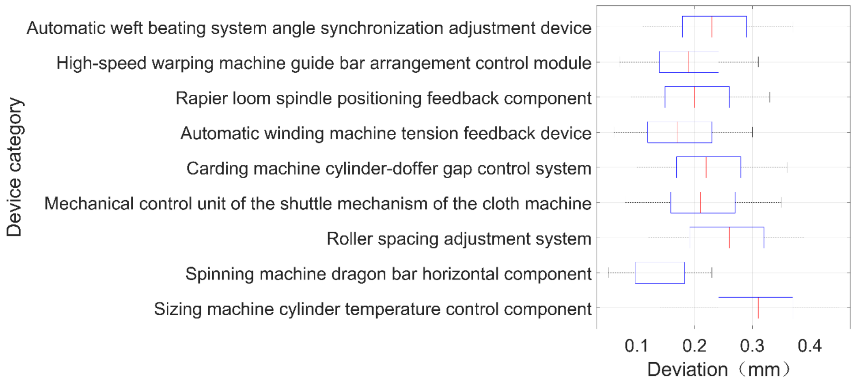

FIGURE 4. Distribution of operational deviations in key components of various textile equipment

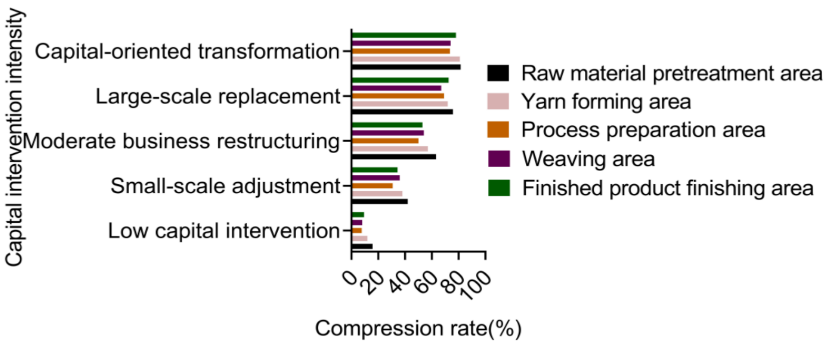

FIGURE 5. Comparison of compression rates in various production areas under different capital intervention levels

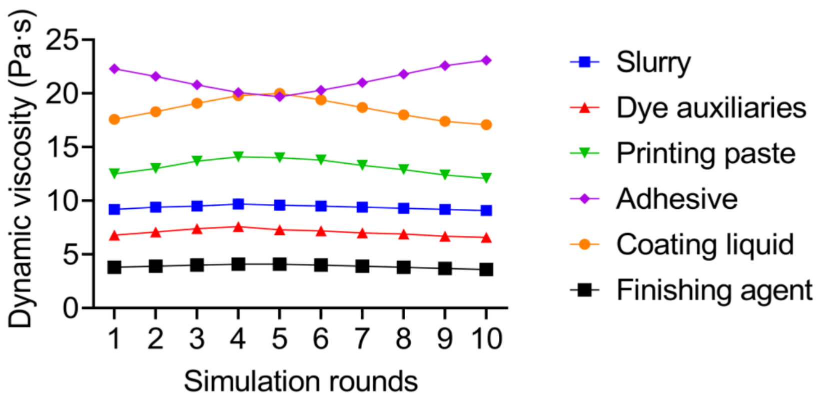

FIGURE 6. Dynamic viscosity changes curves of different chemical materials during ten rounds of simulation

feasibility test, with roller spacing measured by calibrated micro-displacement sensors and a process controller model enabling closed-loop simulation. Registration residuals were below two millimeters RMS, and reconstructed parameter settings matched operator records with an average absolute error of 0.15 millimeters. A validation workshop confirmed semantic fidelity and provided corrective annotations. The pilot validated the end-to-end pipeline and identified operational constraints.

ANALYSIS OF THE INTERACTIVE MECHANISM BETWEEN WORKING-CLASS CULTURAL IDENTITY AND SPATIAL REUSE

This section establishes a five-dimensional evaluation system to assess the impact of different reuse types on the cultural identity of the working class, including historical identity, emotional belonging, technological continuity, discourse participation, and identity recognition. The research objects encompass typical transformation forms such as industrial museums, public memory corridors, creative cultural parks, commercial complexes, and co-working spaces.

The performance of these five space reuse types across each evaluation dimension is depicted in Figure 7.

As shown in Figure 7, the industrial museum achieves the highest scores in historical identity (91%), emotional belonging (88%), and technological continuity (84%), effectively conveying the original logic of craft culture. The public memory corridor closely follows, balancing openness and commemoration. While creative cultural parks demonstrate strong visual appeal and perform well in emotional belonging and identity recognition (73% and 61%, respectively), they are insufficient in technological continuity and worker participation. In contrast, commercial complexes and co-working spaces rank lowest across all five indicators, with discourse participation rates of only 9% and 17%, respectively, indicating that these spaces have lost channels for expressing workers' historical memories as they prioritize functional renewal.

IV. COST IMPLEMENTATION DIFFICULTY AND FEASIBILITY ASSESSMENT

This study includes a comprehensive assessment of implementation costs, practical constraints, and feasibility to ensure the practicality of the proposed approach. The budget for 3D acquisition (terrestrial scanning, photogrammetry, and post-processing) for a medium-sized factory is approximately RMB 50,000–150,000 per site; laser tracker rental for alignment and control measurement is approximately RMB 30,000–80,000; initial investment in developing a digital twin system integrating geometric modeling, semantic encoding, and dynamic control is approximately RMB 200,000–800,000 per site, with subsequent annual costs for data hosting, hardware upgrades, and skills training ranging from RMB 30,000–100,000. The costs for machinery repair and process restoration vary widely, influenced by parts availability, labor costs, and safety regulations. Key risks include a shortage of craftspeople, building code restrictions, and conflicts with commercial reuse. Mitigation strategies include phased pilot projects, capacity building, multi-party financing (such as publicprivate partnerships and employee stock ownership models), and decision-making tools based on lifecycle costs.

V. COMPARISON WITH EXISTING PROTECTION METHODS

This study compares the proposed digital twin strategy, centered around process units, with three common conservation approaches using evaluation metrics such as process logic preservation, technological continuity, worker engagement, and economic scalability. Commercial reuse offers rapid economic returns but often involves dismantling equipment, resulting in low technological continuity and worker engagement. Museumstyle conservation enhances historical identity but requires substantial public funding and disrupts process continuity. In situ restoration of original processes preserves knowledge and semantics but is constrained by a shortage of skilled workers and high labor costs, limiting scalability. The proposed strategy outperforms commercial transfer in terms of technological continuity and simple process restoration in terms of scalability, achieving process fidelity, training simulation, and phased restoration through digital twins.

FIGURE 7. Impact of different reuse types on five dimensions of workers' cultural identity

VI. CONCLUSION

The empirical analysis consistently supports the theoretical framework, linking spatial compression mechanisms to the restructuring of cultural memory. The research demonstrates that capital has transformed production spaces during industrial heritage conversion and has affected the historical memory and cultural identity of the working class. Future efforts should focus on optimizing restoration methodologies, enhancing accuracy, strengthening dynamic analyses of capital and spatial reconstruction, and exploring the balance between production efficiency and cultural memory preservation.

Although the empirical analysis centers on the Yangtze River Delta, the mechanisms identified—such as capital-driven spatial compression, erosion of process knowledge, and reconstruction of worker identity—are not exclusive to this region. Similar patterns have been observed in other textile heritage contexts affected by global industrial restructuring, where capital logic intersects with cultural politics. The analytical framework proposed in this study thus provides transferable tools for understanding industrial heritage transformation across diverse socio-economic environments. Nonetheless, variations in institutional arrangements, cultural traditions, and labor regimes necessitate careful contextualization before direct generalization. This comparative perspective extends the relevance of the findings beyond the local case and fosters dialogue on the protection of global textile heritage.

This study offers a novel perspective on the protection of global textile industrial heritage, advocating for a balanced approach between capital and labor to ensure the sustainability of technological innovation and worker culture.

AUTHOR CONTRIBUTIONS

All work in this study was independently completed by Weixia Han.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

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